

HIGH VELOCITY IMPACT PROPERTIES OF AS-BUILT AND HEAT TREATED Ti6Al4V (ELI) SPECIMENS BUILT THROUGH DIRECT METAL LASER SINTERING

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Date: May 2021

DECLARATION OF INDEPENDENT WORK

DECLARATION WITH REGARD TO INDEPENDENT WORK

I, TEBOHO CHRIS MOLEKO, passport number _____ and student number _____, do hereby declare that this research project submitted to the Central University of Technology, Free State, for the Degree, MASTER OF ENGINEERING IN MECHANICAL ENGINEERING, is my own independent work; and complies with the Code of Academic Integrity, as well as other relevant policies, procedures, rules and regulations of the Central University of Technology, Free State; and has not been submitted before to any institution by myself or any other person in fulfilment of the requirements for the attainment of any qualification.



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SYMBOLS, ABBREVIATIONS AND ACRONYMS

$\dot{\epsilon}$	Strain rate
ρ	Density
σ_{uts}	Ultimate tensile strength
3D	Three-dimensional
AA 5083	Aluminium alloy 5083
AM	Additive manufacturing
ASB	Adiabatic shear band
ASTM	American Society for Testing of Materials
BHN	Brinell hardness number
CAD	Computer aided design
CTE	Coefficient of thermal expansion
CUT	Central University of Technology, Free State
DMLS	Direct metal laser sintering
ELI	Extra low interstitial
E_m	Ballistic mass efficiency
EOS	Electro Optical Systems, GmbH
MPa	Mega pascal
NRF	National Research Foundation
PBF	Powder bed fusion
RHA	Rolled homogeneous armour
SEM	Scanning electron microscope
SLM	Selective laser melting

NOMENCLATURE

As-built specimens	Built specimens without any post DMLS heat treatment.
Ballistic mass efficiency	The weight per unit area of RHA divided by the weight per unit area of the subject material, both required to defeat a given ballistic threat.
Calibre	The internal diameter or bore of a gun-barrel.
Heat treated specimens	Built specimens with post DMLS heat treatment.
Projectile	An object moving off the ground.
Stress relieved specimens	Built specimens with post DMLS stress relieving.
V ₅₀ ballistic limit	The velocity at which a specific projectile is expected to penetrate the armour half of the time.

LIST OF PUBLICATIONS

Peer Reviewed Conference Proceedings

1. **Teboho Moleko, Maina Maringa and Willie du Preez**, Wrought Ti6Al4V as an alloy for high velocity impact applications, *Design and Additive Manufacturing of Titanium Parts pre-conference seminar, Proceedings of the 20th Annual International RAPDASA Conference, Emoya Estate, Bloemfontein, 5 - 8 November 2019*, pp. 66 – 77, ISBN 978-0-6398390-0-4.
2. **Teboho Moleko, Maina Maringa and Willie du Preez**, Justification for high velocity impact testing using as-built and stress relieved DMLS Ti6Al4V (ELI) based on results for wrought Ti6Al4V, *Design and Additive Manufacturing of Titanium Parts pre-conference seminar, Proceedings of the 21st Annual International RAPDASA Conference, Stellenbosch University, Western Cape, 4 - 6 November 2020*, pp. 180 – 191, ISBN 978-0-620-90354-7 (e-book).
3. **Teboho Moleko, Maina Maringa and Willie du Preez**, Comparative analysis of the high velocity impact behaviour of wrought Ti6Al4V and as-built and stress relieved DMLS Ti6Al4V (ELI), *2021 Rapid Product Development Association of South Africa - Robotics and Mechatronics - Pattern Recognition Association of South Africa (RAPDASA-RobMech-PRASA) Conference, CSIR, 3 - 6 November 2021* (accepted for publication)
4. **Teboho Moleko, Maina Maringa and Willie du Preez**, Fractography and Microstructural Analysis of Wrought Ti6Al4V Plates Subjected to High Velocity Impact, *2022 RAPDASA-RobMech-PRASA-CoSAAMI Conference, 8 – 11 November 2022, Stellenbosch* (submitted).
5. **Teboho Moleko, Maina Maringa and Willie du Preez**, Fractography and Microstructural Analysis of As-Built and Stress Relieved DMLS Ti6Al4V (ELI) Plates Subjected to High Velocity Impact, *Hindawi* (Submitted).

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ABSTRACT

Direct metal laser sintering (DMLS) is a metal additive manufacturing (AM) technology specific to the company Electro Optical Systems (EOS). Generally, this technology is known as selective laser melting (SLM) and it fits in the broad category of powder bed fusion (PBF) (ASTM F2792-12a). The process is a laser-based technique that uses the digital input of CAD models to create three-dimensional (3D) parts from metallic powders. In the Centre for Rapid Prototyping and Manufacturing (CRPM), an EOSINT M280 system was used for building the DMLS parts for this study.

The term, high velocity, is used to describe speeds in the range of 50 to 1500 m/s in ballistics. In general, the mechanisms that are activated in ballistic impact depend on the thickness, ductility, strength, stiffness, hardness, toughness, strain rate, density of the target, and velocity of the projectile.

In order to get insight on the high velocity impact behaviour of the Ti6Al4V alloy, preliminary testing was conducted on wrought Ti6Al4V as a prelude to considerations of the as-built and stress relieved DMLS Ti6Al4V (ELI) alloy as an alternative to Rolled Homogeneous Armour steel (RHA) and aluminium alloy AA 5083 for high velocity impact applications. Preliminary ballistic impact testing of wrought Ti6Al4V involved the manufacturing of test plates of different thicknesses, and thereafter ballistic impact testing using 7.62 x 39 mm (.30 calibre) bullets travelling at an average velocity of 702 m/s.

The preliminary testing of the wrought Ti6Al4V revealed that its minimum thickness to prevent through penetration was above 14 mm. This value was found to lie between 14 mm and 18 mm. Based on the foregoing, the value falls between that of RHA and AA 5083 at 11.43 mm and 19.8 mm, respectively.

Fractographic analysis of the wrought Ti6Al4V plates further revealed that, although Ti6Al4V is usually classified as a ductile metal under normal loading conditions, when exposed to high velocity impact, the alloy exhibits both brittle and ductile behaviour.

Microstructural analysis of the wrought Ti6Al4V revealed that the high strain rate imposed on the plates, brought about alteration of the microstructure during high velocity ballistic impact. This was clear from the gradually increasing refinement of grains and decreasing measured average values of the widths of α -laths, radially away from the edges of the penetration holes of the projectiles. Both the refinement of grains and the decreasing average measured values of the widths of α grains were a function of the high rise in temperature followed by cooling.

The effect of impact on the plates tested was to create a compressive stress wave in the direction of impact (longitudinal axis of the penetration hole) and tensile stress waves in the radial and circumferential directions with respect to the penetration hole. These induced stresses tended to lengthen and widen the grains along the radial and circumferential directions, respectively. It was noted, however, that the predominant change in grains towards the edge of the hole was a reduction of size (refinement of grains). This suggested that the effect of grain refinement due to exposure to high temperatures overrode that of the induced stresses.

In addition, the high strain rate and attendant high rise in temperature arising from high velocity impact was enough to cause the formation of adiabatic shear bands (ASBs), whose incidence reduced with distance away from the edge of the projectile hole. The ASBs were seen in this work to be sites in which cracks propagated and therefore formed paths for failure of the material.

After the preliminary ballistic impact testing of wrought Ti6Al4V, a justification was formulated for investigation of the high velocity impact properties of as-built and stress relieved DMLS Ti6Al4V (ELI). The justification yielded values of optimum thickness for the DMLS alloy of 13.64 mm and 10.40 mm, based on the V_{50} ballistic limit and shear strain energy theories, respectively, which were lower than the respective values for wrought Ti6Al4V of 15.38 mm and 14 mm.

Ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI) also revealed a minimum thickness to prevent through penetration greater than 14 mm. This value fell short of the estimated value of 10.40 mm in the justification for testing the alloy, which can be attributed to the assumption made in the calculations of

normal deformation with the usual high plastic deformation encountered at low strain rates.

Visual inspection of the as-built and stress relieved DMLS Ti6Al4V (ELI) ballistically impacted plates unveiled plastic deformation, induced bulging and spalling on the entry side of the penetration holes for all the plate thicknesses. Furthermore, apart from the 8 mm thick plate, all the plates exhibited ductile failure on the exit side of the penetration hole, evidenced by the existence of petals there.

Fractographic analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates revealed brittle behaviour at the entry points of the penetration holes and ductile behaviour at the exit points of the penetration holes for all the plate thicknesses.

Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates further revealed that the high strain rates imposed on the plates, also brought about alteration of the microstructure during high velocity ballistic impact, as was observed for wrought Ti6Al4V. This was evidenced by a gradual increase of the β phase fraction towards the edge of the projectile hole. There was an attendant decrease in hardness towards the edge of the projectile hole as evidenced by the Vickers hardness measurements.

It was posed that due to the low thermal conductivity of Ti6Al4V (ELI) of 6.7 W/m-K, the heat generated by the high induced strain rates during high velocity impact, could not be conducted away effectively from the point where it was generated. This retention of heat is thought to have led to softening of the material and the formation of ASBs near the edge of the projectile hole. Moreover, the average velocity of the projectiles and the related primary and secondary penetrations in the present work was high enough to induce a temperature rise above the beta transus temperature over the period of impact. Though the time periods of impact (typically is about 2 – 5 ms) are much shorter than the normal heat treatment periods typified by heating and soaking, cooling in the present case occurred at ambient conditions and may thus be considered as fast cooling. Therefore, while there was not enough time to support whole scale transformation of α to β grains upon impact, there was adequate time for β grains to transform back to α grains after impact to form α/β lamellae. This effect was observed to reduce with distance away from the edge of the penetration hole.

The results obtained from the studies here revealed that as-built and stress relieved DMLS Ti6Al4V (ELI) manufactured through the DMLS process using an EOSINT M280 system with standard process parameters, can be used for high velocity impact applications, such as in the military and the aerospace industry.

CHAPTER 1 - INTRODUCTION

1.1. Background

Metallic materials for use in conditions of high velocity impact are needed in many industries that include the automotive, military and aerospace sectors [1]. The military requires high velocity impact-resistant materials in main battle tanks, light combat vehicles, ballistic armour, naval ships and body armour for protection against high velocity projectiles [1, 2].

In the aerospace industry almost every part that is exposed on the aeroplane during flight stands a risk of experiencing high velocity impact from bird strikes and other objects that may be in its path [1]. In all these industries, finding a suitable metal is essential, as people's lives could be at risk if a selected metal fails [2]. An example of such a scenario is if a projectile were to penetrate through metal used for protection in an armoured vehicle to hit passengers inside [2].

Over the past years, many metals have been tested extensively for use in armour for protection against ballistic attacks. Nevertheless, there are only four practical metallic alloy contenders for armour applications, namely aluminium, magnesium, steel and titanium alloys [2, 3]. Steel and aluminium alloys are the most commonly used metal alloys today, mainly due to their price and their amenability to working and welding [2, 3].

During the 1950s and 1960s Rolled Homogeneous Armour steel (RHA) and aluminium alloy AA 5083 were developed for ballistic armour and have been widely used since [2]. Although RHA and AA 5083 are still used today, they do have some limitations in their respective applications, such as low specific strength and low strength of the welded joints for AA 5083 and large weight due to the high density of RHA [2]. Magnesium and titanium alloys although expensive, have desirable properties for use as ballistic armour [2, 3].

Titanium is an attractive alternative material for designers of armour. It's most widely used alloy, grade 5 Titanium (Ti6Al4V), possesses a relatively low density of 4.45 g/cm³, whilst having relatively high values of ultimate tensile strength (σ_{uts}) and hardness of 900 to 1300 MPa and 300 to 350 BHN, respectively [4, 5]. Furthermore,

titanium alloys also have good fracture toughness and high corrosion resistance [5, 6].

Titanium alloy Ti6Al4V components may be produced through a variety of methods, including casting and direct metal laser sintering (DMLS) among others [7]. The DMLS process is a metal additive manufacturing (AM) technology specific to the company Electro Optical Systems, GmbH (EOS) [7]. Generally, this technology is known as selective laser melting (SLM) and it fits in the standard category of powder bed fusion (PBF) (ASTM F2792-12a) [8].

The process is a laser-based technique that uses digital input of computer aided design (CAD) models to create three-dimensional (3D) parts from metallic powders [7, 8]. In the Centre for Rapid Prototyping and Manufacturing (CRPM) of the Central University of Technology, Free State (CUT), the EOSINT M280 system was used for building DMLS parts from Ti6Al4V (ELI) powder for this study [7].

The DMLS process gives an advantage of little waste being generated compared to traditional machining of parts, since it is a material addition process unlike computer numerical control (CNC) machining which is a material removal process [7, 8]. Furthermore, this process can achieve complex geometries such as in parts that are designed with internal features and passages, which cannot be easily cast or otherwise machined [7, 8].

This research was conducted to investigate if additively manufactured Ti6Al4V(ELI) could be used as an alternative over AA 5083 and RHA, given its advantages of high specific strength, hardness, high corrosion resistance and toughness, as well as the advantages of additive manufacturing over traditional methods of manufacture.

1.2. Problem Statement

Choosing metallic materials for use in conditions of high velocity impact is a complicated problem due to the fact that the material of choice in such applications has to meet many requirements including, weight, hardness, fatigue strength, impact resistance, ease of fabrication and joining and cost [2, 3].

Although RHA (MIL-A-12560) and AA 5083 (MIL-A-46026) are still used today by the military for armour plating in main battle tanks and naval ships, they do have some

shortcomings in their respective applications [2]. The significant disadvantages of AA 5083 are its low specific strength of $130 \text{ MPa-cm}^3/\text{g}$ and the low strength values of its welded joints, which do not exceed 300 Mpa [2, 10]. RHA on the other hand, has a higher specific strength of $150 \text{ MPa-cm}^3/\text{g}$, but this comes at an expense of significantly increased weight due to its high density of 7.86 g/cm^3 [2].

Today's aerospace industry's construction of an aircraft involves using aluminium together with carbon fibre reinforced polymer composites [6]. The main problem of using the two materials together is the mismatch of their coefficients of thermal expansion (CTE) and electrical conductivity, which in turn creates stress concentrations at their joints and galvanic corrosion, respectively [6]. For the foregoing reasons, over the past decade aluminium has already been replaced by Ti6Al4V in military aircraft and in most commercial aircraft [6].

When manufacturing complex parts from RHA and AA 5083 in the military industry and aluminium and steel in the aerospace industry, welding is typically used to achieve the desired shape [2, 10]. Welding joints are problematic because they act as sites of stress concentration and this eventually can bring about fatigue cracking on the manufactured part [2].

These disadvantages imply a need for alloys with a high specific strength, suggesting a low density. Low density creates the advantage of weight-reduction in main battle tanks and other combat vehicles where RHA is used and in aircraft where steel is used. Moreover, it lowers the construction requirements of strength for roads and bridges in the first case and improves fuel consumption in both cases. The other need is for a manufacturing process that can achieve complex geometries in parts made from such an alloy without resorting to welding. Furthermore, from such a process, assembly of parts can also be avoided or limited.

Ti6Al4V (ELI) manufactured through the DMLS process using the EOSINT M280 system with standard process parameters, is a potential alloy for high velocity impact applications, in both the military and aerospace industry. This is because the most widely used titanium alloy, Ti6Al4V possesses a relatively low density of 4.45 g/cm^3 , whilst having a specific strength ($220 \text{ MPa-cm}^3/\text{g}$) that is much higher than those of RHA ($150 \text{ MPa-cm}^3/\text{g}$) and AA 5083 ($130 \text{ MPa-cm}^3/\text{g}$) [2]. Furthermore, the alloy has

a ballistic mass efficiency (E_m) (1.5) that is higher than those of RHA (1) and AA 5083 (1-1.2) [2]. However, its suitability for these applications has not been confirmed.

Replacing RHA and AA 5083 with Ti6Al4V in their respective applications would offer a solution to the constraints stated in the foregoing paragraphs. The replacement would offer the advantage of higher specific strength, resulting in weight-reduction in main battle tanks and other combat vehicles where RHA is used and, in an aircraft, where steel is used, hence lowering the construction requirements of strength for roads and bridges in the first two cases and improving fuel consumption in all three cases. In addition, it would offer higher hardness and toughness, as well as higher corrosion resistance than AA 5083. A further benefit of the adoption of additive manufacturing would be that complex geometries in parts could be achieved, without resorting to welding or assembly.

1.3. Aim of the Study

The aim of this research was to investigate the high velocity impact properties of DMLS Ti6Al4V (ELI) parts built by the EOSINT M280 system with standard process parameters, as-built and then stress relieved.

1.4. Objectives

The objectives of the study were as follows:

1. To review the theory of propagation of elastic waves, plastic deformation, heat conduction and radiation, and the formation and propagation of cracks in general applied to Ti6Al4V alloy of different microstructures under conditions of high velocity impact.
2. To develop analytical models for use in predicting the response of DMLS Ti6Al4V (ELI) to high velocity impact.
3. For projectiles with an average velocity of 702 m/s, determine the relationship between the extent and intensity of lateral and longitudinal damage accumulation in relation to the plate thickness.

4. For projectiles with the same average velocity, in case of through penetration determine fracture features formed in the projectile holes in relation to the plate thickness.
5. For projectiles with the same average velocity, determine the optimum panel plate thickness to avoid through penetration in order to compare the alloy's weight-saving capability to the currently used alloys based on its density.

1.5. Research Approach

Research was conducted by first reviewing literature on Ti6Al4V, AM, the propagation of elastic waves in solids, and the behaviour of materials under high velocity impact. Preliminary ballistic impact testing was first conducted on wrought Ti6Al4V in order to obtain an indication of its possible utility in this way. Wrought Ti6Al4V was chosen due to the closeness of its mechanical properties to those of DMLS Ti6Al4V (ELI).

The next step was to develop the high velocity testing instructions and design the test setup based on literature. Prior to this testing, tensile test samples were machined from the wrought plates and put under a tensile loading to verify the mechanical properties of the material.

Following onto this, preliminary ballistic impact testing of the wrought Ti6Al4V plates was undertaken, and the results documented and compared to the same data for RHA and AA 5083. Fractographic and microstructural analyses of the plates then carried out and the results also documented. Based on these results and their analyses, a justification was formulated for the further testing of as-built and stress relieved DMLS Ti6Al4V (ELI).

The next step was the manufacturing of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates at CRPM. The plates were tested using the same test instruction as in the preliminary testing of wrought Ti6Al4V and documented. Furthermore, fractographic and microstructural analyses were also carried out on the tested as-built and stress relieved DMLS Ti6Al4V (ELI) plates.

In the present study, a comparative study of the response of wrought Ti6Al4V and as-built and stress relieved DMLS Ti6Al4V (ELI) was then carried out, and

conclusions of the research were made. Figure 1.1 shows a flow diagram of the process used to achieve the objectives of this research project.

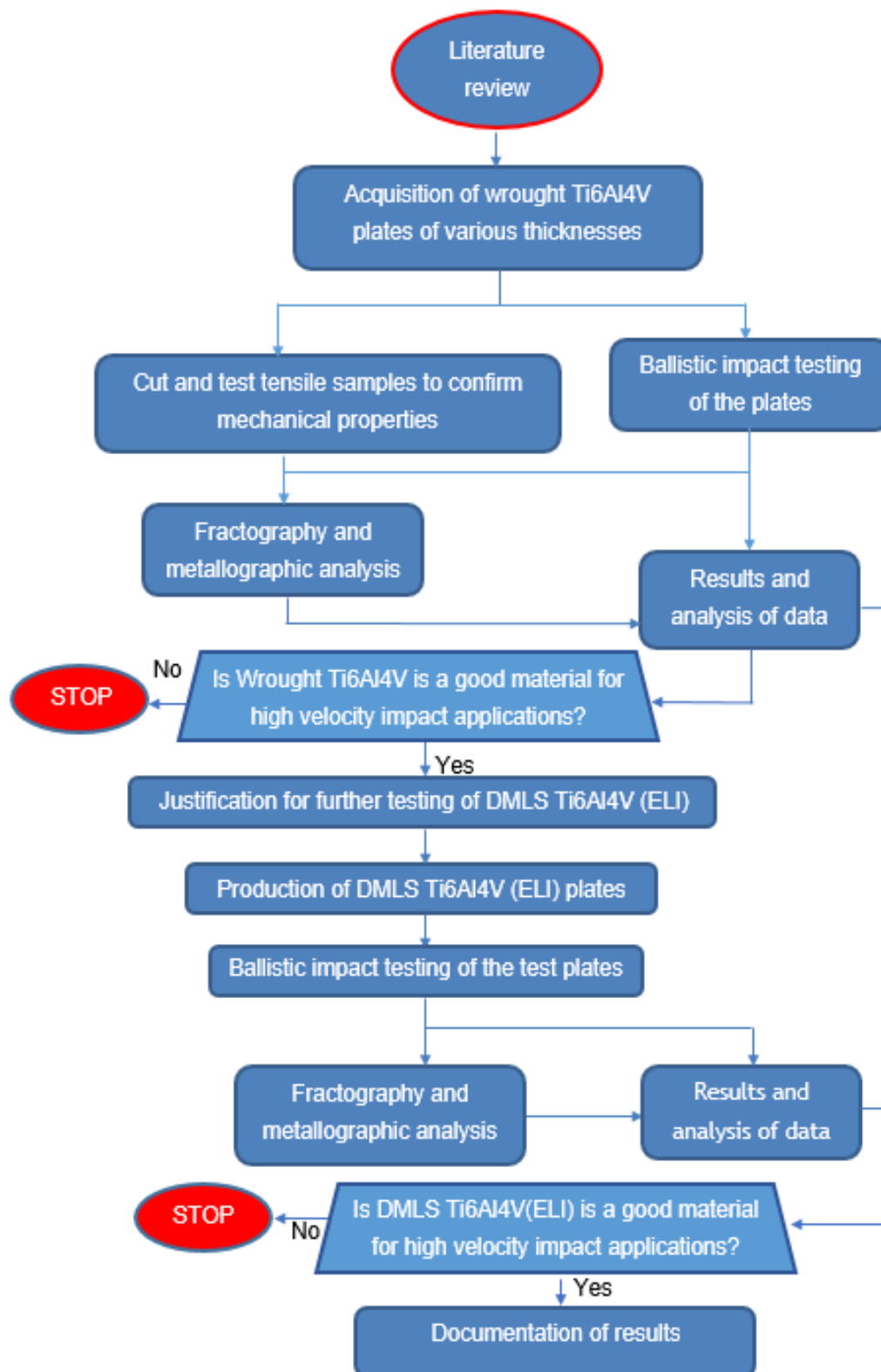


Figure 1.1: Flow diagram of the research methodology in this work

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CHAPTER 2 - LITERATURE REVIEW

2.1. Introduction

This chapter covers the history and background of titanium, occurrence and types of titanium ore, general production and metallurgy of titanium and its alloys. Furthermore, the chapter also contains material on DMLS as an AM technology used to produce Ti6Al4V parts. The chapter further describes the heat treatment of Ti6Al4V and the mechanical properties of arising microstructures. Furthermore, the theory of impact with special attention on high velocity impact and failure under this latter category of impact is covered. The chapter contains material on the propagation of and energy dissipated by stress waves in solid materials and details on materials used in high velocity ballistic impact conditions.

2.2. Titanium

Titanium is commonly used in various forms including, pure titanium metal (Ti) as well as the compounds titanium dioxide (TiO_2), titanium tetrachloride (TiCl_4) and titanium trichloride (TiCl_3) [3, 11]. Most titanium is not used in its metal form but as titanium dioxide (TiO_2) [3]. Titanium dioxide (TiO_2) is a white pigment present in paints, paper and plastic. The oxide is mostly used as a pigment because of its whiteness which improves brightness and opacity [3]. Table 2.1 provides detail of some physical and mechanical properties of pure titanium.

Table 2.1: Some physical and mechanical properties of pure titanium [2]

Property	Value	
Density, g/cm ³ (lb/in. ³)	4.51	(0.163)
Melting temperature, °C (°F)	1660	(3020)
Specific heat, cal/g · °C (J/kg · K)	519	(0.124)
Thermal conductivity, Btu · ft ² /ft · h · °F	~9	
Thermal expansion (0–315 °C, or 32–600 °F), μm/m · °C (μin./in. · °F)	~3	(~5)
Electrical resistivity, μΩ · cm (circular mil · Ω/ft)	42	(250)
Magnetic susceptibility, emu/g	3.17	
Tensile modulus, ×10 ³ MPa (×10 ⁶ psi)	~101	(~14.7)
Compression modulus, ×10 ³ MPa (×10 ⁶ psi)	~103	(~15)
Shear modulus, ×10 ³ MPa (×10 ⁶ psi)	~44	(~6.4)
Poisson's ratio	~0.4	
Tensile strength, MPa (ksi)	240	(35)
Tensile yield strength (0.2%), MPa (ksi)	170	(25)
Compression yield strength (0.2%), MPa (ksi)	170	(25)
Elongation in tension, %	35	
Shear strength, MPa (ksi)	~140	(~20)
Charpy impact strength, J (ft · lbf)	27–54	(20–40)
Fatigue strength, F_{tu}	0.5–0.6	
Notched fatigue strength, ($K_t \geq 4$), F_{tu}	0.2–0.3	
Creep strength (315 °C, or 600 °F, 10 h, 0.2%), MPa (×10 ³ psi)	<83	(<12)
Rupture strength (315 °C, or 600 °F, 1000 h), MPa (×10 ³ psi)	<69	(<10)
Bend radius, R/t	~4	
Hardness (1500 kg load), HB	~65	

2.2.1. Allotropes of titanium

Allotropy is the characteristic of an element being able to exist in more than one crystal structure or phase, depending on the temperature and pressure [6, 10]. Titanium in its natural form has two allotropic forms, namely the α and β forms. The hexagonal close packed α form changes to the body centred cubic β form at the β -transus temperature of 882 ± 2 °C [3, 10]. Figure 2.1 shows the crystal structures of α HCP and β BCC phases of pure titanium.

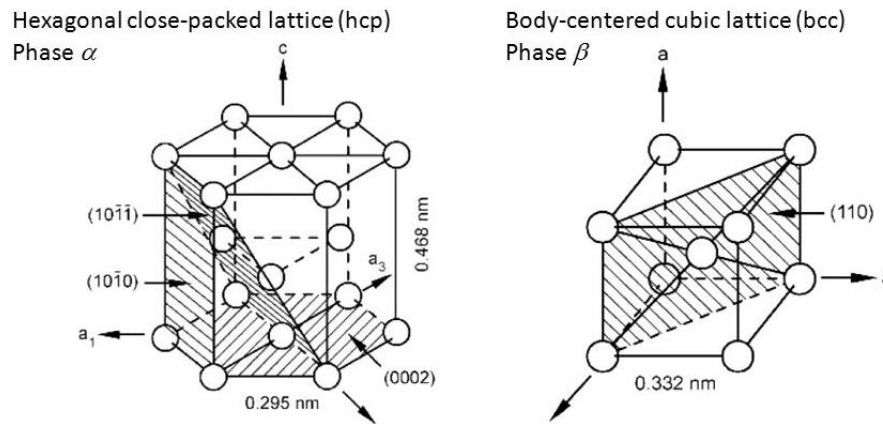


Figure 2.1: Crystal structures of α HCP and β BCC phases of pure titanium [1]

2.3. Titanium Alloys and Their Classification

Titanium alloys are classified according to the influence of the alloying elements used on the β -transus temperature [3, 18]. The α -stabilizer elements extend the α -phase field to higher temperatures, while on the other hand the β -stabilizer elements shift the β -phase field to lower temperatures [18, 19]. The β -stabilizing elements are further subdivided into β -isomorphous and β -eutectic elements [18, 19].

The neutral elements have a minor influence on the β -transus temperature [3, 19]. Alpha-stabilizer elements of titanium include aluminium (Al), oxygen (O_2) and nitrogen (N_2), while β -stabilizer elements include vanadium (V), molybdenum (Mo), niobium (Nb), tantalum (Ta), and nickel (Ni) [18, 19]. Tin (Sn) and zirconium (Zr) are considered as neutral elements [18, 19]. Figure 2.2 shows the influence of alloying elements on the phase equilibrium diagram of titanium alloys.

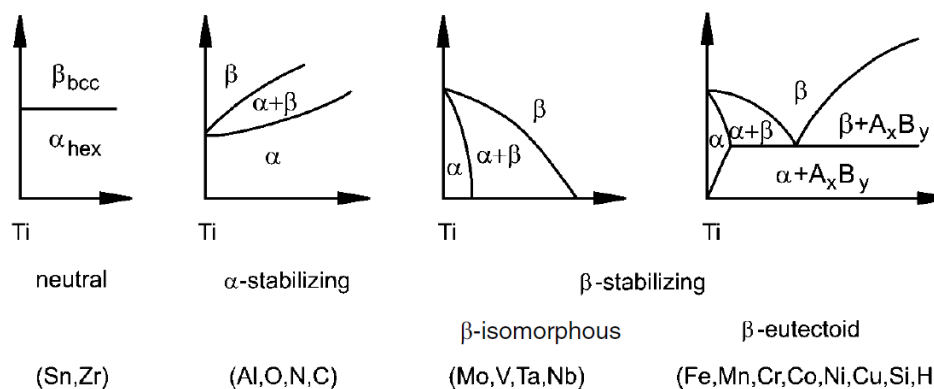


Figure 2.2: The influence of alloying elements on the phase equilibrium diagrams for titanium alloys [19]

Titanium alloys are classified into α , $\alpha + \beta$ and β alloys, with further subdivision into near α and metastable β alloys [18, 19]. Figure 2.3 shows a schematic of a 3D phase diagram used to classify titanium alloys.

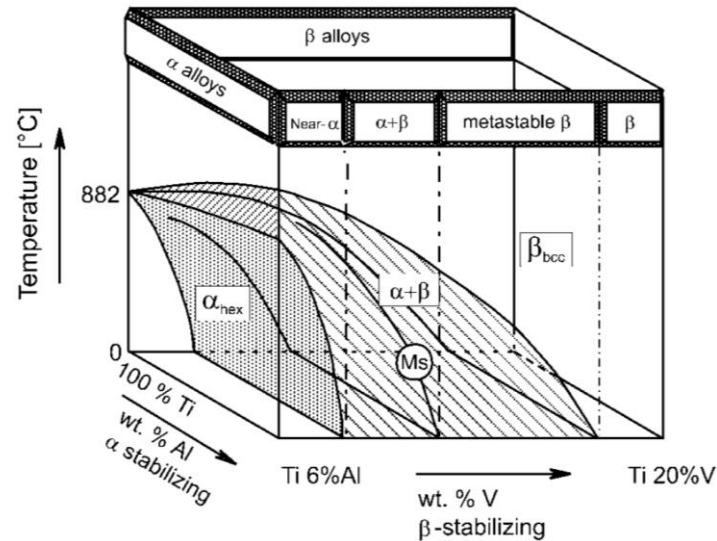


Figure 2.3: Schematic of a three-dimensional phase diagram to classify titanium alloys [1]

From the scheme in Figure 2.3 it is clear that the α alloys include pure titanium and alloys solely alloyed with α -stabilizer elements or neutral elements [18, 19]. When β -stabilizing elements are added in small fractions, they are referred to as near- α alloys [18, 19]. The $\alpha + \beta$ alloys on the other hand have a β volumetric fraction ranging from 5 to 40% [3, 19].

2.4. Additive Manufacturing

According to ASTM F2792-12a AM is a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [20, 21]. There are many terms used to describe AM and common synonyms for the process include: “additive fabrication, additive process, additive techniques, additive layer manufacturing and freeform fabrication”. The primary applications of AM are in design/modelling, functional prototyping and direct part-production [20, 21].

The AM process relies on the extraction of information from a computer-aided design or CAD model files and conversion of such files into .stl files [21]. In this process the

3D model prepared from CAD software is estimated by triangles that best fit the given outline and is then sliced into layers, with each layer containing information for printing [21].

2.4.1. Direct Metal Laser Sintering

The terminology DMLS is a metal additive manufacturing technology specific to the company EOS [21]. Figure 2.4 shows a schematic diagram of a DMLS system.

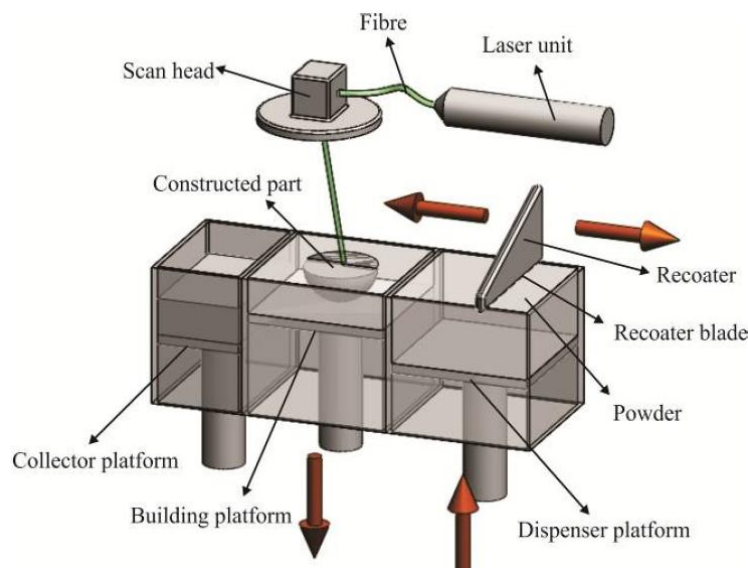


Figure 2.4: Schematic diagram of a DMLS system [22]

The building platform is lowered by a layer thickness while the recoater blade is still to the extreme right. The dispenser platform is then moved up to supply the amount of powder required for the next layer [21, 22]. The recoater blade then moves from the right to the left position and in this way spreads the metal powder supplied by the dispenser, evenly on the building area and the excess metal powder falls into the collector [21, 22].

The scan head then moves the laser beam on a two-dimensional cross section and is precisely switched on and off during exposure at designated areas as required by the CAD data of the particular layer [21, 22]. The laser beam melts the powder and also fuses it onto previously fused layers below the fresh layer of powder [22]. This process continues layer by layer until the part to be built is complete [22]. The molten powder is turned into solidified parts that attain their final properties during the

building process but may require post-processing treatment like stress relief, tempering, or surface treatment depending on their application [21, 22].

2.5. Titanium Alloy Ti6Al4V

The titanium alloy Ti6Al4V has as primary alloying elements, aluminium at 6 wt.% and vanadium at 4 wt.% [23]. The extra low interstitial (ELI) titanium alloy Ti6Al4V (ELI), also referred to as grade 23 Titanium alloy, is a Ti6Al4V (grade 5 Ti alloy) of higher purity resulting from the reduced levels of interstitial elements within the alloy such as nitrogen, oxygen and carbon [23, 26]. Table 2.2 shows the chemical composition of titanium and titanium alloys.

Table 2.2: Chemical composition of titanium and titanium alloys [25]

	Ti	Al	V	FE	C	O	N	H
Titanium Grade 1 (CPTi)	balance	-	-	0.2	0.1	0.18	0.03	0.015
Wrought annealed Ti6Al4V alloy	balance	5.5-6.75	3.5-4.5	0.3	0.08	0.2	0.05	0.015
As-laser sintered Ti6Al4V alloy	balance	5.5-6.75	3.5-4.5	0.3	0.08	0.2	0.05	0.015

Table 2.3 shows the mechanical properties of Ti6Al4V.

Table 2.3: Mechanical properties of Ti6Al4V [25]

Properties	Wrought annealed Ti6Al4V alloy	As-laser sintered Ti6Al4V alloy
Hardness[HV]	300-400	320±12
Density (ρ) g/cm ³	4.43	4.41
0.2% Proof of Strength [MPa]	800 - 1100	1070 ± 50
Ultimate Tensile Strength [MPa]	900 - 1200	1200 ± 50
Percentage Elongation [%]	6 - 10	11 ± 3
Area Reduction [%]	15 - 25	-

Ti6Al4V is an $\alpha + \beta$ alloy at room temperature and its properties can be controlled through regulated cooling during formation and by heat treatment after formation, both in order to adjust the microstructure and precipitation states of the β or α components [23]. At room temperature the microstructure at equilibrium of this alloy consists mainly of the α -phase (HCP) with some retained β -phase (BCC) [23, 24].

The temperature at which titanium alloys undergo an α to β transformation and vice versa, depends mainly on the amounts of the alloying elements, aluminium and vanadium, as they are responsible for stabilisation of the α and β -phases, respectively [24, 25]. The lowest temperature at which a 100% β phase can exist is called the beta transus and it is about 995°C for the Ti6Al4V alloy [23].

Wrought Ti6Al4V ordinarily available in the market has an equiaxed microstructure, while as-built and stress relieved DMLS Ti6Al4V (ELI) has a martensitic α' microstructure [26, 29]. Additionally, Ti6Al4V can exist in four different microstructures at room temperature, as a function of the specific heat treatment process it is exposed to, namely acicular martensite α' , fully lamellar, equiaxed and duplex microstructures [23, 26].

The martensitic α' microstructure is distinguishable by the randomly oriented fine needle-shaped morphology [23]. The fully lamellar microstructure compared to the equiaxed microstructure is distinguishable by a greater α/β surface area and more orientated colonies of alternate α and β grains that form lamellae [23, 26]. Equiaxed microstructure has a uniform structure composed of equiaxed α grains and grain boundaries of β grains [23, 26]. Moreover, the bimodal microstructure consists of primary alpha (α_p) grains and colonies of α laths that are separated by ribs of β grains in the form of lamellae [26]. The circumstances leading to each of these microstructures are discussed in section 2.5.1. Figure 2.5 shows these four microstructures of Ti6Al4V.

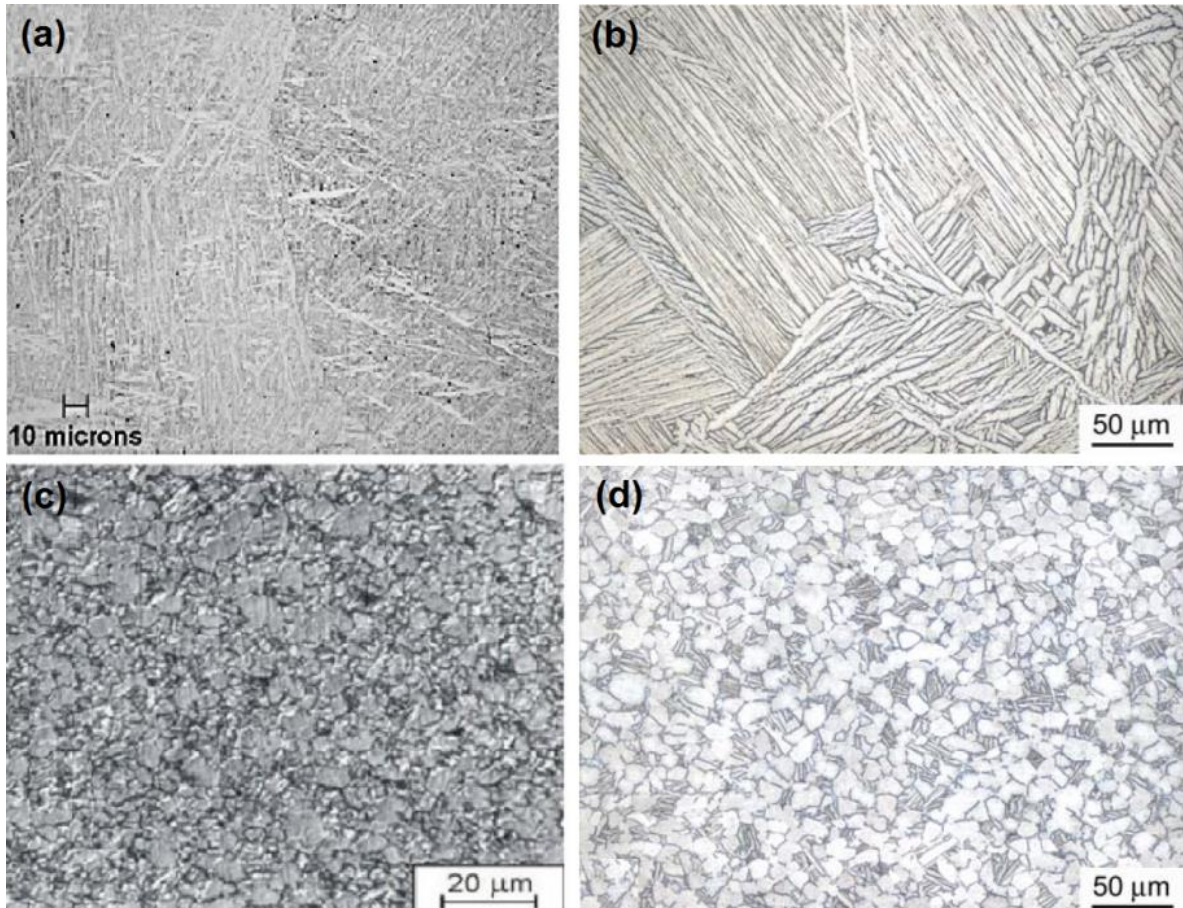


Figure 2.5: Ti6Al4V microstructures (a) martensitic α microstructure, (b) lamellar microstructure, (c) equiaxed microstructure and (d) bimodal microstructure [26]

As the temperature of the Ti6Al4V alloy increases the amount of α grains in the microstructure of the two phase region decreases [23, 26]. The foregoing statement is substantiated by the Ti6Al4V phase diagram in Figure 2.6, which shows the amount of α in the microstructure decreases as the temperature of the alloy increases [26].

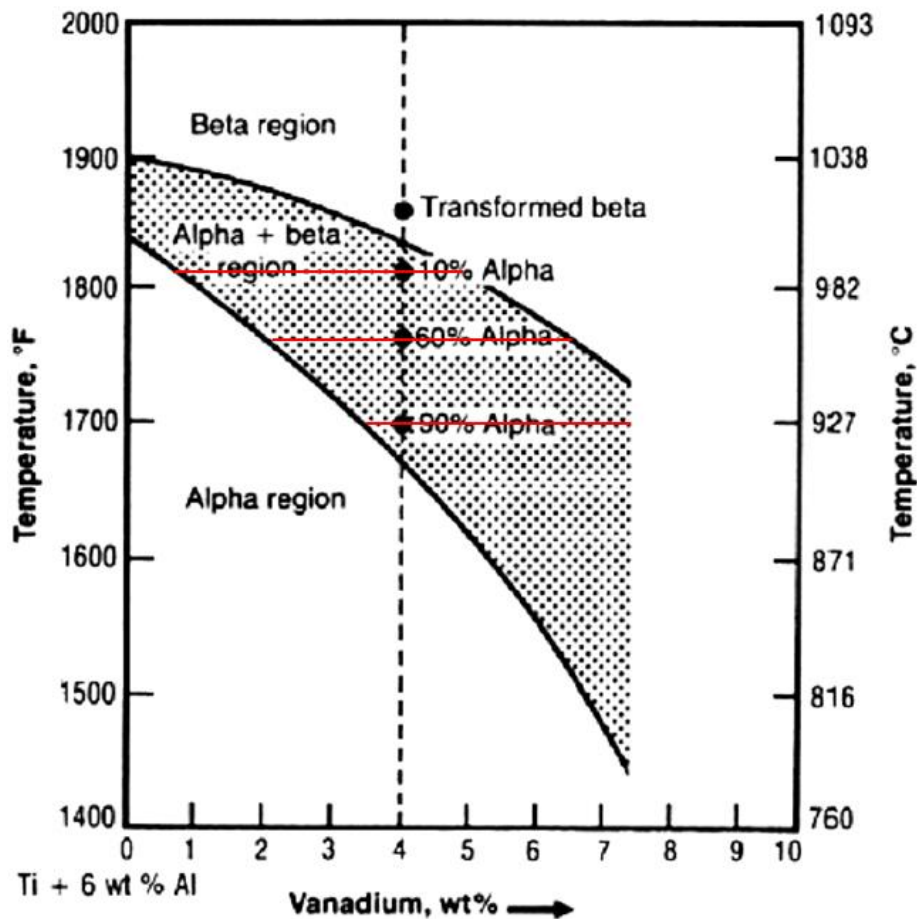


Figure 2.6: Ti6Al4V phase diagram [26]

Depending on the cooling rate and heat treatment, the microstructures of Ti6Al4V can further be divided into several types, namely grain boundary allotriomorph α , Widmanstätten, basketweave and bi-lamellar [23, 26].

2.5.1. Heat treatment of Ti6Al4V

Heat treatment is mainly applied to $\alpha + \beta$ titanium alloys due to the existence of different equilibria at different temperatures and constitutions [23]. Thus the α phase at room temperature starts transforming at elevated temperatures upon intersection of the first phase transformation line in the phase diagram [23]. The strength of annealed alloys increases gradually and linearly with increasing alloy content [23]. The quenching of the alloys from the β -phase field gives a martensitic transformation, with improved strength whose specific value depends on the composition [23, 27].

For low alloyed titanium alloys, rapid quenching from the β -phase field gives maximum strength at M_f (martensite finish) [23]. For highly alloyed titanium alloys, rapid quenching from the β -phase field gives the lowest strength but after aging the maximum strength is achieved [23, 27].

Upon heat treating Ti6Al4V, the alloy can undergo an equilibrium or a non-equilibrium phase transformation to an $\alpha + \beta$, $\alpha' + \beta$ or full martensite α' -phase at room temperature, depending on the heating temperature and cooling rate [23, 27]. The equilibrium phase transformation is that of the $\alpha + \beta$, which can exist as either a lamellar, equiaxed or duplex microstructure [26].

Slowly cooling Ti6Al4V from the β -phase field, causes a partial transformation from a β to α -phase resulting in a microstructure containing a lamellar structure [28]. This type of microstructure is characterized by relatively low tensile ductility, moderate fatigue properties, and good creep and crack growth resistance [24, 28]. On the other hand, slow cooling from the $\alpha + \beta$ phase field produces an equiaxed microstructure [23, 24]. An equiaxed microstructure has high nucleation resistance but low propagation resistance [28].

Since, the bimodal microstructure consists of primary alpha (α_p) grains and colonies of α laths that are separated by ribs of β grains in the form of lamellae, this makes the bimodal microstructure preferable for fatigue resistant products [26, 28]. Furthermore, DMLS Ti6Al4V has a fine martensitic α' microstructure and this can be attributed to rapid cooling which takes place during the DMLS process [26, 28]. This type of microstructure has a higher hardness and strength but is also more brittle than the equiaxed, bimodal or lamellae microstructures [26].

Quenching of Ti6Al4V from the β -phase field produces fine acicular α' microstructure, which is transformed from the β -phase by rapid nucleation and grain growth [27, 28]. Air (slow) cooling from the $\alpha + \beta$ phase, on the other hand, provides an α_p -phase in a matrix of transformed β -phase [28]. Figure 2.7 shows the microstructures of quenched and air cooled Ti6Al4V.

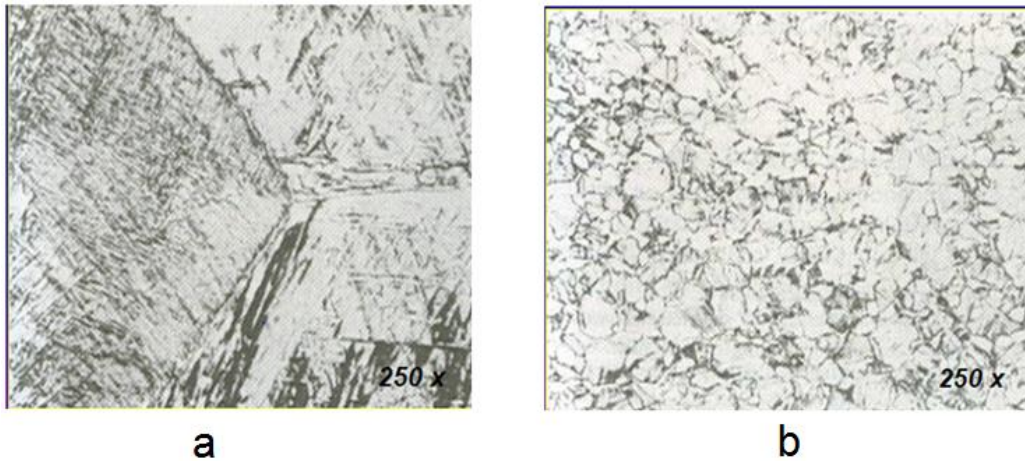


Figure 2.7: Quenched and air cooled microstructures of Ti6Al4V (a) acicular α' and (b) primary alpha (α_p) phase in a matrix of transformed β phase [28]

The acicular α' martensite microstructure has an HCP structure [27, 28]. Rapid cooling of this alloy increases its hardness and brittleness. Increasing the β -stabiliser solute content during solution heat treatment also alters the final microstructure of the alloy [28]. Figure 2.8 is a schematic of possible microstructures of Ti6Al4V due to an increase in the β -stabiliser.

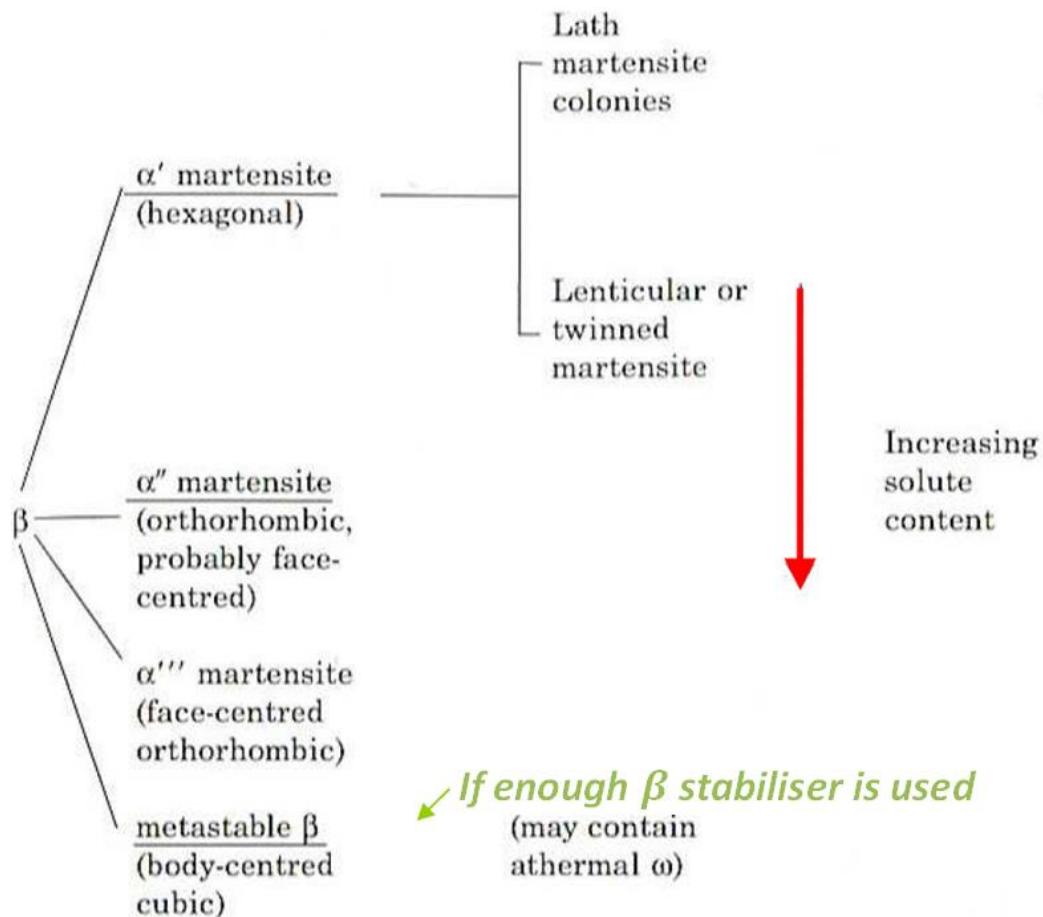


Figure 2.8: Schematic of possible microstructures of Ti6Al4V due to an increase in the β -stabiliser [28]

Quenching from the $\alpha + \beta$ phase field below the beta transus temperature but above the martensite start temperature (M_s), leads to a microstructure that consists of an α_p -phase embedded in transformed β -phase (α' martensite) [28]. Figure 2.9 shows Ti6Al4V alloy α' martensite after solution heat treatment at 954°C and then water quenching.

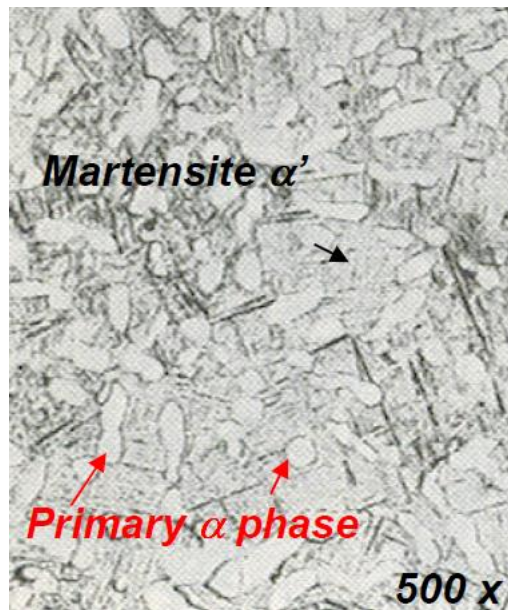


Figure 2.9: Ti6Al4V α' martensite after solution heat treatment at 954°C and then water quenching [28]

On the other hand, quenching from the $\alpha + \beta$ phase field (below M_s) leads to a microstructure that consists of a α_p -phase and small amounts of untransformed β -phase [28]. Figure 2.10 shows Ti6Al4V primary alpha (α_p) phase and small amounts of untransformed β -phase, after solution heat treatment at 843°C and then water quenching.



Figure 2.10: Ti6Al4V primary alpha (α_p) phase and small amounts of untransformed β -phase after solution heat treatment at 843°C and then water quenching [28]

In general, increasing the cooling rate enhances the α nucleation rate in the β grain boundaries, therefore improving growth of the alpha platelets into the initial β grains [23]. The length and the width of these α platelets are dependent on the cooling rate.

The microstructure of the alloy after solution and aging treatment consists of a β matrix and precipitates of the α -phase [28]. Hardening the surface of this alloy has a negligible effect on the strength but reduces the ductility [28]. The yield strength and ultimate tensile strength are higher in the water quenched and aged condition [23, 24].

2.6. Impact Phenomena

In mechanics impact is defined as a force or shock load created over a short time period when two or more bodies collide [1]. The effect of impact depends on several factors, including the relative velocity of the colliding bodies to one another, the relative mechanical properties of the two bodies and the relative behaviour of the two colliding bodies upon contact [30, 31].

The impact phenomena can be characterized in numerous ways according to the impact angle, the geometry and material characteristics of the target or projectile, as well as the striking velocity [31, 32]. Regarding the striking or initial velocity (V_i), multiple categories of ballistic impact loads can be defined depending on the application [30, 31]. High velocity impact is typically simulated through ballistic testing, which is the firing of a high speed projectile at a target, followed by investigation of damage on the target [30, 33]. High velocity impact in this category of impact is characterized by a projectile travelling in a velocity range of 50 to 1500 m/s for general applications [30]. Table 2.4 shows the classification of ballistic impact and details cases where this occurs in life.

Table 2.4: The classification of ballistic impact [30]

Ballistic impact	Classification	Velocity range V_s (m/s)	Example
Military application	Sub ordnance	25 – 500	Drop tests, pneumatic guns
	Nominal ordnance or ordnance	500 – 1300	Propellant fired conventional gun
	Ultra ordnance	1300 – 3000	Special purpose guns, warhead fragments
	Hypervelocity	> 3000	Light-gas guns, shaped charges
General application	Low/moderate velocity impact	< 50	Automobile crashes
	High velocity impact	50 – 1500	Projectile impacts, bird strike in aircraft engines, etc.
	Hypervelocity impact	> 1500	Debris impact on satellites

2.6.1. Failure under ballistic impact

Failure under ballistic impact is due to the interaction of a variety of mechanisms, including fracture due to the initial stress wave, growth of fracture in the radial direction, spalling, scabbing, plugging, discing, dishing, frontal or rearward petalling, fragmentation in the case of brittle targets and ductile hole-enlargement [30, 35]. It has commonly been observed in ballistic experiments that plugs tend to form in hard thick plates, dishing and petalling occurs in thin ductile plates, and ductile hole-enlargement and spalling occur in softer, thick plates [35]. A combination of ductile failure and spalling is characteristic of perforation in thick plates [32, 35]. In case of through penetration, the other characteristic feature of a ballistic hole in metals is an enlarged diameter at the entry, convergence followed by divergence at mid depth and a diameter with a smaller enlargement at the exit [35]. Figure 2.11 shows various failure modes in ballistic impacted plates.

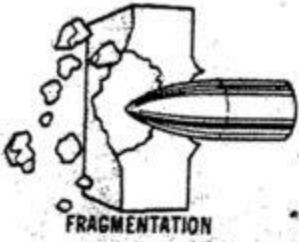
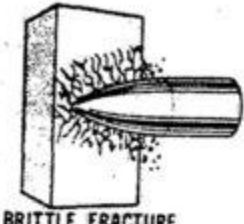
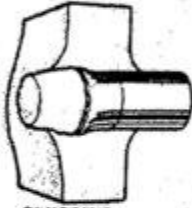
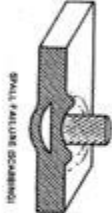
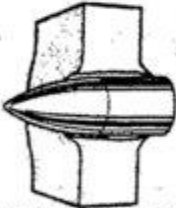
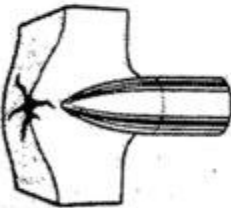
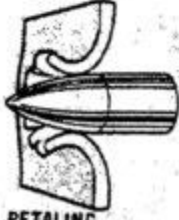
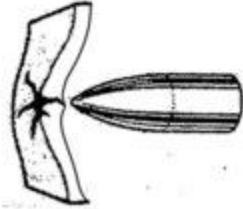
	final stage of perforation back plate damage	initial stage of perforation back plate damage
brittle	 FRAGMENTATION	 BRITTLE FRACTURE rigid back (no damage)
intermediate	brittle tendency: Discing ductile tendency: plugging  PLUGGING	brittle tendency: circumferential cracks ductile tendency: disc/plug started 
ductile	 DUCTILE HOLE GROWTH	 Star cracks
ductile	 PETALING thin plates only	 Star cracks

Figure 2.11: Various failure modes in ballistic impacted plates [30]

Penetration of a target due to high velocity impact occurs in four phases, including the transient, primary penetration, secondary penetration and recovery phases, which occur in this listed order [35]. The first phase, which is the transient phase, is characterized by a short but also intense pressure spike that occurs when the projectile first comes in contact with the target it strikes [31, 35]. The ensuing phase, which is the primary penetration phase, is described as the period during which the

projectile acts as a propulsive force, and therefore gives off its kinetic energy to the target in a hydrodynamic manner [31, 34].

The next phase is the secondary phase also referred to as cavitation phase and begins after the projectile exits the system and therefore stops being a source of energy [31]. In this stage the deformation is not caused by the kinetic energy of the projectile but instead the energy density behind the shock wave, which continues to deform the material. Lastly comes the recovery phase in which the crater, now formed from through penetration of the projectile, recovers or contracts slightly [31]. Figure 2.12 shows these four phases of penetration and the attendant relative magnitudes of pressure.

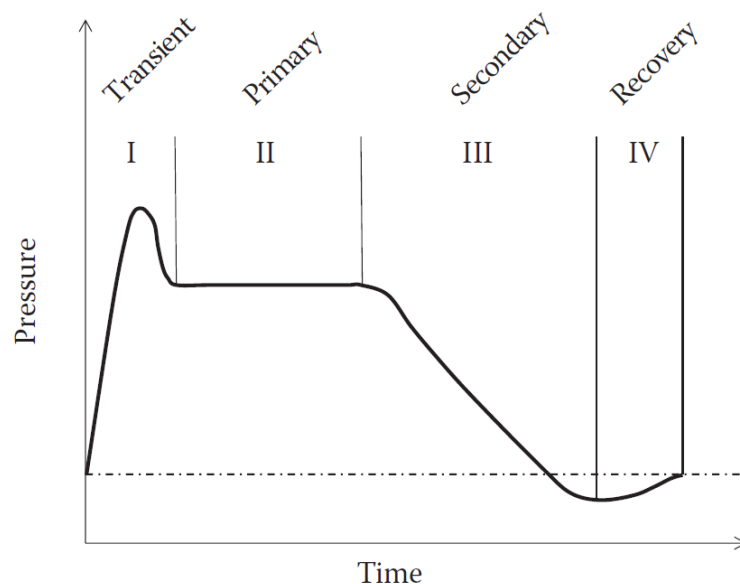


Figure 2.12: The pressure versus time profile of the four phases of high velocity impact penetration [31]

2.6.2. Fractography of ballistic impacted plates

In the penetration of a target, the projectile leaves a hole with a fractured surface [36]. It is important in this case to determine whether the fracture formed is ductile or brittle, to get insight into the behaviour of the target material [36]. A ductile fracture is a type of fracture that is characterized by extensive plastic deformation [37, 38]. The term ductile rupture refers to the failure of ductile materials. When this type of failure occurs, the material pulls apart forming dimples, micro-cavities and voids before failure instead of failure through cracking [36, 38].

On the other hand, brittle fracture is characterized by little or no plastic deformation prior to failure, which is denoted by formation of cracks, chevron and cleavage marks as surface features on the fractured surface [36, 39]. Chevron marks are typically created due to a fracture which progresses rapidly through the structure and in their arrangement point to the origin of the failure [36, 39]. Figure 2.13 shows a SEM micrograph exhibiting dimple and cleavage rupture mechanisms at a fracture zone, while Figure 2.14 is a micrograph of ductile fracture surface dimples.

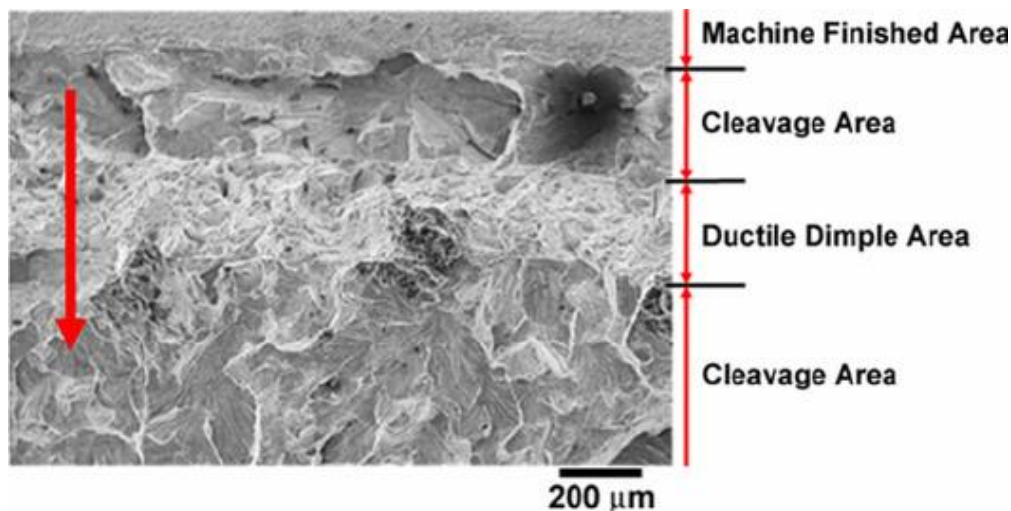


Figure 2.13: SEM micrograph exhibiting dimple and cleavage rupture mechanisms at a fracture zone [40]

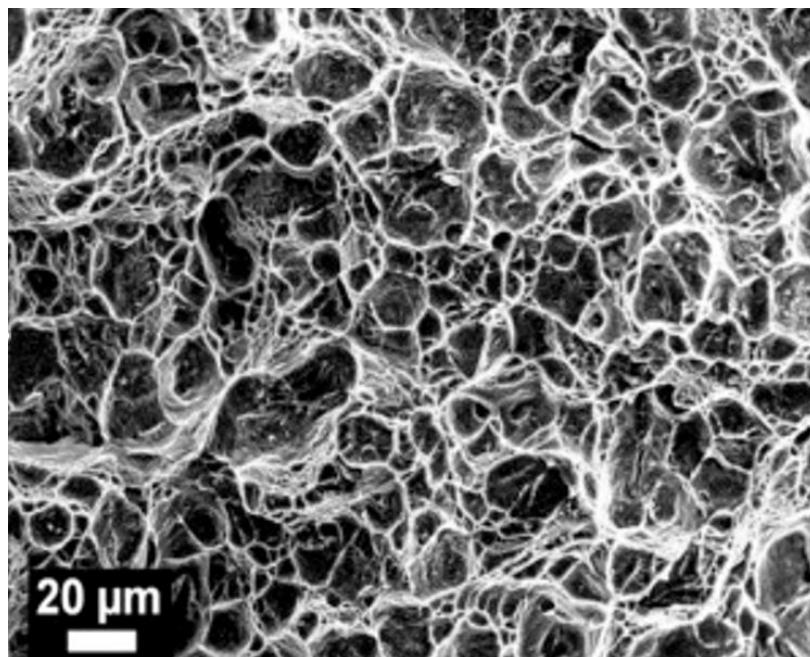


Figure 2.14: SEM micrograph of ductile fracture surface dimples [38]

Figure 2.15 is a micrograph showing microcavities and dimples on the fracture surface of an armour steel target impacted at 160 m/s [36].

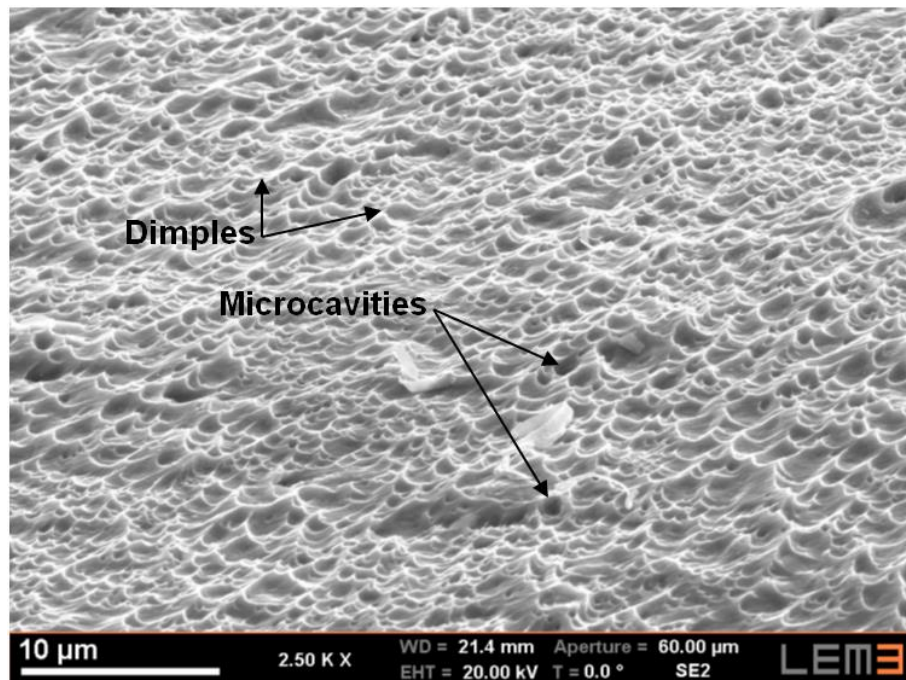


Figure 2.15: SEM micrograph displaying microcavities and dimples on the fracture surface of an armour steel target impacted at 160 m/s [36]

Adiabatic shear bands (ASBs) are localized regions of intense shear during high strain rate deformations [41, 42]. Furthermore, during high strain rate deformations there is a conversion of plastic work to heat [41]. In metals with a low thermal conductivity, the heat produced is retained in the zone where it is created and leads to thermosoftening and the formation of ASBs [41]. Adiabatic shear bands are common in cases of high strain rate and usually occur in cases of ballistic impact failure [42]. Figure 2.16 shows optical microstructures of the adiabatic shear bands observed in Ti6Al4V plates with: (a) lamellar microstructure, (b) fully equiaxed microstructure and (c) bimodal microstructure.

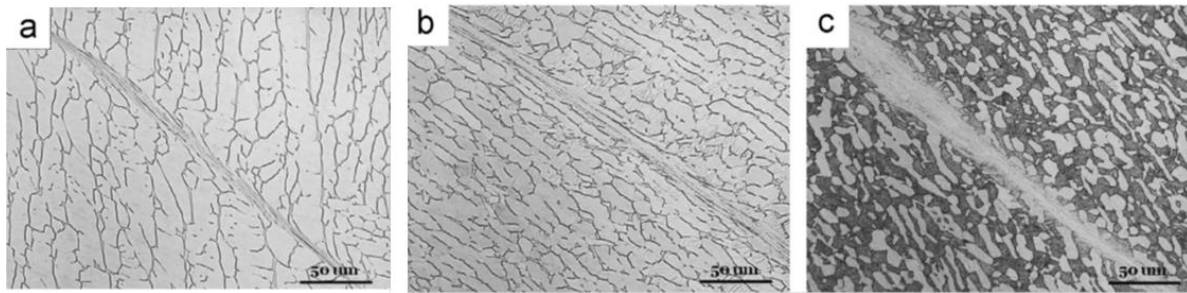


Figure 2.16: Optical microstructures of the adiabatic shear bands observed in Ti6Al4V plates with: (a) lamellar microstructure, (b) fully equiaxed microstructure and (c) bimodal microstructure [42]

2.6.3. Changes in the microstructure of the target material due to effects of high strain rates

When metals deform plastically, significant amounts of heat are generated, especially in cases of localized deformation such as in the case of high velocity impact [43]. Even when there is full penetration during high velocity impact, some of the energy from the projectile is still converted into heat [42, 43]. If the deformation is rapid, the heat generated can lead to a large increase of temperature, as there is no time to conduct heat away from the deforming area [42, 43]. The rapid increase of temperature causes thermal softening of the metal, which in turn causes a change in the microstructure and therefore mechanical properties of the material [42, 44]. It has been found that in steel targets there is an adiabatic temperature rise that exceeds a 1000 K at an impact velocity of 550 m/s [45].

During ballistic impact, failure of a material can occur isothermally, adiabatically or in a transition stage from isothermal to fully adiabatic depending on the strain rate [30]. In metals and their alloys, failure becomes adiabatic if the strain rate during impact exceeds 10^2 s^{-1} [30]. In the adiabatic shearing or failure process, conduction of the heat generated by plastic deformation is negligible due to the short period of occurrence [30, 46]. Therefore, the temperature T at a given time step can be calculated using Equation (1), the formula for calculating internal energy e , with V_0 as the reference volume, T_0 as the ambient temperature and C_V as the specific heat capacity of the metal at a constant volume [30, 46].

$$e = \frac{1}{V_o} \int C_v dT \cong \frac{C_v(T - T_o)}{V_o} \Rightarrow T = \frac{V_o e}{C_v} + T_o \quad (1)$$

It is important to take note that Equation (1) only considers the effect of strain and not that of strain rate, which is limiting as it is high strain rates that lead to adiabatic deformation [43, 47].

The work done during plastic deformation is not all converted into heat, because some of it is locked up within the dislocations in the crystal lattice structures of respective materials [43, 48].

The efficiency (η) of conversion of the work of plastic deformation into heat is normally assumed to be a constant parameter of 0.9 [43]. Taking into account the strain rate and assuming a constant efficiency of conversion of the work of plastic deformation into heat, the adiabatic temperature rise ΔT can be estimated through calculation using Equation (2) [47]. In the equation, the symbol ϵ is the strain and σ the stress.

$$\Delta T = \frac{\eta}{\rho C_v} \int \sigma d\epsilon = \frac{\eta}{\rho C_v} \int K \epsilon^n d\epsilon = \frac{\eta K}{\rho C_v} \int \epsilon^{(d\sigma/d\epsilon)} d\epsilon \quad (2)$$

This equation can be written as:

$$T - T_o = \frac{\eta}{\rho C_v} \int \sigma d\epsilon = \frac{\eta}{\rho C_v} \int K \epsilon^n d\epsilon = \frac{\eta K}{\rho C_v} \int \epsilon^{(d\sigma/d\epsilon)} d\epsilon \quad (3)$$

The final temperature (T) can therefore be expressed as:

$$T = \frac{\eta}{\rho C_v} \int \sigma d\epsilon + T_o = \frac{\eta}{\rho C_v} \int K \epsilon^n d\epsilon + T_o = \frac{\eta K}{\rho C_v} \int \epsilon^{(d\sigma/d\epsilon)} d\epsilon + T_o \quad (4)$$

The strain hardening exponent denoted by the symbol (n) in Equations (2) to (4) is a function of the gradient of the curve for plastic deformation, thus $n = \phi(d\sigma / d\epsilon)$. In all the three equations, the symbol ρ is the mass density and C_v the specific heat capacity at constant volume [47].

For Ti6Al4V, as with other metals and alloys, plastic deformation does bring about strain or work hardening also referred to as cold working, as deformation takes place

at room temperature [49]. The work hardening is caused by the generation and movement of dislocations within the crystal structure of the metal or alloy and thus an increase in the density of dislocations [50]. As the density of dislocations increases, the resistance to their motion becomes more pronounced as they become more and more entangled [49, 50]. This, therefore, implies that the stress necessary to deform the metal increases with an increase in strain beyond the elastic limit and strain rate [50].

2.7. Stress Waves in Solid Materials

During ballistic impact, stress waves are induced in the target as a result of shock impact by the projectile [34]. These waves propagate radially outwards, in a direction perpendicular to the direction of impact, from the localized contact area [51, 52]. The propagation of stress waves has a significant effect on the deformation of a target during the initial deformation stage and then becomes weaker during the middle and final stages of propagation [53].

Stresses caused by an intermediate and dynamic loading rate, having strain rates in the range 10 to 10^4 s^{-1} , are transmitted in solids in the form of elastic stress waves [54]. Furthermore, if the stress induced in a material is increased beyond the yield stress of the material, the material starts behaving plastically [54].

As established in section 2.6, high velocity impact prevails for impact by projectiles travelling in the velocity range of 50 to 1500 m/s during ballistic impact [30]. Table 2.5 shows the impact response of materials under different loading strain rates [30].

Table 2.5: Impact response of materials under different loading strain rates
[30]

Strain rate $\dot{\epsilon}$ (s^{-1})	Striking velocity V_s (m/s)	Effect or material response	Method of loading
0 - 10^0	< 50	Primarily elastic and some local plasticity	Mechanical devices, compressed air guns
10^0 - 10^2	50 - 500	Primarily plastic	Mechanical devices, Compressed air guns
10^2 - 10^4	500 - 1000	Viscous – material strength still significant	Powder guns
10^4 - 10^5	1000 - 3000	Fluid like behavior in materials; pressures approach or exceed material strength; density a dominant parameter	Powder guns, gas guns
10^5 - 10^7	3000 - 12000	Hydrodynamic behaviour - material compressibility not ignorable	Explosive acceleration
10^7 - 10^8 & above	> 12000	Explosive impact - colliding solids get vaporized	

Based on the earlier statement that high velocity impact takes place in the velocity range of 50 to 1500 m/s, Table 2.5 shows that at a velocity above 50 m/s a material will be primarily plastic, within a velocity range of 500 – 1000 m/s viscous and above 1000 m/s fluid like behaviour [30]. If a compressed air gun or mechanical device is used in the velocity range of 50 – 5000 m/s, the upper limit of induced strain rate will be $10^4 s^{-1}$ as shown in Table 2.5 [30]. This is the strain rate of transition from isothermal to fully adiabatic deformation and adiabatic shearing or failure will start to take place [30, 46].

There are different kinds of stress waves which can propagate through a material and they are characterised by the motion of the particles in the material. The three primary stress waves are longitudinal, transverse, and Rayleigh or surface waves [52].

2.7.1. Longitudinal stress wave

Longitudinal stress waves are also referred to as pressure waves (P-waves) [52]. A longitudinal stress wave is created when the particles in the material move in the

same direction as the incident wave [52]. When particles are forced to move closer in this stress wave, this causes the creation of compressive stresses in the material [30, 52]. Tensile stress waves occur when the wave propagating through the material causes particles to move further apart [6]. Depending on the boundary conditions, this type of wave can change from a compression stress wave to a tensile stress wave and vice-versa [30]. Figure 2.17 shows plane longitudinal compressive and tensile waves.

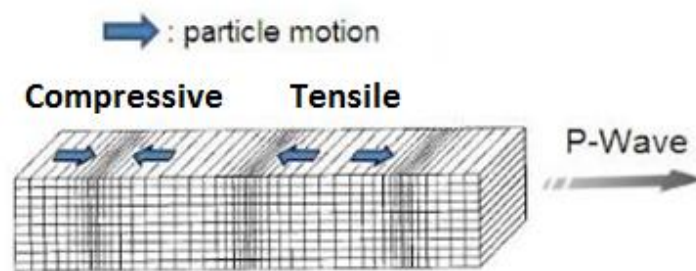


Figure 2.17: Plane longitudinal compressive and tensile waves [58]

2.7.2. Transverse stress wave

This type of stress wave is also referred to as a shear wave (S-wave) [52]. A transverse stress wave is created when the particles in a material move in a direction that is perpendicular to the wave front [6]. Transverse waves cause shear stresses in a material in which the waves propagate and are dangerous for materials with low shear moduli [52]. Figure 2.18 shows a plane transverse wave.

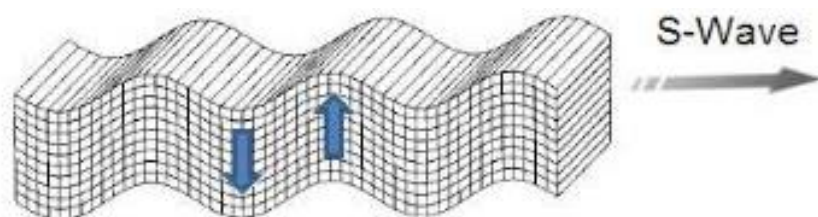


Figure 2.18: Plane transverse wave [58]

2.7.3. Rayleigh stress wave

A Rayleigh wave is a destructive wave that acts on the surface of a material. This type of wave propagates in an elliptical counter-clockwise way, which then results in an up and down motion combined with a back and forth motion [52]. Such waves

have high energy on the surface but exponentially decay as they propagate into the material [52]. The amplitude of such waves decreases a lot slower than other kinds of stress waves, which makes them destructive [52]. Figure 2.19 shows an image of a Rayleigh wave.

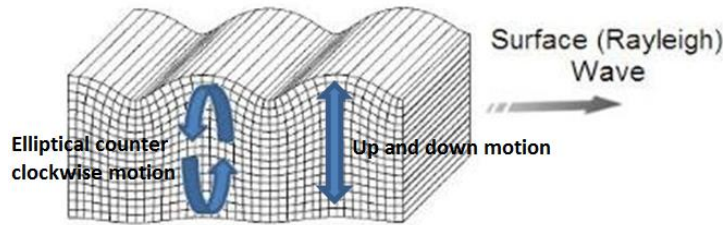


Figure 2.19: Image of a Rayleigh wave [58]

2.8. Analysis of Elastic Stress Waves

For elastic waves to propagate, the induced stress must be less than the yield strength of the material. The velocity of elastic stress waves in materials is constant for each material, which behaves linear elastically [31, 52]. Furthermore, the velocity of elastic stress waves is dependent on the following physical and mechanical properties of the material: the modulus of elasticity (E), density (ρ) and the Poisson's ratio (ν), in the relationships shown in the Equations (5) and (6) for longitudinal and transverse waves, respectively [54]. In Equations (5) and (6), the symbols C_L and C_T represent the longitudinal wave velocity and the transverse wave velocity, respectively.

$$C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (5)$$

$$C_T = \sqrt{\frac{E}{2\rho(1+\nu)}} = \sqrt{\frac{G}{\rho}} \quad (6)$$

It is evident from the two equations that the velocity of a stress wave increases with an increase in the magnitude of the ratios (E/ρ) and (G/ρ), and so will its effect on the rate of deformation of a material [52]. The degree of deformation of a material is a function of the stress wave amplitude, whilst the aforementioned is a function of the velocity of the stress wave [51]. The stress wave amplitude determines the stress

load and therefore strain on the material, whilst the velocity of the stress wave determines the rate of deformation of the material [34, 42].

2.9. Energy Dissipated by Elastic Waves

Many processes of energy dissipation occur within a material during impact [55]. For elastic deformation, stress waves and vibrations dissipate most of the energy, whilst most of the inelastic energy goes into creation and propagation of cracks [51]. An estimation of the amount of energy dissipated by stress waves (W) can be done starting from the differential equation of the rate of work done on a target during impact that is shown in Equation (7) [56, 57]. In Equation (7), the symbol r is the radius of contact between the projectile and the target, $P(t)$ the pressure on the contacting surface of the target and $\bar{u}$ the mean displacement of the surface of the target.

$$\frac{dW}{dt} = \pi r^2 P(t) \frac{d\bar{u}}{dt} \quad (7)$$

2.10. Materials for use in Conditions of High velocity Ballistic Impact

Essentially, to identify material prior to testing as having good ballistic performance, the material should have a high hardness to blunt the projectile and also high ductility to absorb the energy from the projectile during impact [31, 34]. Nevertheless, not all materials with high tensile yield strength are suitable for shock loading, because high strength normally comes with high brittleness [30]. In general the mechanisms that are activated in ballistic impact depend on the thickness, ductility, toughness, stiffness, hardness, strength, strain rate ($\dot{\epsilon}$), and density (ρ) of the target and projectile, and velocity of the projectile [30, 31, 34].

According to the military standard MIL-A-12560H (MR), it normally takes an 11.43 mm thick RHA plate to stop a 7.62 x 39 mm projectile, also called a .30 calibre bullet travelling at about 700 m/s. Moreover, according to the military standard MIL-DTL-

46027K (MR), it normally takes an AA 5083 plate with a thickness greater than 19.8 mm to stop the same projectile travelling at the same velocity.

New choices of materials, such as ceramics, polymers, polymer fibres and lower density metals, have significantly decreased the weight of the armour needed for protection [31, 59]. Although ceramics continue to be studied, they have a downside of low fracture toughness. Polymers suffer the setbacks of low impact strength and poor moisture resistance, which causes swelling of reinforcing fibres [59, 60].

The inability of any single material to possess all required ballistic properties of high strength, hardness, stiffness and toughness, has led to the development of hybrid armour comprised of hard material at the front (the side facing the projectile) joined to ductile material at the back [31, 59]. The hard material is used to blunt projectiles during impact, while the ductile material absorbs their energy [60].

DMLS Ti6Al4V (ELI) is attractive, because of its high specific values of strength, hardness and toughness, hence the reason for its study here. Furthermore, the alloy has a specific strength that is within the same range to that of both RHA and aluminium 5083 at a value ranging from 0.244 to 0.271 MPa-m³/kg. Additionally, the alloy has a ballistic mass efficiency that is higher than that of both RHA and aluminium 5083 at a value of 1.5.

The low density of the alloy comes with an advantage of weight reduction in main battle tanks and other combat vehicles where RHA is used and in an aircraft where steel is used. This leads to a lowering of the requirements for the construction strength of roads and bridges in the first case and improved fuel consumption in both cases.

The other advantage is that parts made from the alloy can be manufactured through DMLS, which can achieve complex geometries in parts, without resorting to welding and parts assembly. Welding joints are problematic, because they act as sites of stress concentration and this eventually can bring about fatigue cracking in the manufactured part.

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CHAPTER 3 - METHODOLOGY

3.1. Introduction

This work is primarily experimental and is supported by some numerical modelling and analytical models to validate the experimental results and create a justification for testing of DMLS Ti6Al4V(ELI), respectively. In order not to distract from the flow of thought, the supporting material is all placed in the appendix.

This chapter contains details of the preparation of specimens, experimental procedures and equipment used to undertake preliminary high velocity ballistic impact testing of wrought Ti6Al4V and high velocity ballistic impact testing of as-built plus stress relieved DMLS Ti6Al4V (ELI) plates. Details of the preliminary tensile testing undertaken on wrought Ti6Al4V, procedures for fractographic analysis preparation of sections of plates with through projectile holes and microstructural analysis are also described briefly, for both alloys. Furthermore, the numerical simulation of the bullet impact and penetration into as-built and stress relieved DMLS Ti6Al4V (ELI) plates is also described briefly.

3.2. Preparation of Specimens for Preliminary Tensile Testing of Wrought Ti6Al4V

Thirty specimens of wrought Ti6Al4V target plates with dimensions 100 mm by 100 mm were acquired for high velocity ballistic impact testing in this work. The specimens were acquired in five sets of different thicknesses, six plates for each thickness of 6 mm, 10 mm, 12 mm, 14 mm and 18 mm. The plates were then labelled by punching numbers according to a unique numbering system on them to ensure traceability throughout the study. In this way each plate was allocated its own unique number, for example 6-1 for the first 6 mm thick plate and 6-2 for the second one and so forth.

Two additional 18 mm thick plates were also acquired, and from them a set of 6 tensile samples were machined. The tensile samples were subsequently tested to confirm whether the mechanical properties of the supplied material were as per the provided certificate for the material and if they adhered to ASTM F 1472-08, which is the standard for wrought Ti6Al4V.

The tensile samples used were machined according to the Council for Scientific and Industrial Research (CSIR) CAD model for a scaled down tensile sample with M12 threads at the ends. This CAD model complies with the ASTM E8M standard and has been consistently used for mechanical testing by the participants in the national Collaborative Program in Additive Manufacturing. The CAD drawing with dimensions of the machined scaled down sample is shown in Figure 3.1. Figure 3.2 shows a photograph of the machined wrought Ti6Al4V tensile samples.

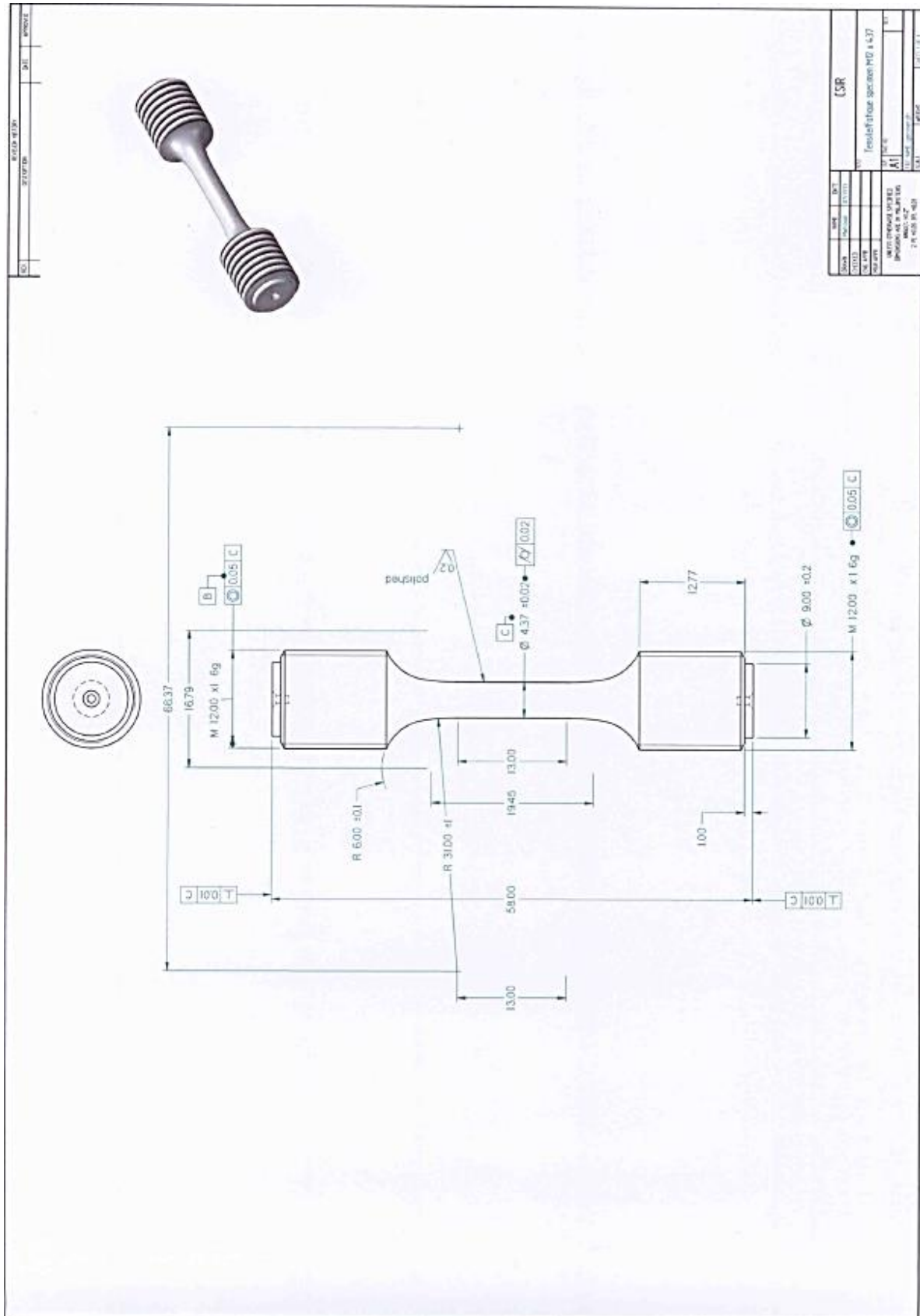


Figure 3.1: CAD drawing for machining of tensile samples compliant with ASTM E8M



Figure 3.2: Machined wrought Ti6Al4V tensile sample

A tensile sample was drawn on AutoCAD Inventor and run through a numerical simulation to determine the location of maximum Von Mises stress points to ensure accurate results during the tensile testing. The reason for doing the simulation was to confirm that the maximum Von Mises stresses for the sample design remained within the gauge length. The sample was modelled according to the dimensions on the drawing in Figure 3.1. Upon modelling the sample and running a simulation under tensile load, the Von Mises stress distribution obtained was as shown in Figure 3.3.

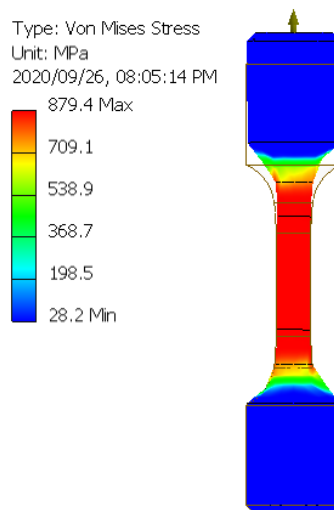


Figure 3.3: Von Mises stress distribution on the machined tensile samples

From Figure 3.3, it can be seen clearly that the maximum Von Mises stress occurs within the gauge length and is therefore, the expected zone of failure. This, therefore, validated the design for the scaled down samples as during testing the aim is to have the samples fail in this area.

The reasons for desiring tensile specimens to fail along the gauge length is that this is the part along which measurements for elongation are taken and is, because of its uniform cross-sectional area, the zone of uniform stress whose magnitude is easily determined from its known uniform cross-sectional area and the applied load.

3.3. Tensile Testing of Wrought Ti6Al4V Specimens

The MTS Criterion Model 43 tensile testing machine at CRPM was used to conduct tensile tests at a test rate of 0.015 mm/min which adheres to ASTM E8 (Standard Test Methods for Tension Testing of Metallic Materials).

Figure 3.4 shows the MTS Criterion Model 43 tensile testing machine with a clamped test sample. The samples were first marked using a marker on both ends, with specific numbers for example 1.1 for the first sample, 1.2 for the second sample and so on, in order to keep track of them. The samples were then loaded in uniaxial tension until failure and the test results recorded and analysed.



Figure 3.4: MTS Criterion model 43 tensile testing machine and test set up

3.4. High Velocity Ballistic Impact Testing of Wrought Ti6Al4V

Prior to conducting the high velocity ballistic impact tests on the wrought Ti6Al4V, a comprehensive test instruction was compiled and submitted to the Armaments Corporation of South Africa SOC Ltd (ARMSCOR). The approved test instruction was followed during testing to ensure consistency, safety and a logical flow in testing. The test instruction provided information on the test setup, measurements

and measuring equipment, testing equipment, safety during testing and the testing procedure that was to be followed during the tests.

3.4.1. Test setup

Figure 3.5 is a photographic image of the test setup showing the various pieces of equipment used for testing, while Figure 3.6 is a schematic of the test setup.



Figure 3.5: Image of the test setup on the Gerotek testing range

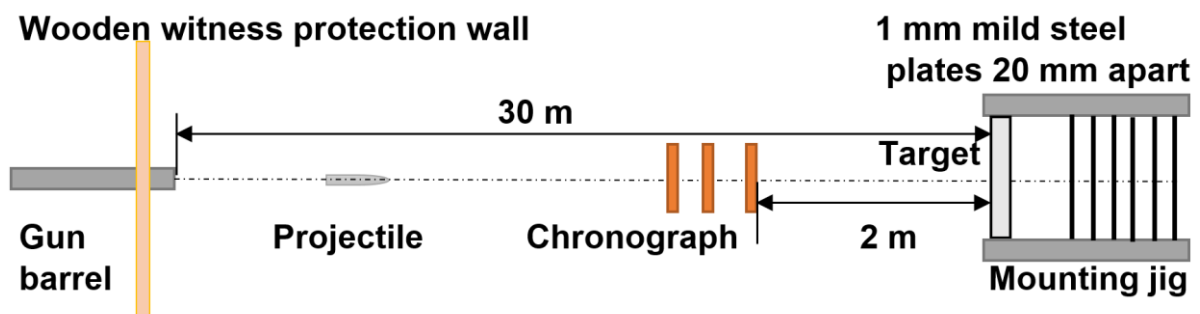


Figure 3.6: Schematic of the test setup on the Gerotek testing range

3.4.2. Measurements and measuring equipment

Gun chronograph: The chronograph shown in Figure 3.5 was placed at a distance of 2 m in front of the target and was used to measure the velocity of the bullet at that point. A subtraction of 1.82 m/s on the chronograph reading was done to obtain the actual striking velocity on the target. The value of 1.82 m/s was arrived at from the known distance between the chronograph and the target and the known fact that the bullet experienced a reduction in velocity of 0.91 m/s per meter.

Mild steel plates: A system of 15 mild steel witness plates, each 1 mm thick, were placed in the mounting frame, behind the test plates, for use in determining the residual velocity of projectiles in case of through penetration. The plates were spaced 20 mm apart.

3.4.3. Testing equipment

Rifle: A high calibre rifle was used to propel the projectiles (bullets) towards the target, at approximately 90° to the front face of the target. The outlet of the barrel of the rifle was placed 30 m from the target upon advice of the personnel at the testing range based on their knowledge that at this distance the bullet would have stabilized and would therefore impact the target with little or no yaw.

Projectile: The projectiles used for the tests were 7.62 x 39 mm armour piercing incendiary (API) bullets. Figure 3.7 is an image of carton with wrapped 7.62 x 39 mm AP bullets.



Figure 3.7: Image of wrapped 7.62 x 39 mm API bullets

The geometric properties of the projectile used are reported in Table 3.1 below: In the table, the acronym OD stands for outer diameter.

Table 3.1: Projectile geometric properties

Projectile	OD [mm]	Length [mm]	Mass [g]	Core OD [mm]	Core Length [mm]	Core Mass [g]
7.62 X 39 API bullet	7.92	27.2	7.04	6	22.36	3.95

Mounting jig: A mounting jig was designed on Autocad inventor and fabricated in the Product Development Technology Station (PDTS) workshops of the Central University of Technology, Free State (CUT). The mounting jig was used to mount the targets and to secure the 1 mm thick mild steel witness plates. The jig was further mounted onto an existing frame at the testing range that his shown in Figure 3.5. Figure 3.8 is the CAD model of the mounting jig.

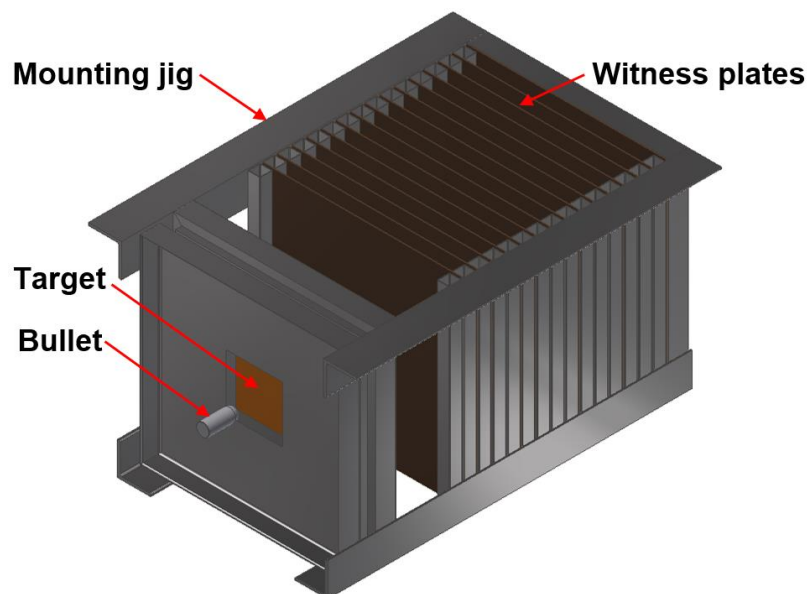


Figure 3.8: CAD model of the mounting jig and projectile

Wooden witness protection wall: The wooden witness protection wall served to protect personnel taking part in testing from ricochets of the projectile or fragments bouncing off the target.

3.4.4. Safety precautions

All safety requirements that apply to a fire arms testing range were used in conducting the tests.

3.4.5. Testing matrix

Table 3.2 shows the testing matrix that was used for plates of different thicknesses.

Table 3.2: Testing matrix used during high velocity ballistic impact testing of wrought Ti6Al4V plates

Testing order	Target plate thickness (mm)	Number of target plates	Number of shots per target plate	Number of shots per target plate thickness
1	18	6	1	6
2	14	6	1	6
3	12	6	1	6
4	10	6	1	6
5	6	6	1	6
Total number of shots				30

The first step was to sort the test plates according to their respective thicknesses and labelling to ensure the correct testing order was followed according to the matrix shown in Table 3.2. The next step was to mount a dummy target on the mounting jig and fire a few shots in order to adjust the telescope of the rifle to ensure the best accuracy. During this process the functioning of the chronograph was also verified. Prior to each test shot, each test piece was mounted on the jig and secured by tightening the clamps of the jig to keep the test plate in place. The witness plates were then placed in their respective slots.

All personnel at the testing range were then evacuated from in front of the rifle and located behind the witness protection wall. Upon verifying all personnel were in a safe location, shooting was then done. The first set of shots were fired on the first six 18 mm thick plates, one at a time. With every shot that was fired, the velocity of the bullet from the chronograph was recorded. In the case of through penetration for any

target plate, the number of mild steel witness plates that the bullet went through was recorded and the penetration holes in each witness plate marked clearly.

The subsequent sets of tests were carried out on the 14 mm, 12 mm, 10 mm, and 6 mm thick plates in this specific order, following the process explained in the previous paragraph.

3.5. Fractography of High Velocity Ballistic Impacted Wrought Ti6Al4V

The 6 mm, 10 mm, 12 mm and 14 mm thick wrought Ti6Al4V target plates, which were exposed to ballistic impact testing were wire cut into four sections along the lines shown in Figure 3.9. Fractography was not conducted on the 18 mm thick plates because they did not experience through penetration. In the figure, the red arrow indicates the DMLS build direction (BD).

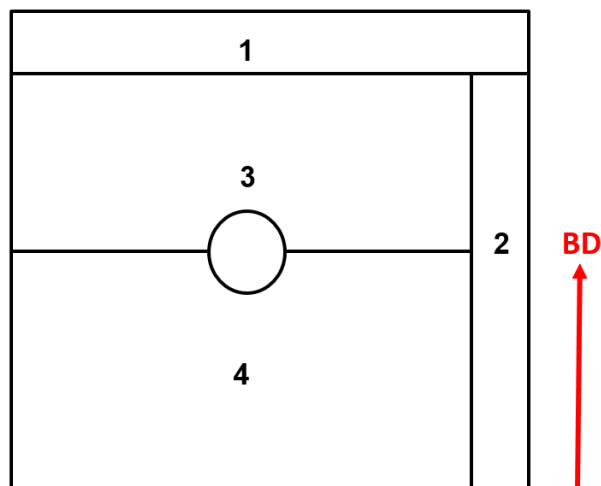


Figure 3.9: Lines of wire cutting of the Ti6Al4V target plates

Two of the four sections cut, sections 3 and 4 in Figure 3.9, were cut through the projectile hole. The other two sections, sections 1 and 2 in the same figure, were cut a distance away from the projectile hole.

Upon wire cutting of the plates, the JEOL JSM-6610 scanning electron microscope was used to study the projectile hole and cut surfaces on the plates. Figure 3.10 is an image of the JEOL JSM-6610 SEM.



Figure 3.10: The JEOL JSM-6610 scanning electron microscope used in this study

The flat surfaces on the sections cut out of the ballistically tested plates in accordance with Figure 3.9, were then cleaned with ethanol and investigated in the scanning electron microscope/energy dispersive spectroscopy (SEM/EDS) to check if the chemical composition of the wrought Ti6Al4V corresponded to the composition specified in the ASTM F 136 – 08 standard, which is an international standard specification for wrought Ti6Al4V. The SEM/EDS analytical facility was also applied to seek for traces of foreign material on the projectile hole surfaces.

3.6. Microstructural Analysis of High Velocity Ballistic Impacted Wrought Ti6Al4V

For the microstructural analysis, all four sections 1, 2, 3 and 4 that were used for the fractographic analysis from the 6 mm, 10 mm, 12 mm and 14 mm thick target plates, were further cut to size into specimens a, b, c, d, e and f along the red dotted lines shown in Figure 3.11. Microstructural analysis was not conducted on the 18 mm thick plates because they did not experience through penetration. In the figure, the red arrow indicates the DMLS build direction (BD).

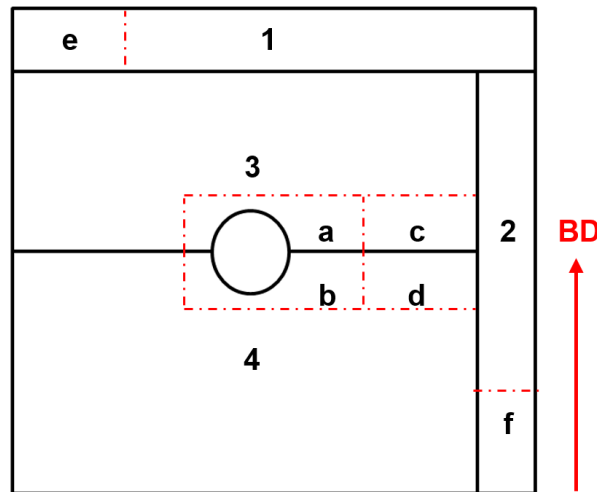


Figure 3.11: Lines of wire cutting specimens a, b, c, d, e and f

After wire cutting specimens a, b, c, d, e and f, these specimens were each mounted in Multi-fast non-conductive resin using a Struers CitoPress-1 machine. The mounting process began with the placing of the specimens, one at a time, into the Struers CitoPress-1 machine with the surface to be studied facing downwards.

The next step was addition of 25 ml of Multifast non-conductive resin and thereafter the machine was started. The parameters set for the mounting process on the machine, were a mounting time of 5.5 minutes, of which 3.5 minutes were for heating the resin up to 180°C and compacting it at a pressure of 250 bar, followed by subsequent water cooling for 2 minutes.

The mounted samples were then ground and polished using the Struers Tegramin-25 machine in accordance with the guidelines provided by Struers for Ti6Al4V. Figure 3.12(a) and (b) are images of the Struers CitoPress-1 and Struers Tegramin-25 machines used, respectively.

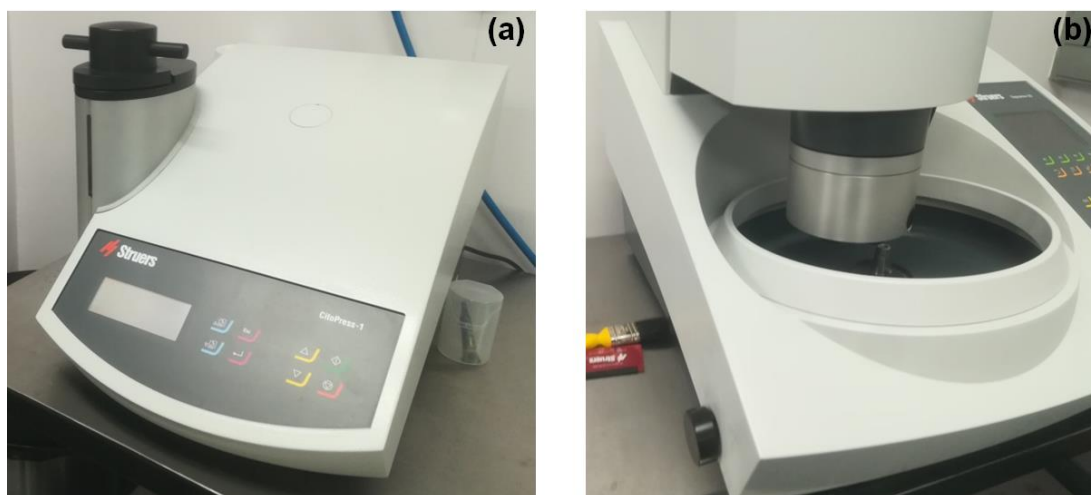


Figure 3.12: (a) Struers CitoPress-1 and (b) Struers Tegramin-25 machines

Table 3.3 contains the grinding and polishing procedure for Ti6Al4V recommended by Struers.

Table 3.3: The grinding and polishing procedure for Ti6Al4V recommended by Struers

Process	Disc	Lubricant	Force (N)	Speed (rpm)	Time(min)
Coarse grinding	320 SiC	Water	25	300	1.50
Fine grinding	MD-Largo	DiaPro All/Lar.9	30	150	5.00
First polishing	MD-Mol	DiaPro Mol.3	25	150	2.20
Final polishing	MD-CHEM	OP-S Suspension	20	150	1.50

Upon completion of grinding and polishing, the specimens were all cleaned with tap water and finally in the UC-O2 ultrasonic cleaner for 2 minutes. The specimens were then dried using a smooth cloth before etching. The specimens were etched in an ESCO fume hood using Kroll's reagent in order to reveal the microstructure. Using an electric engraving pen, the resin mounts of specimens *a*, *b*, *c*, *d*, *e* and *f*, were then marked to ensure traceability when conducting microstructural analyses. The

markings were made to distinguish between the different plate thicknesses. Figure 3.13 is an image of the ESCO fume hood.



Figure 3.13: ESCO fume hood in which the specimens were etched

Microstructural analyses of the specimens were then undertaken using a ZEISS Axioscope .5 Pol optical microscope. Specimens e and f of each target plate were analysed to confirm the initial microstructure of the target plate prior to ballistic testing, on the assumption that the effects of the impact did not reach their location on the plates. On the other hand, specimens a, b, c and d were aimed at studying the microstructure of the impacted plates, radially outwards from the projectile hole. Figure 3.14 is an image of the ZEISS Axioscope .5 Pol optical microscope that was used for the microstructural analysis.

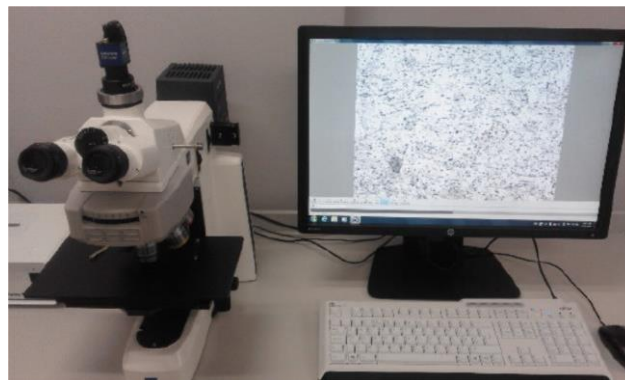


Figure 3.14: ZEISS Axioscope .5 Pol optical microscope

Micrographs were taken on specimens a and b, extracted from a set of 3 plates for each plate thickness. The micrographs were obtained from near the edge of the projectile hole and at distances of 2 mm, 4 mm and 6 mm from here moving radially

outwards, in order to investigate the change in microstructure with distance away from the penetration hole during impact.

Furthermore, on each micrograph obtained, the thicknesses of the α laths were measured under the microscope at ten different positions and the average value calculated in order to investigate the effect of distance away from the penetration hole on their thicknesses. These measurements were done in areas where the α laths were best defined on the micrographs.

Upon testing wrought Ti6Al4V, it was deemed necessary to develop a justification for further high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI). In doing so, the theories of the V_{50} ballistic limit and absorbed strain energy were used to estimate the optimum thickness for through penetration of the material. The justification can be found in the appendix.

3.7. Preparation of Specimens for High Velocity Ballistic Testing of As-built and Stress Relieved DMLS Ti6Al4V (ELI)

After formulating a justification for further testing of as-built and stress relieved DMLS Ti6Al4V (ELI), the next step taken was to build four sets of plates of different thicknesses through DMLS. Three plates each of thickness of 8 mm, 10 mm, 12 mm and 14 mm, were built in an EOSINT M 280 machine at CRPM from Ti6Al4V (ELI) powder supplied by TLS Technik. Table 3.4 gives the composition of this powder as specified by the supplier. The chemical composition corresponded to the ASTM standard for Ti grade 23.

Table 3.4: Ti6Al4V (ELI) powder chemical composition

	Ti (wt %)	Al (wt %)	V (wt %)	O (wt %)	N (wt %)
Ti6Al4V powder from TLS Technik	balance	6.44	3.99	0.12	<0.001

The plates were built perpendicular to the Z-direction of the machine with planar dimensions of 100 mm by 100 mm. The thicknesses of the plates chosen were informed by the calculations in the justification for further testing. The plates were built in a processing environment of argon gas, with the machine set to the standard

process parameters. Table 3.5 shows the standard process parameters of the EOSINT M 280 DMLS machine that were used to build the plates.

Table 3.5: Standard process parameters of the EOSINT M 280 DMLS machine

Parameter	Laser power (W)	Beam diameter (μm)	Scan speed (mm/s)	Hatch spacing (μm)	Layer thickness (μm)	Powder bed temperature ($^{\circ}\text{C}$)
Value	170	80	1200	100	30	45

Upon completion of the building process, the plates were stress relieved in a vacuum furnace and thereafter cut from the built platform using a band saw.

3.8. High Velocity Ballistic Impact Testing of As-built and Stress Relieved DMLS Ti6Al4V (ELI)

The testing procedure used for testing wrought Ti6Al4V that was presented in section 3.4 was also followed for the testing of the as-built and stress relieved DMLS Ti6Al4V (ELI), with variations only in the testing matrix. Table 3.6 shows the testing matrix that was used for plates of different thicknesses of as-built and stress relieved DMLS Ti6Al4V (ELI).

Table 3.6: Testing matrix used during high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI) plates

Testing order	Target plate thickness (mm)	Number of target plates	Number of shots per target plate	Number of shots per target plates thickness
1	8	3	1	3
2	10	3	1	3
3	12	3	1	3
4	14	3	1	3
Total number of shots				12

Upon completion of the high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI), fractography and microstructural analysis of the plates

were conducted following the same procedures presented in sections 3.5 and 3.6, respectively.

3.9. Simulation of Bullet Impact on and Penetration into As-built and Stress Relieved DMLS Ti6Al4V (ELI) Plates

Upon testing the as-built and stress relieved DMLS Ti6Al4V (ELI) plates, numerical simulation of the process was carried out at Flamengro, ARMSCOR. Unfortunately, there were restrictions to the information they could share, for security reasons.

The numerical simulations were conducted based on the particle-in-cell (PIC) numerical method developed by Los Alamos National Laboratory in the late 1950s [1]. This numerical method was specifically implemented to solve problems of extremely high velocity impacts [1, 2]. These impacts are characterized by the generation of strong shock waves and subsequent high pressures in the materials that undergo impact [1, 2]. The pressure generated exceeds the ultimate tensile strength of the material by several orders of magnitude [1, 2].

This PIC method, therefore, assumes full hydrodynamic behaviour in the material and does not consider the material's strength and failure behaviour [1, 2]. While hydrocodes have evolved significantly from the PIC method the hydrodynamic assumption lends its name to this class of software [1, 2].

For the numerical simulation studies, Abaqus Explicit® software was used, an explicit non-linear commercial hydrocode software package, which is owned by Dassault Systèmes [3]. It uses finite element, finite volume, and finite difference numerical schemes to solve non-linear solid, fluid and gas dynamics problems. The following inputs were used to run the simulations on the plates [3].

3.9.1. Projectile geometric properties

The projectile geometry in the CAD format used as an input for simulation is illustrated below in Figure 3.15.

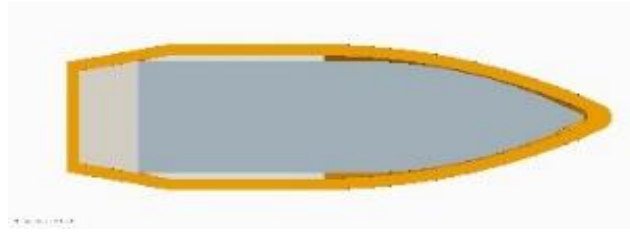


Figure 3.15: Geometry of the projectile - 7.62 x 39 API bullet used in the simulation

The geometric properties of the projectile are presented Table 3.7. In the table, the acronym OD stands for outer diameter.

Table 3.7 Projectile geometric properties used in the simulation

Projectile	OD [mm]	Length [mm]	Mass [g]	Core OD [mm]	Core Length [mm]	Core Mass [g]
7.62 X 39 API bullet	7.92	27.2	7.04	6	22.36	3.95

3.9.2. Material properties used in the simulation

The dimensions and properties of the 7.62 X 39 mm API projectile which consists of 3 layers that was used for experimental work were used for numerical analysis here. The outmost layer, the jacket, was taken to be 4340 steel. Inside the jacket the thin layer of liner material was taken to be antimonial lead. The final part of the projectile, the core, was taken to be hardened steel (N12e). A Von-Mises constitutive model was used for all these materials. The results of the simulation carried out are reported in Chapter 4.

The material properties and Johnson-Cook constitutive parameters for the jacket, core and layer of liner used for simulation are shown in Table 3.8.

Table 3.8: Simulation material properties

		Steel N12e	Steel 4340	Lead	DMLS Ti6Al4V (ELI)
	Density, ρ [k.m ⁻³]	7222.2			
Shock EOS	Initial acoustic velocity, C_0 [m.s ⁻¹]	4569		11340	
	Hugoniot slope coefficient, S_1 [-]	1.49		2006	
	Grüneisen Gamma, Γ [-]	2.17		1.429	
	Shear modulus, G [MPa]	81800		2.74	
J-C Strength Model	Yield Stress, A [MPa]	1580	792	24	700
	Strain Hardening Constant, B [MPa]	2905	510	300	400
	Strain Hardening Exponent, n [-]	0.117	0.26	1.0	0.15
	Strain Rate Constant, C [-]	0.075	0.014	0.1	0.0017
	Thermal Softening Exponent, m [-]	1.17	1.03	1.0	0.633
J-C Failure Model	Damage Parameter, D_1	0.036	0.050	[-]	0.068
	Damage Parameter, D_2	0.083	3.440	[-]	5.328
	Damage Parameter, D_3	- 3.000	-2.120	[-]	-2.554
	Damage Parameter, D_4	0.000	0.002	[-]	0.000
	Damage Parameter, D_5	0.000	0.610	[-]	0.000

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- [1] **Johnson L. N.**, 1996. The Legacy and Future of CFD at Los Alamos. *1996 Canadian CFD Conference*, pp.1-23.
- [2] **Harlow F. H.**, 1962. The Particle In-Cell Method for Numerical Solution of Problems in Fluid Dynamics. *The University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico*, pp.1-42.
- [3] Wikipedia, n.d. *Abaqus*. [Online] Available at: [Abaqus - Wikipedia](#) [Accessed 21 June 2021].

CHAPTER 4 - RESULTS AND DISCUSSION

The material contained in this chapter has been published in peer reviewed media as follows:

1. Teboho Moleko, Maina Maringa and Willie du Preez, Wrought Ti6Al4V as an alloy for high velocity impact applications, *Design and Additive Manufacturing of Titanium Parts pre-conference seminar, Proceedings of the 20th Annual International RAPDASA Conference, Emoya Estate, Bloemfontein, 5 - 8 November 2019*, pp. 66 – 77, ISBN 978-0-6398390-0-4.
2. Teboho Moleko, Maina Maringa and Willie du Preez, Justification for high velocity impact testing using as-built and stress relieved DMLS Ti6Al4V (ELI) based on results for wrought Ti6Al4V, *Design and Additive Manufacturing of Titanium Parts pre-conference seminar, Proceedings of the 21st Annual International RAPDASA Conference, Stellenbosch University, Western Cape, 4 - 6 November 2020*, pp. 180 – 191, ISBN 978-0-620-90354-7 (e-book).
3. Teboho Moleko, Maina Maringa and Willie du Preez, Comparative analysis of the high velocity impact behaviour of wrought Ti6Al4V and as-built and stress relieved DMLS Ti6Al4V (ELI), *2021 Rapid Product Development Association of South Africa - Robotics and Mechatronics - Pattern Recognition Association of South Africa (RAPDASA-RobMech-PRASA) Conference, CSIR, 3 - 6 November 2021* (accepted for publication)

4.1. Introduction

This chapter contains details of the results from tensile testing, preliminary high velocity ballistic impact testing of wrought Ti6Al4V, and fractographic analysis and microstructural analysis of the alloy. The chapter further contains the results from the high velocity ballistic impact testing, visual inspection, fractographic analysis and microstructural analysis of as-built and stress relieved DMLS Ti6Al4V (ELI). Details of the results obtained from the simulation of bullet impact on and penetration of as-built and stress relieved DMLS Ti6Al4V (ELI) plates are also described. In this section, references are used to show that the experimental findings here are consistent with what other researchers reported.

4.2. Tensile Testing of Wrought Ti6Al4V

The results obtained from the tensile testing of the wrought Ti6Al4V specimens are tabulated in Tables 4.1 and 4.2. Table 4.1 presents the experimental % elongation values, while Table 4.2 shows the second part of the test results. Mechanical properties obtained from the tests of the wrought Ti6Al4V specimens were average yield stress of 880.2 MPa with a standard deviation of 6 MPa, average ultimate tensile stress of 924.3 MPa with a standard deviation of 6 MPa, percentage elongation of 17.7% with a standard deviation of 2.1% and modulus of elasticity of 125 GPa with a standard deviation of 5.6 GPa.

Table 4.1: Experimental initial dimensions and values of % elongation of wrought Ti6Al4V specimens after tensile testing

Name	Initial Length (mm)	Final Length (mm)	Elongation (%)	Initial Diameter (mm)	Final Diameter (mm)	Area Reduction (%)
Test Run 1	15.7	18.4	17.3	4.1	3.4	29.1
Test Run 2	15.6	18.3	17.0	4.1	3.4	31.2
Test Run 3	15.9	18.9	18.9	4.1	3.3	35.5
Test Run 4	14.6	17.4	18.9	4.1	3.4	31.9
Test Run 5	16.1	18.4	14.1	4.1	3.3	33.5
Test Run 6	14.5	17.4	20.0	4.1	3.4	30.6
Mean	15.4	18.1	17.7	4.1	3.3	32.0
Minimum	14.5	17.4	14.1	4.1	3.3	29.1
Maximum	16.1	18.9	20.0	4.1	3.4	35.5
Standard Deviation	0.7	0.6	2.1	0.0	0.1	2.3
Supplier specifications for the material	-	-	16	-	-	-

Table 4.2: Experimental values of some mechanical properties of wrought Ti6Al4V determined through tensile testing

Name	Label	Modulus (GPa)	Yield Stress (MPa)	UTS (MPa)	Peak Load (kN)
Test Run 1	1.1	120.9	886.5	932.3	12.0
Test Run 2	1.2	127.3	886.5	929.1	12.0
Test Run 3	1.3	122.1	882.5	927.1	12.0
Test Run 4	2.1	120.9	878.3	918.3	11.9
Test Run 5	2.2	135.2	872.5	921.8	11.9
Test Run 6	2.3	123.4	874.6	917.5	11.9
Mean		125.0	880.2	924.3	12.0
Minimum		120.9	872.5	917.5	11.9
Maximum		135.2	886.5	932.3	12.0
Standard Deviation		5.6	6.0	6.0	0.0
Supplier specification for material			988	1034	

Figure 4.1 shows the load versus extension graphs for the 6 samples that were tested. The figure is significant as it shows a good repeatability of the tensile stress versus strain curves of the material.

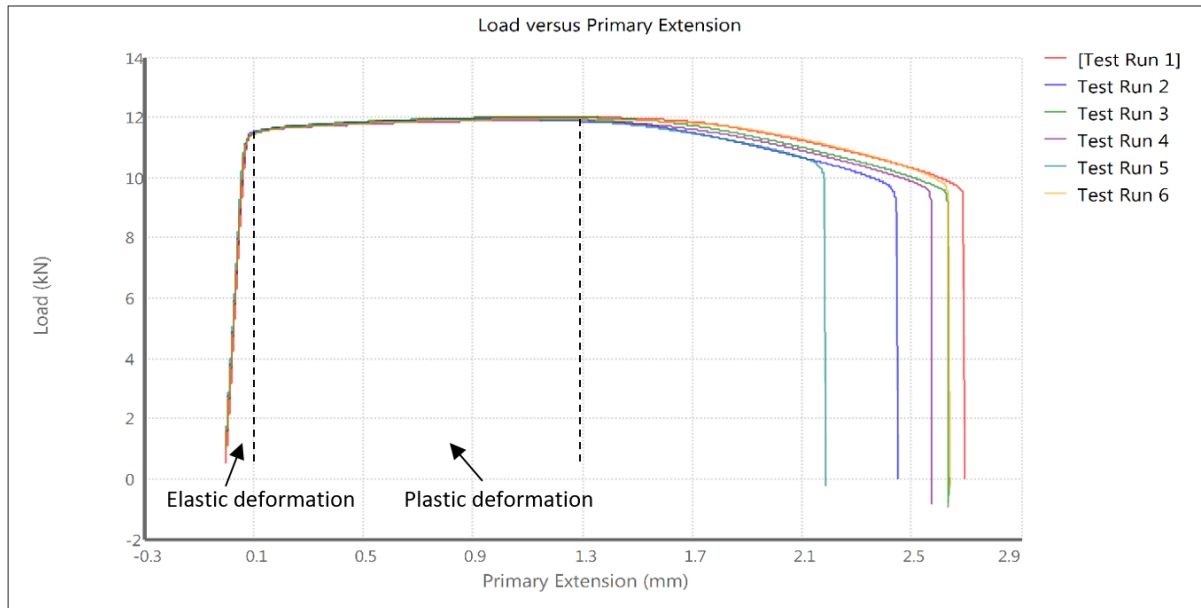


Figure 4.1: Load versus extension graphs for wrought Ti6Al4V

From Table 4.2, the average yield stress of 880.2 MPa obtained from the tests is lower than the specified yield stress of 988 MPa in the supplier's material certificate shown in Figure B.1 in appendix B. Furthermore, the average ultimate tensile stress obtained from the tests at a value of 924.3 MPa also falls below the 1034 MPa in the same material certificate. The deviation of these test results from the values in the supplier's material certificate of about 10.9% and 10.7%, respectively, is significant and calls for further confirmatory testing. However, as this was not the focus of the present work, the matter was not followed up.

On the other hand, as shown in Table 4.1, the average percentage elongation of 17.7% obtained from the tests is above the value of 16% that is specified in the material certificate. The difference of about 6.3% between the test results and those in the supplier's material certificate is minimal.

4.3. High Velocity Ballistic Impact Testing of Wrought Ti6Al4V

Table 4.3 shows the results from high velocity ballistic impact testing of wrought Ti6Al4V. In the table the symbols stand for: v_{chron} chronograph velocity reading, v_i impact velocity, t target plate thickness and CP complete penetration. The calculations conducted to obtain v_{chron} are covered in Section 3.4.2.

The actual distance and angle shown in the table represent distance from the exit of the gun barrel to the target and impact angle, respectively. The entries, “no penetration” and “point pen” indicate no penetration of the core through the target and nicking of the target, in that order. The entry, “core stuck”, refers to the core being stuck in the target, while for entries such as, “+ 4 x 1 mm MS”, the number four refers to the fact that four 1 mm mild steel witness plates were penetrated by the bullet.

Table 4.3: High velocity ballistic impact test results for wrought Ti6Al4V

Material Type			Material Identification			Ammunition type
Titanium alloy			Ti6Al4V Grade 5 titanium			7,62 x 39 mm API bullet, Type 56
Shot number	Actual Distance (m)	Angle (Deg.)	v_{chron} (m/s)	v_i (m/s)	t (m)	Results
1	30	0	703	701	18	No penetration
2	30	0	698	696	18	No penetration
3	30	0	703	701	18	No penetration
4	30	0	701	699	18	No penetration
5	30	0	704	702	18	No penetration
6	30	0	702	700	18	No penetration
7	30	0	701	699	14	Failed - Point pen
8	30	0	704	702	14	Failed - CP
9	30	0	700	698	14	Failed - CP
10	30	0	704	702	14	Failed - CP core stuck
11	30	0	702	700	14	Failed - CP
12	30	0	707	705	14	Failed - CP
13	30	0	717	715	12	Failed - CP + 4 x 1 mm MS
14	30	0	703	701	12	Failed - CP + 3 x 1 mm MS
15	30	0	700	698	12	Failed - CP + 6 x 1 mm MS
16	30	0	706	704	12	Failed - CP + 2 x 1 mm MS
17	30	0	704	702	12	Failed - CP + 5 x 1 mm MS

18	30	0	700	698	12	Failed - CP + 4 x 1 mm MS
19	30	0	711	709	10	Failed - CP + 4 x 1 mm MS
20	30	0	705	703	10	Failed - CP + 9 x 1 mm MS
21	30	0	703	701	10	Failed - CP + 7 x 1 mm MS
22	30	0	695	693	10	Failed - CP + 9 x 1 mm MS
23	30	0	707	705	10	Failed - CP + 7 x 1 mm MS
24	30	0	696	694	10	Failed - CP + 7 x 1 mm MS
25	30	0	716	714	6	Failed - CP + 10 x 1 mm MS
26	30	0	699	697	6	Failed - CP + 6 x 1 mm MS
27	30	0	701	699	6	Failed - CP + 9 x 1 mm MS
28	30	0	697	695	6	Failed - CP + 9 x 1 mm MS
29	30	0	698	696	6	Failed - CP + 11 x 1 mm MS
30	30	0	716	714	6	Failed - CP + 8 x 1 mm MS
Average			703	701		
Standard deviation			6	6		
Coefficient of variation (%)			0.9	0.9		

The coefficient of variation is a statistical measure of the relative scattering of data points in a data series around the mean and is defined as the percentage ratio of standard deviation to the mean. The actual distance and angle shown in Table 4.3 represent distance from the exit of the gun barrel to the target and impact angle, respectively. The entries, “no penetration” and “point pen” indicate no penetration of the core through the target and nicking of the target, in that order. The entry, “core stuck”, refers to the core being stuck in the target, while for entries such as, “+ 4 x 1 mm MS”, the number four refers to the fact that four 1 mm mild steel witness plates were penetrated by the bullet.

From Table 4.3, the average impact velocity for the tests was found to be 701 m/s, with a standard deviation of 6 m/s, which gives rise to a coefficient of variation of 0.9% that is well below the limiting value of 6%. The variations between the minimum and maximum impact velocities v_i for the 18 mm, 14 mm, 12 mm, 10 mm and 6 mm thick plates of 6 m/s, 4 m/s, 17 m/s, 16 m/s and 12 m/s, respectively, were small with a coefficient of variation of 0.53%.

From Table 4.3, it can also be seen that the minimum thickness to prevent through penetration for the wrought Ti6Al4V was found to be just above 14 mm. Figure 4.2 shows an image of a wrought Ti6Al4V 14 mm plate with a bullet core stuck in it.

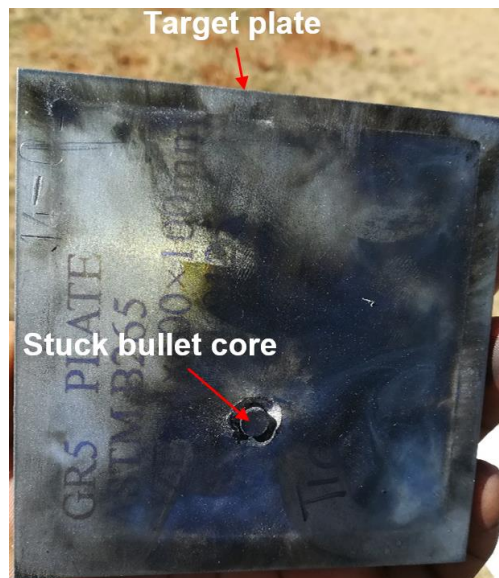


Figure 4.2: wrought Ti6Al4V 14 mm plate with a bullet core stuck in it

The entry “CP core stuck” used in Table 4.3 refers to a scenario such as the one shown in Figure 4.2.

4.4. Visual inspection of Wrought Ti6Al4V Ballistically Impacted Plates

Through visual inspection of the 6 mm thick plates, it was deduced that the plates had a primarily brittle failure mode. This is based on the penetration holes punched through the plates, with minimal shear deformation visible. Furthermore, the fact that the fracture surfaces on the holes were almost perpendicular to the direction of the forces applied by the projectiles also supports this deduction. Figure 4.3 (a and b) are images of a typical hole in the 6 mm thick plates, while Figure 4.3 (c) is a schematic showing the direction of the radial forces in a fracture hole and the perpendicular fracture surface.

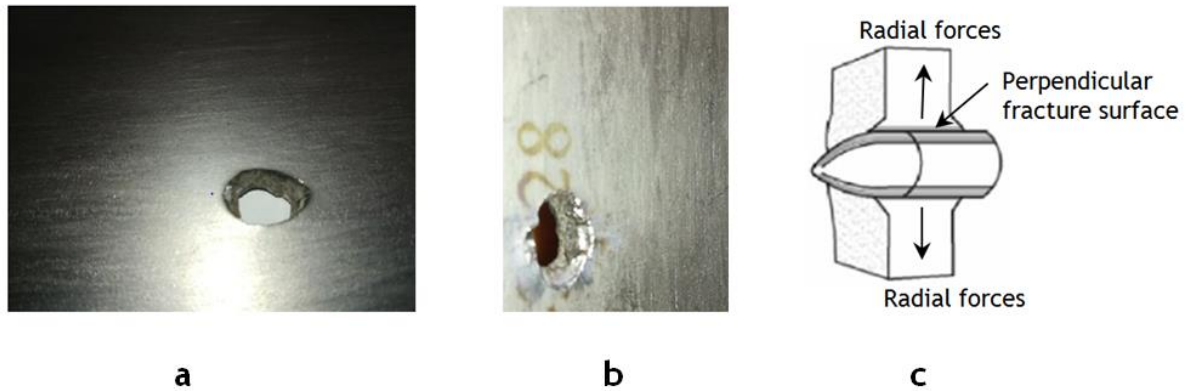


Figure 4.3: (a) and (b) Images of a typical hole in the 6 mm thick plates; (c) schematic showing the direction of the radial forces in a fracture hole and the perpendicular fracture surface

The 10 mm, 12 mm and 14 mm thick plates exhibited petals on the projectile exit side and bulging on the entry side of the plates. The existence of petals indicates the presence of internal tensile fracture in a direction perpendicular to that of the projectile on the exit side of the plate, before arrival of the projectile. It was observed that the extent of the petalling increased with an increase in the thickness of the plates. Furthermore, the 14 mm thick plates in some cases showed cases of scabbing, while others actually stopped the projectile as shown in Figure 4.5 and Figure 4.2, respectively. Figure 4.4 also shows of scabbing on a 14 mm thick plate.



Figure 4.4: Scabbing a 14 mm thick plate

Figure 4.5 shows a typical image of rearward petalling in a 10 mm thick plate.

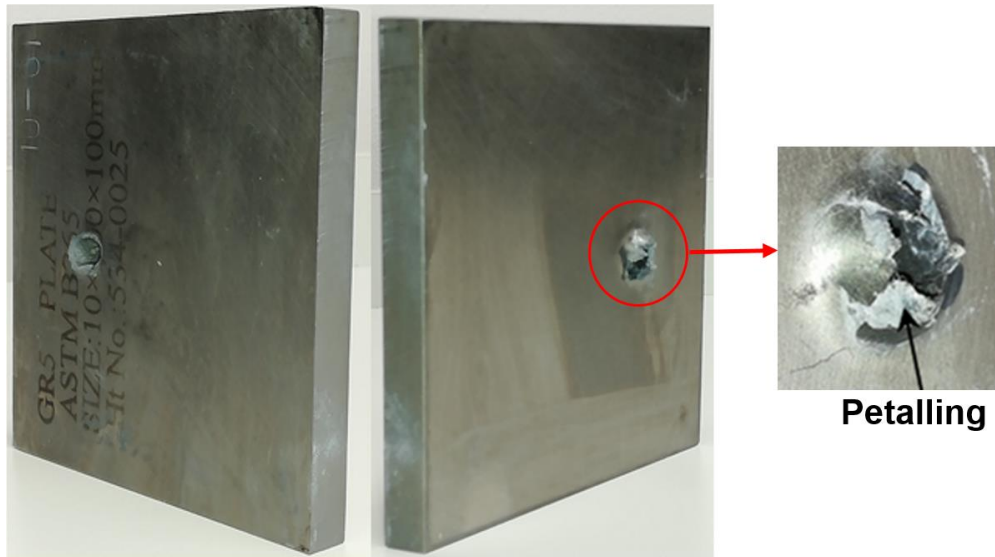


Figure 4.5: Typical rearward petalling of a 10 mm thick plate

The presence of petals and bulging on its own is not enough to determine the mode of failure of the plates, therefore fractographic analysis is conducted on the fracture surfaces of the plates.

4.5. Fractographic Analysis of Wrought Ti6Al4V Ballistically Impacted Plates

To understand the deformation behaviour along the surfaces of the penetration holes for the 6 mm, 10 mm, 12 mm and 14 mm thick plates, fractographic studies were carried out on their half-sections 3 and 4, as described in section 3.5, and also shown in Figure 3.9, using a SEM. For the 6 mm thick plates, SEI micrographs were taken at the projectile hole entrance and exit points based on their thickness compared to the other plates. Furthermore, micrographs were taken at the projectile hole entrance, middle and exit points for all the other plate thicknesses. It should be noted that in the micrographs, the letters DOP stand for direction of penetration.

4.5.1. Fractography of wrought Ti6Al4V 6 mm thick plates

Figure 4.6(a) is a secondary electron image (SEI) of the surface of a penetration hole through a 6 mm thick plate. Figure 4.6(b) is a magnified image at the entry point of the projectile hole and Figure 4.6(c) a magnified image at the exit point of the projectile hole through the same plate.

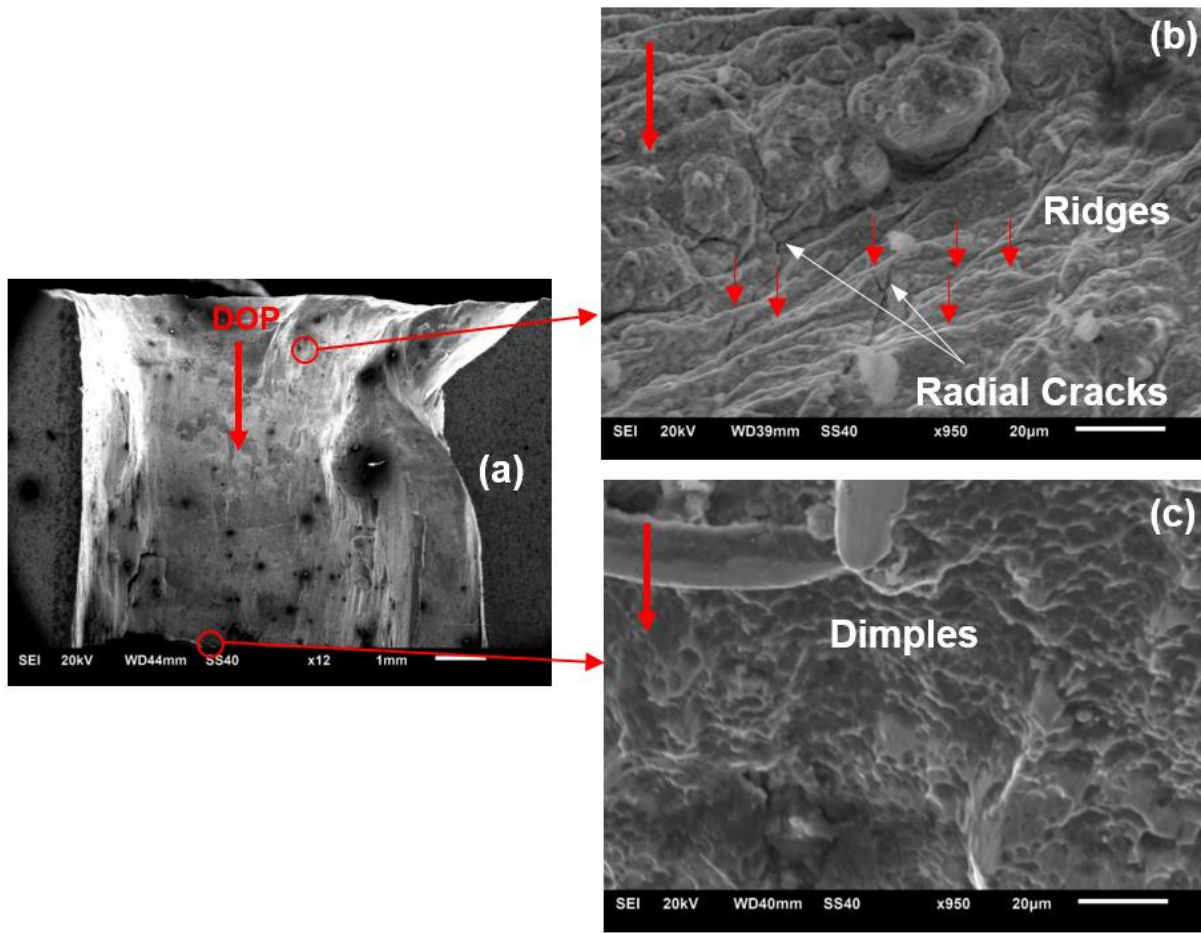


Figure 4.6: SEM SEI micrographs (a) of the penetration hole through a 6 mm thick plate; (b) higher magnification of the indicated area at the entry point of the projectile hole and (c) higher magnification of the indicated area at the exit point of the projectile hole

In Figure 4.6(b), there is a clear network of ridges and radial cracks that can be seen at the entry point of the projectile hole. The radial cracking at the entry point of the projectile hole is characteristic of brittle failure in conditions of ballistic impact, while the ridges on the fracture surface also correspond with brittle failure [1, 2, 3, 4, 5].

Dimples are visible on the micrograph in Figure 4.6(c), which is an indication that the metal fractured in a ductile mode at the exit point of the projectile hole [6, 7, 9].

4.5.2. Fractography of wrought Ti6Al4V 10 mm thick plates

Figure 4.7(a) is a SEI micrograph of the surface at the entry point of the penetration hole through a 10 mm thick plate. Figure 4.7(b) is a higher magnification micrograph at the entry point through the same plate.

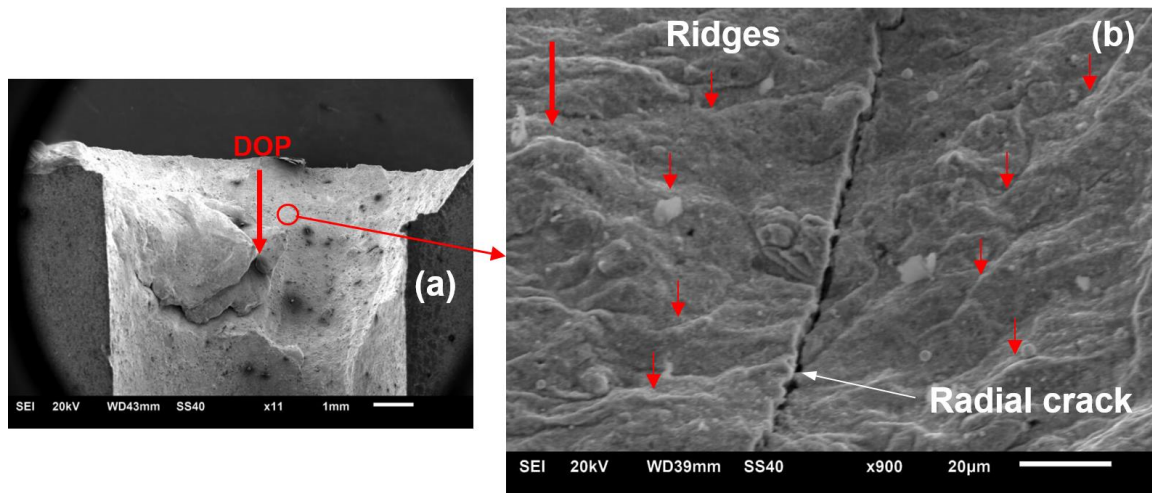


Figure 4.7: SEM SEI micrographs (a) at the entry point of the penetration hole through a 10 mm thick plate and (b) a higher magnification micrograph of the indicated area at the entry point of the projectile hole

There were signs of brittle failure at the entry point of the penetration hole through the 10 mm thick plates. Evidence of this can be seen in Figure 4.7(b), in the form of ridges and radial cracks on the fracture surface [1, 3, 4]. Figure 4.7(a) shows a narrowing down of the projectile hole diameter from the entry point inwards, which is characteristic of the geometry of a ballistic impact hole [1, 3, 4]. The opening up of the hole at the entry is thought to have been due to spalling [1, 3, 4].

Figure 4.8(a) is a SEI micrograph of the surface at the middle point of the penetration hole through a 10 mm thick plate. Figure 4.8(b) is a higher magnification SEI micrograph at the middle point of the projectile hole through the same plate.

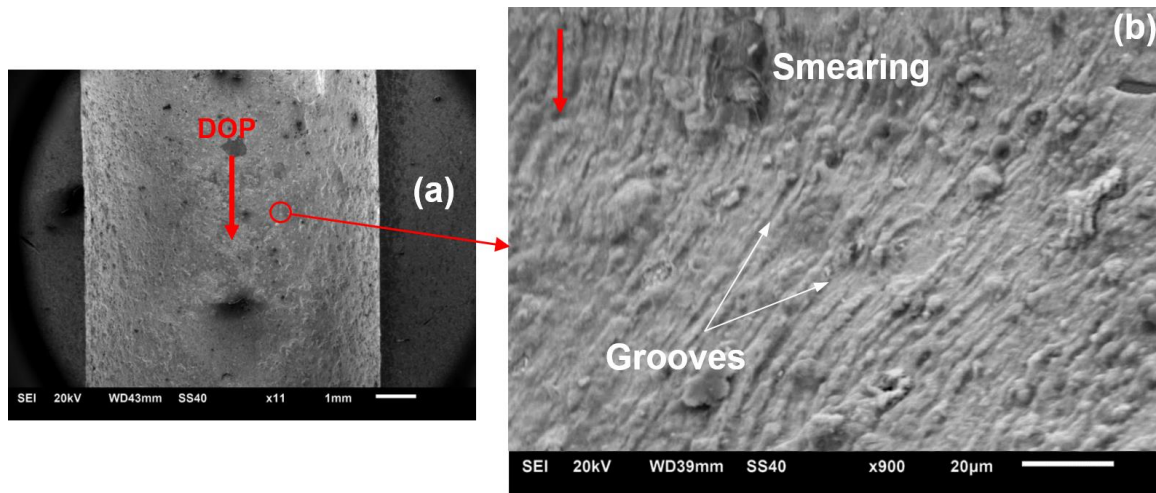


Figure 4.8: SEM SEI micrographs (a) at the middle point of the penetration hole through a 10 mm thick plate and (b) higher magnification micrograph of the indicated area at the middle point of the projectile hole

Figure 4.8(b) shows a fracture area with grooves. The grooves can be attributed to the smearing resulting from the friction effect of the projectile as it penetrated the material [9]. The fracture surface in the figure does not show any distinctive fracture features [10,11].

Figure 4.9(a) is a micrograph of the surface at the exit point of the penetration hole through a 10 mm thick plate. Figure 4.9(b) is a higher magnification micrograph of the point shown in Figure 4.9(a).

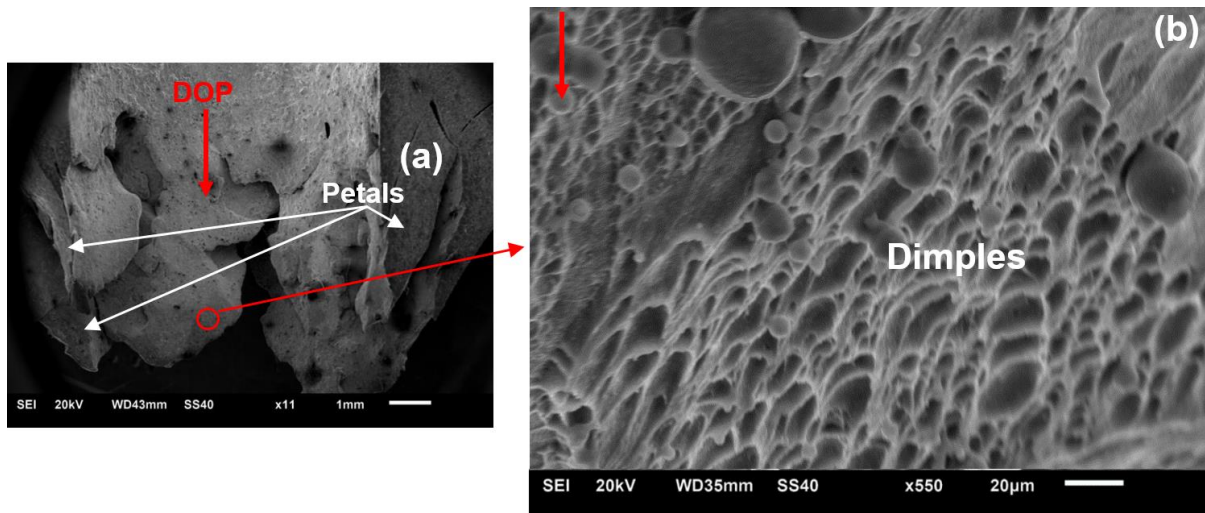


Figure 4.9: SEM SEI micrographs (a) at the exit point of the penetration hole through a 10 mm thick plate and (b) higher magnification micrograph of the indicated area at the exit point of the projectile hole

Figure 4.9(b) shows a fracture surface with dimples at the exit point of the penetration hole. The formation of dimples suggests a ductile mode of failure at the projectile hole exit [7, 9, 12].

Furthermore, it can be seen in Figure 4.9(a) that there is a formation of petals at the exit point of the penetration hole of a 10 mm thick plates. This observation validates the earlier made claim during the visual inspection of the plates.

4.5.3. Fractography of wrought Ti6Al4V 12 mm thick plates

Figure 4.10(a) is a SEI micrograph of the surface at the entry point of the penetration hole through a 12 mm thick plate. Figure 4.10(b) is a higher magnification micrograph at the entry point through the same plate.

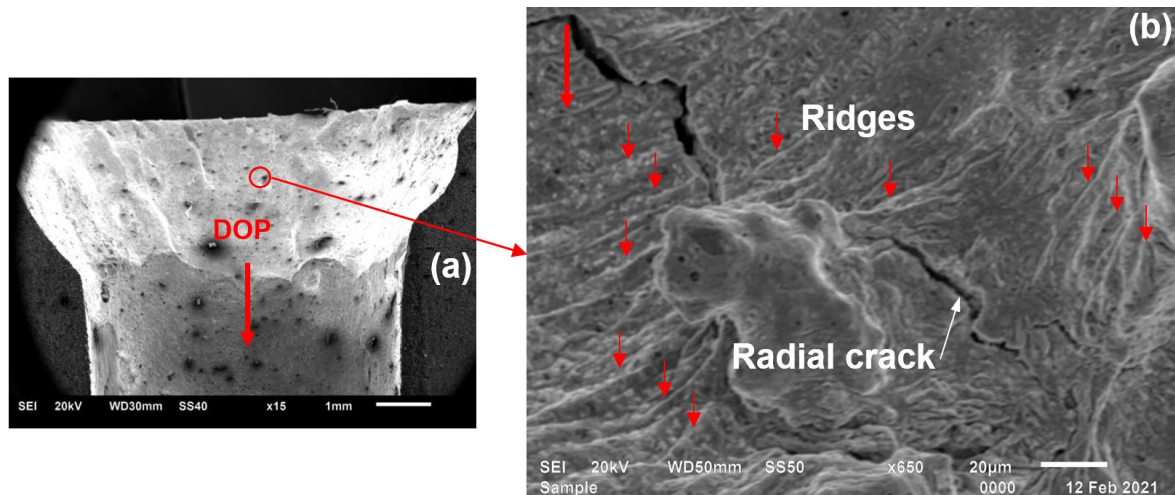


Figure 4.10: SEM SEI micrographs (a) at the entry point of the penetration hole through a 12 mm thick plate and (b) a higher magnification micrograph of the indicated area at the entry point of the projectile hole

Figure 4.10(b) shows a fracture surface with ridges and radial cracks at the entry point of the penetration hole and is consistent with the findings in [1, 3]. The ridges and radial crack features in this micrograph denote a brittle mode of failure at the entry point of the penetration hole [1, 3, 4]. Similar to the 10 mm thick plates, the 12 mm thick plates show a narrowing down of the projectile hole diameter from the entry point inwards [1, 3].

Figure 4.11(a) is a SEI micrograph of the surface at the middle point of the penetration hole through a 12 mm thick plate. Figure 4.11(b) is a higher magnification micrograph at the middle point of the projectile hole through the same plate.

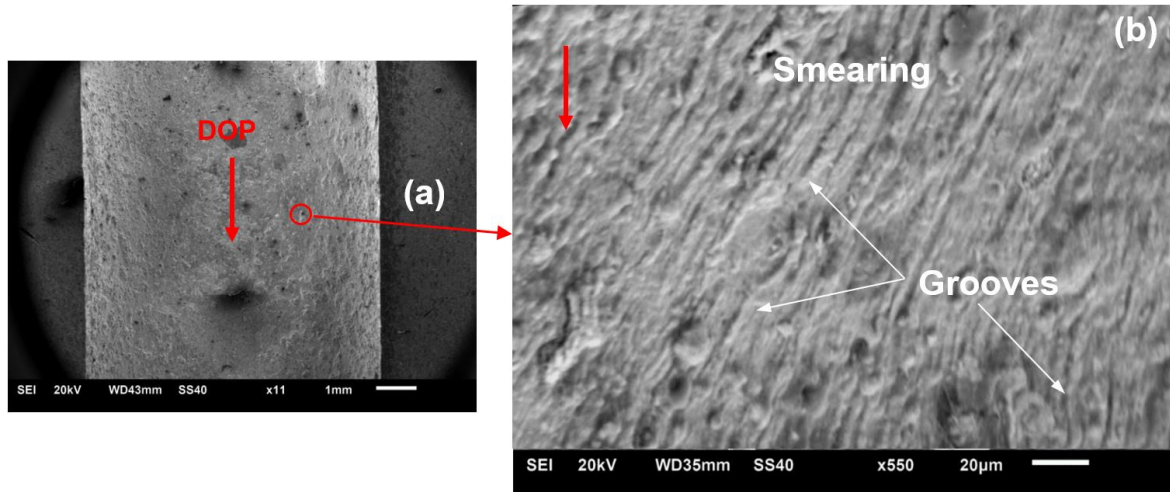


Figure 4.11: SEM SEI micrographs (a) at the middle point of the penetration hole through a 12 mm thick plate and (b) higher magnification micrograph of the indicated area at the middle point of the projectile hole

Similar to the middle points of the penetration holes through the 6 mm and 10 mm thick plates, the fracture surface in Figure 4.11(b) shows grooves and signs of smearing [9]. Due to the smearing, it is not possible to identify fracture features in this micrograph that would allow determination of the prevailing fracture mode [10, 11].

Figure 4.12(a) is a SEI micrograph of the surface at the exit point of the penetration hole through a 12 mm thick plate. Figure 4.12(b) is a higher magnification micrograph at the exit point of the projectile hole through the same plate.

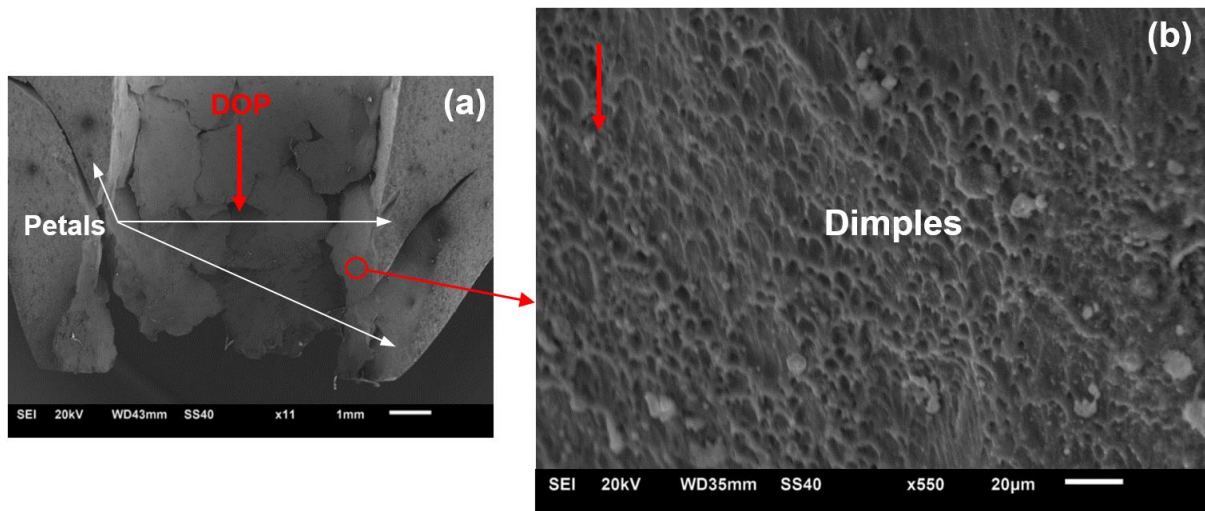


Figure 4.12: SEM SEI micrographs (a) at the exit point of the penetration hole through a 12 mm thick plate and (b) higher magnification micrograph of the indicated area at the exit point of the projectile hole

From Figure 4.12(b), it can be seen that dimples are the predominant fracture features. These dimples confirm a ductile fracture mode at the exit point of the penetration hole [7, 9, 12]. Figure 4.12(a) shows the presence of petalling.

4.5.4. Fractography of wrought Ti6Al4V 14 mm thick plates

Figure 4.13(a) is a SEI micrograph of the surface at the entry point of the penetration hole through a 14 mm thick plate. Figure 4.13(b) is a higher magnification micrograph at the entry point through the same plate.

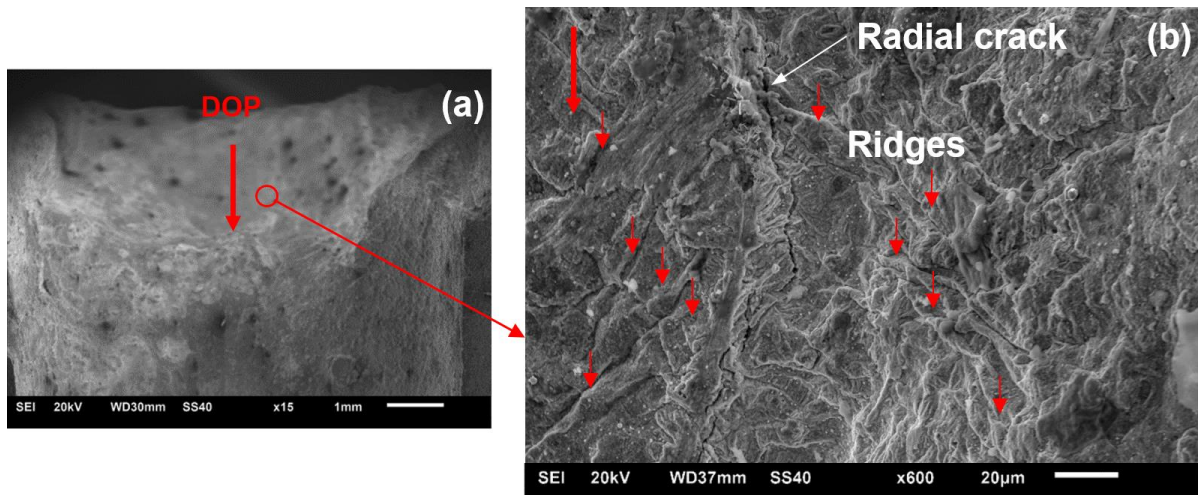


Figure 4.13: SEM SEI micrographs (a) at the entry point of the penetration hole through a 14 mm thick plate and (b) a higher magnification micrograph of the indicated at the entry point of the projectile hole

From Figure 4.13(b), it can be seen that there are ridges and radial cracks at the entry point of the penetration hole [1, 3]. Similar to the case for the 6 mm, 10 mm and 12 mm thick plates, the prevalence of these fracture features for the 14 mm thick plate here suggests a brittle mode of fracture.

Figure 4.14(a) is a SEI micrograph of the surface at the middle point of the penetration hole through a 14 mm thick plate. Figure 4.14(b) is a higher magnification micrograph at the middle point of the projectile hole through the same plate.

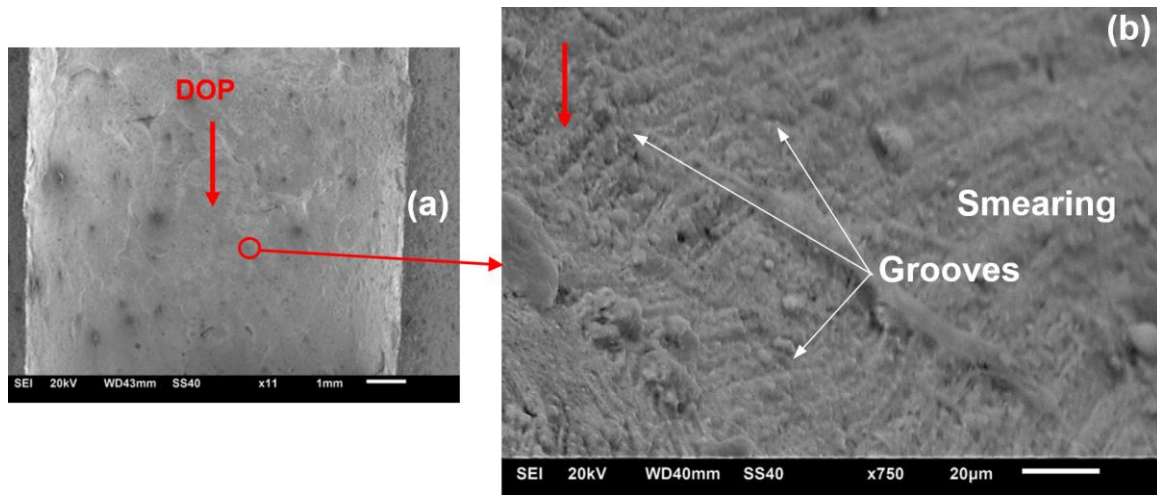


Figure 4.14: SEM SEI micrographs (a) at the middle point of the penetration hole through a 14 mm thick plate and (b) higher magnification micrograph of the indicated area at the middle point of the projectile hole

Similar to the 10 mm and 12 mm thick plates, the 14 mm thick plates showed fracture surfaces with grooves and signs of smearing at the at the middle point of the penetration holes [9]. Also in this case it is impossible to identify the mode of fracture due to a lack of clearly defined fracture features [10, 11].

Figure 4.15(a) is a SEI micrograph of the surface at the exit point of the penetration hole through a 14 mm thick plate. Figure 4.15(b) is a higher magnification micrograph at the exit point of the projectile hole through the same plate.

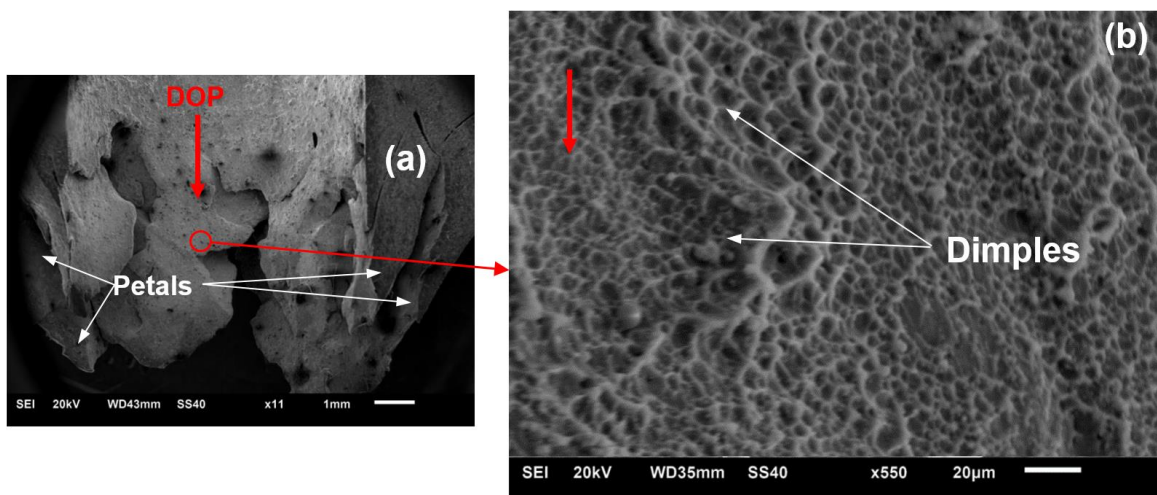


Figure 4.15: SEM micrographs (a) at the exit point of the penetration hole through a 14 mm thick plate and (b) higher magnification micrograph of the indicated area at the exit point of the projectile hole

The predominant surface feature on this micrograph is dimpling, which confirms ductile fracture [7, 9, 12]. Similar to the 10 mm and 12 mm thick plates, the 14 mm thick plates show signs of petalling at the exit of the projectile hole.

All the micrographs at the entry points of the penetration holes through all the plate thicknesses exhibit a predominance of cracks and ridges, which denotes brittle fracture [1, 3]. Furthermore, from the same micrographs, apart from Figure 4.13(b), it can be seen that the identified cracks are inclined to the horizontal direction (direction of penetration of the projectile). This inclination is perpendicular to that of the induced tensile waves that propagate circumferentially away from the projectile hole. This is consistent with shear failure of materials along the directions of maximum shear stress [1, 14].

The fracture surfaces lacked clearly defined fracture features at the middle points of the penetration holes for all the plate thicknesses. It was not possible in such cases to determine the prevailing mode of failure of the material. The fracture surfaces showed grooves, which can be attributed to smearing resulting from the friction effect of the projectiles as they penetrated the various plates [9]. That the grooves were inclined at an angle relative to the direction of penetration is likely to result from the rotational motion of the projectiles as they went through the respective plates [10, 11].

The predominant surface features were dimples at the exit points of the penetration holes through all the plate thicknesses. The predominance of dimples at the exit points of the penetration holes confirms ductile fracture [7, 9, 12].

Furthermore, the tensile shock waves reflected from the exit free edges of the plates at the exit points of the penetration holes led to orthogonal failure planes to the direction of penetration of the projectile, ahead of the projectile, which then opened up with through penetration of the projectile, leading to the formation of petals [13, 14]. The coalescence of microvoids caused the dimples here as a result of tensile failure due to the reflected tensile stress wave and shear failure due to the effect of the penetrating projectile [7].

The ductile failure at the exit point implies a lower strain rate than existed at the entry point, allowing the material to deform as it would typically do under lower strain rates [12].

4.6. Microstructural Analysis of High Velocity Ballistic Impacted Wrought Ti6Al4V

This section focuses on the microstructural analyses of wrought Ti6Al4V specimens a, b, c, d, e and f extracted from the 6 mm, 10 mm, 12 mm and 14 mm thick plates in Figure 3.11. The microstructural analysis here was conducted following the procedure discussed in Section 3.6.

The micrographs were obtained from the edge of the projectile hole and at distances of 2 mm, 4 mm and 6 mm from the edge, moving radially outwards, in order to investigate the change in microstructure with distance away from the penetration hole during impact. On each micrograph obtained, the thicknesses of the α laths were measured at ten different positions and the average value calculated in order to investigate the effect of distance away from the penetration hole on their thickness. These measurements were taken on areas where the α laths were best defined on the micrographs.

The adiabatic temperature rise in metals has been reported to exceed 1000 K at an impact velocity of 550 m/s [15, 16]. In the present work, testing was carried out with projectiles travelling at an average speed of 702 m/s before impact. It is, therefore, expected that a temperature gradient was set up at impact declining from the surface of the penetration hole radially outwards into the test plates and thus the expectation of a radial microstructural gradient.

4.6.1. Microstructural analysis of wrought Ti6Al4V plates near the edge of the projectile holes

Figures 4.16(a), (b) and (c), 4.17(a), (b) and (c), 4.18(a), (b) and (c) and 4.19(a), (b) and (c) are optical micrographs near the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively. In each figure is shown the delineations of ten α laths that were selected randomly on each micrograph, whose widths were measured and their statistics of centrality and scatter calculated.

Figure 4.16(d), (e) and (f) are enlarged areas of Figure 4.16(a), (b) and (c), respectively. The selected areas in these figures are presented to show that (i) a comparison of the thickness of α lathes cannot be done with the naked eye and (ii) there was no bias in selecting areas from which to determine the thicknesses of alpha lathes. The enlargements are presented to show the enlargements of the elected areas that were carried out on a microscope in order to enable measurement of the thicknesses of α lathes.

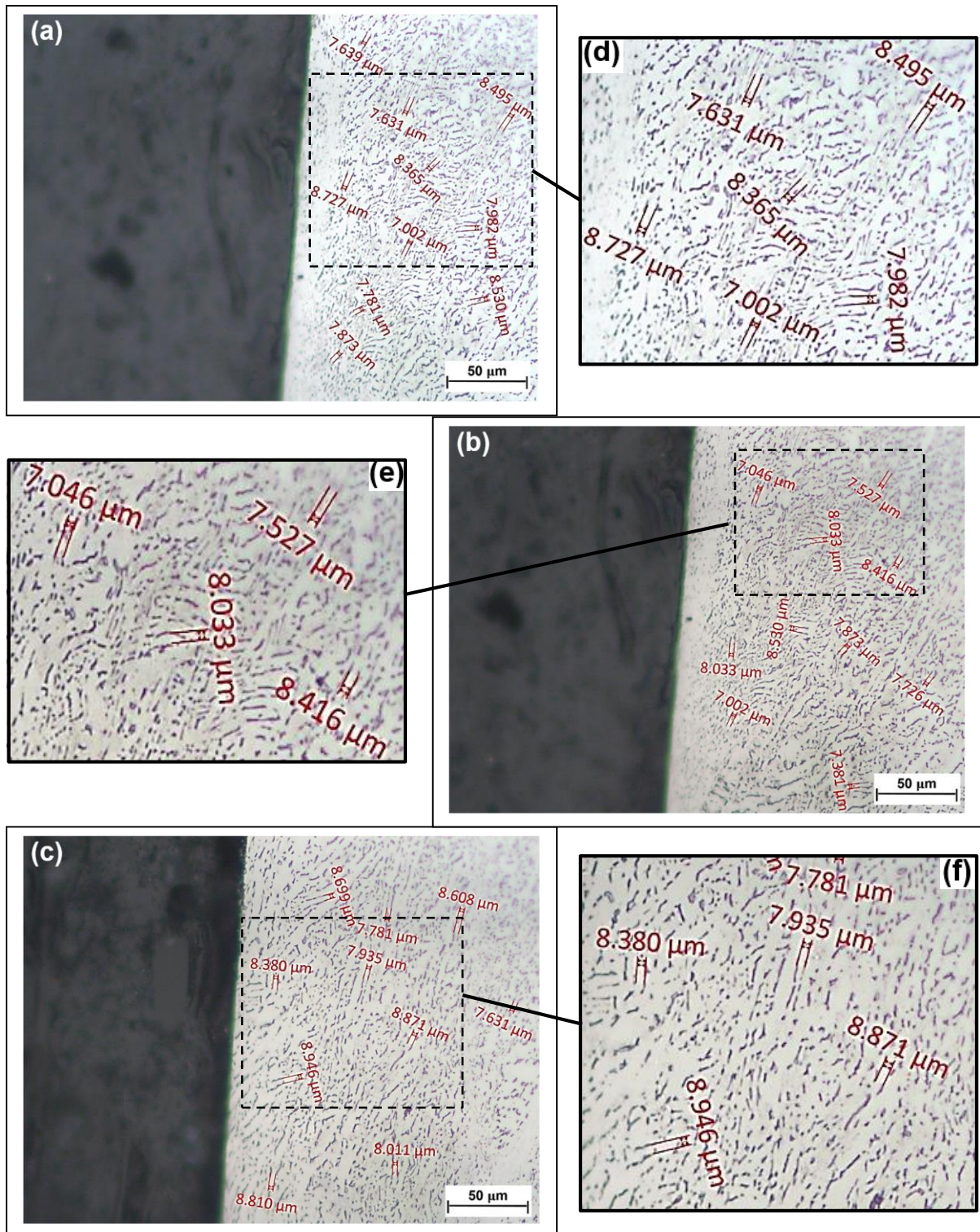


Figure 4.16: Optical micrographs near the edges of projectile holes through the 6 mm thick plates

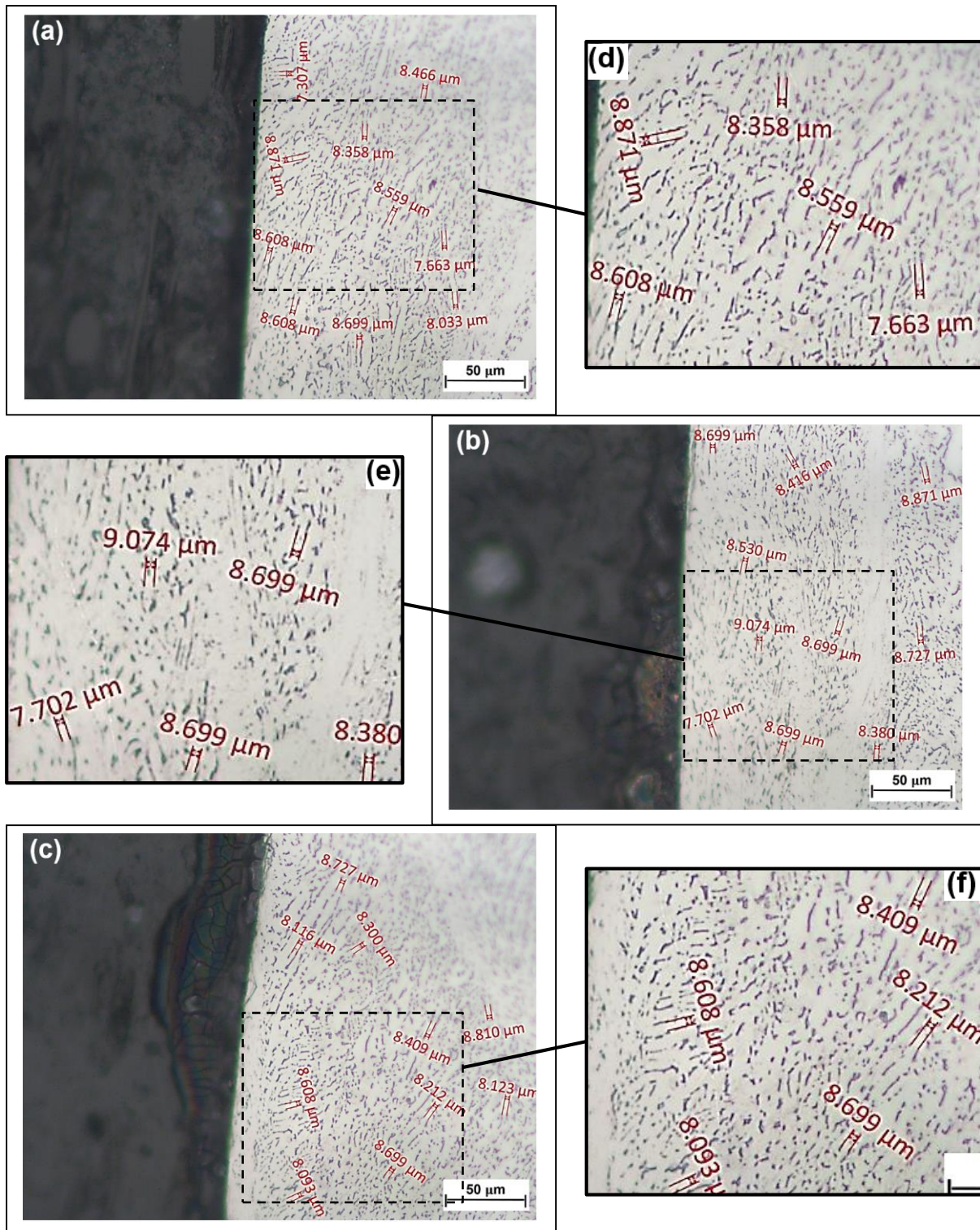


Figure 4.17: Optical micrographs near the edges of projectile holes through the 10 mm thick plates

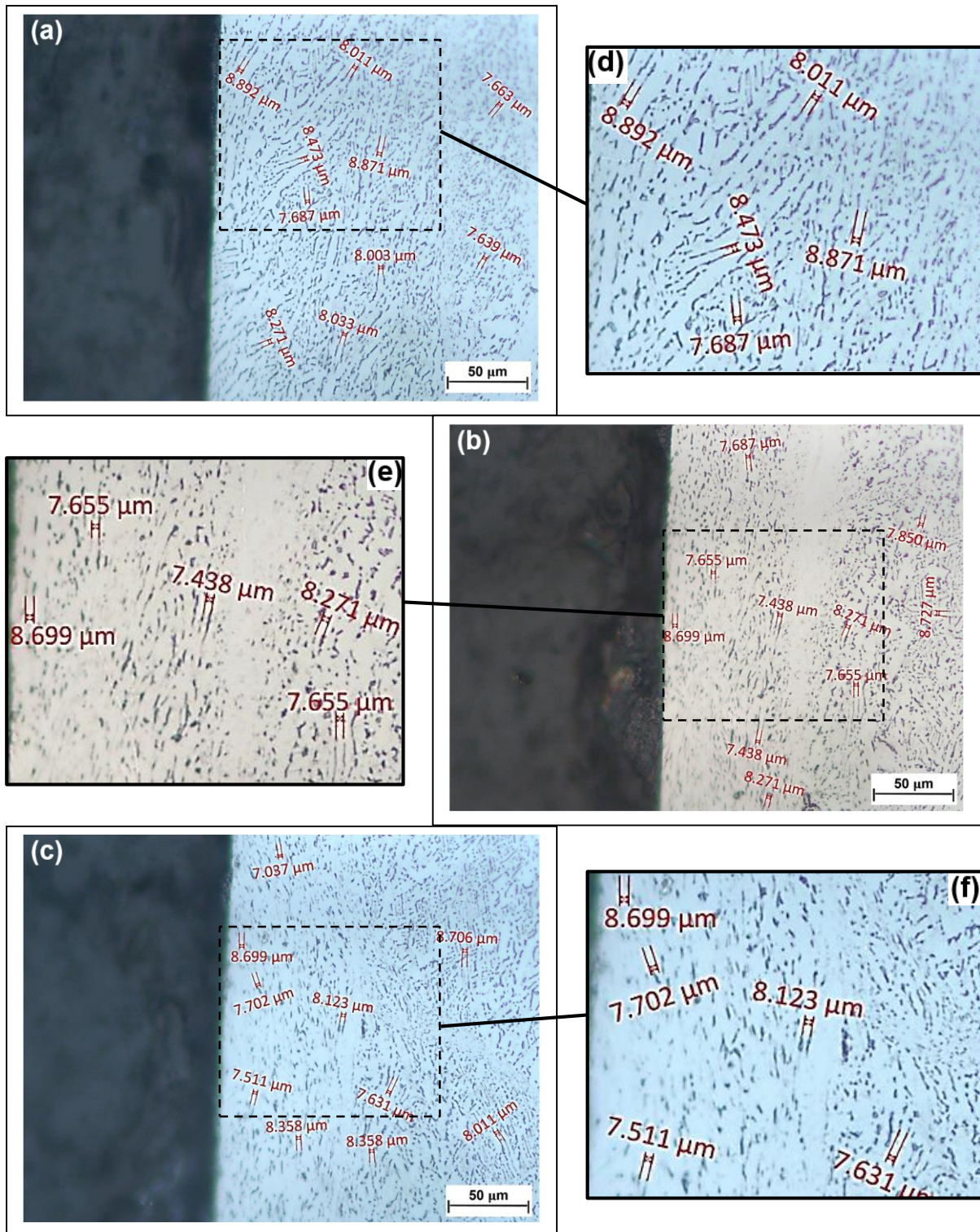


Figure 4.18: Optical micrographs near the edges of projectile holes through the 12 mm thick plates

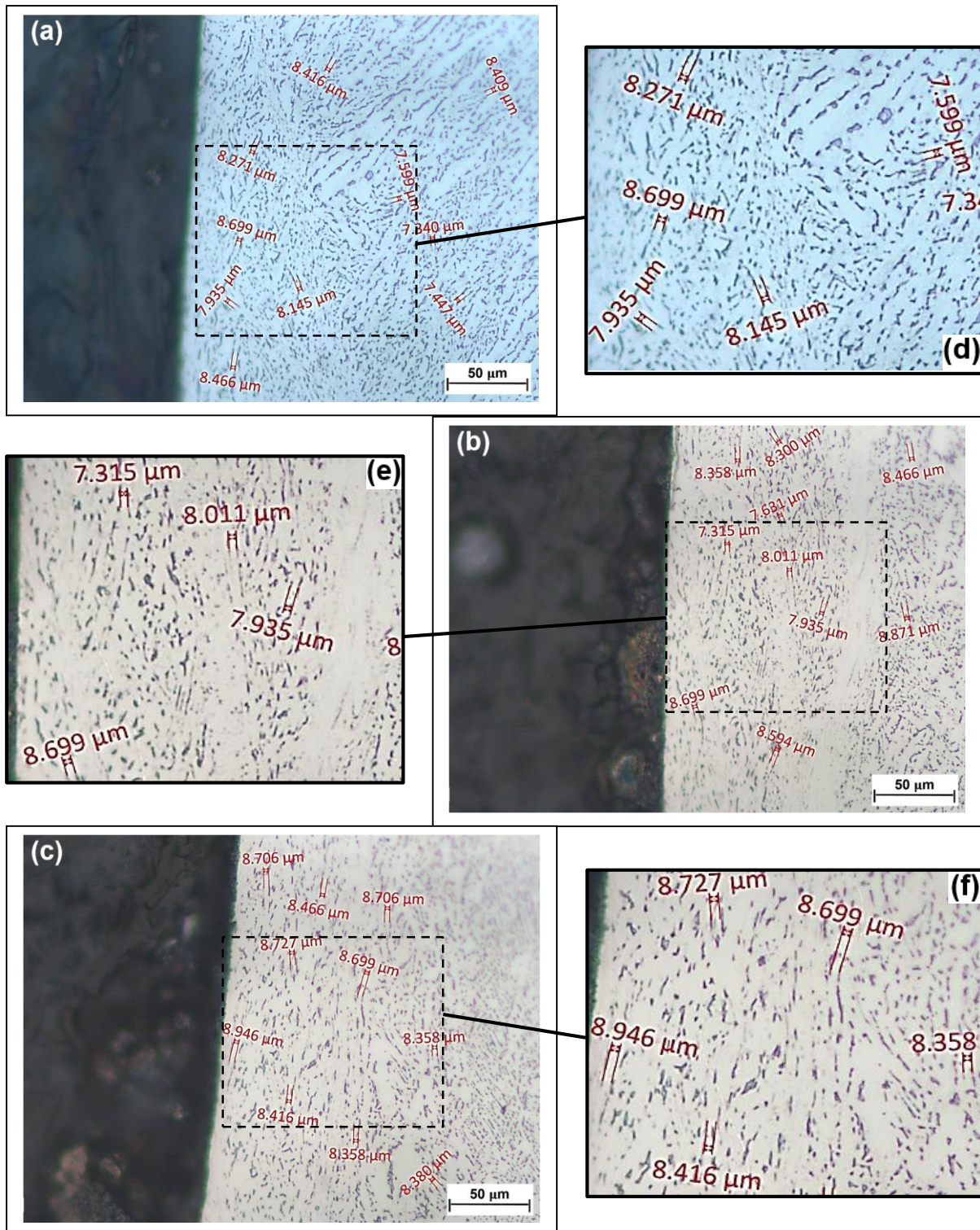


Figure 4.19: Optical micrographs near the edges of projectile holes through the 14 mm thick plates

Table 4.4 and Figure 4.20 show measurements of the thicknesses of the α laths near the edges of projectile holes in the micrographs shown in Figures 4.16, 4.17, 4.18 and 4.19 for each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

Table 4.4: Thickness of the α laths near the edge of the projectile hole

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.16(a)	8.00	0.53
	Figure 4.16(b)	7.76	0.52
	Figure 4.16(c)	8.37	0.49
10 mm	Figure 4.17(a)	8.34	0.50
	Figure 4.17(b)	8.58	0.37
	Figure 4.17(c)	8.36	0.26
12 mm	Figure 4.18(a)	8.15	0.47
	Figure 4.18(b)	7.97	0.49
	Figure 4.18(c)	8.00	0.59
14 mm	Figure 4.19(a)	8.07	0.47
	Figure 4.19(b)	8.19	0.53
	Figure 4.19(c)	8.61	0.17

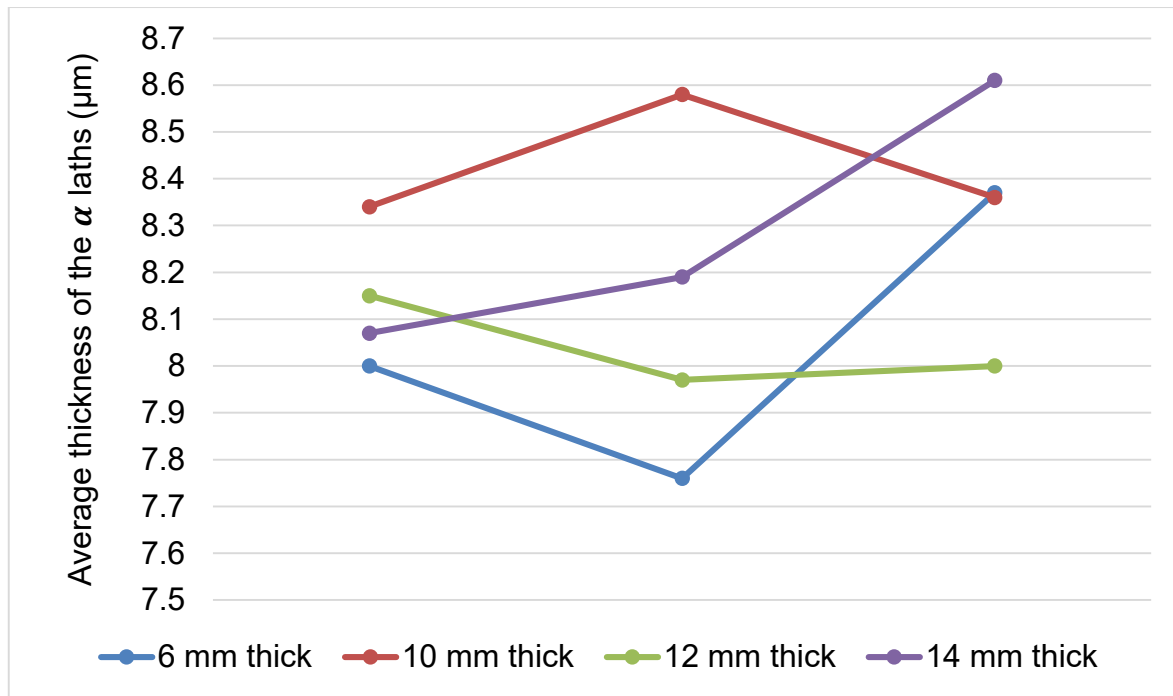


Figure 4.20: Average thickness of the α laths near the edge of the projectile holes for plates with different thicknesses

From Table 4.4 and Figure 4.20, it can be seen that the average thickness of the α laths near the edge of the projectile holes through the 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range 7.76 μm - 8.61 μm . Additionally, the standard deviation of the thickness of the α laths are seen in the table to fall within the range 0.17 - 0.59.

Based on the similarities of the microstructure of all the plate thicknesses near the edge of the projectile hole seen in Figure 4.16- Figure 4.19, the key features in them were studied in detail based on a closer examination of one of the three 10 mm thick plates, which was selected randomly.

Figure 4.21(a), (c) and (d) are optical micrographs at and near the edge of the projectile hole for the randomly selected plate of 10 mm thickness. Figure 4.21(b) is a scanning electron microscope (SEM) micrograph showing adiabatic shear bands (ASBs) near the edge of the projectile hole. It should be noted that micrographs (b), (c) and (d) are higher magnification micrographs of micrograph (a).

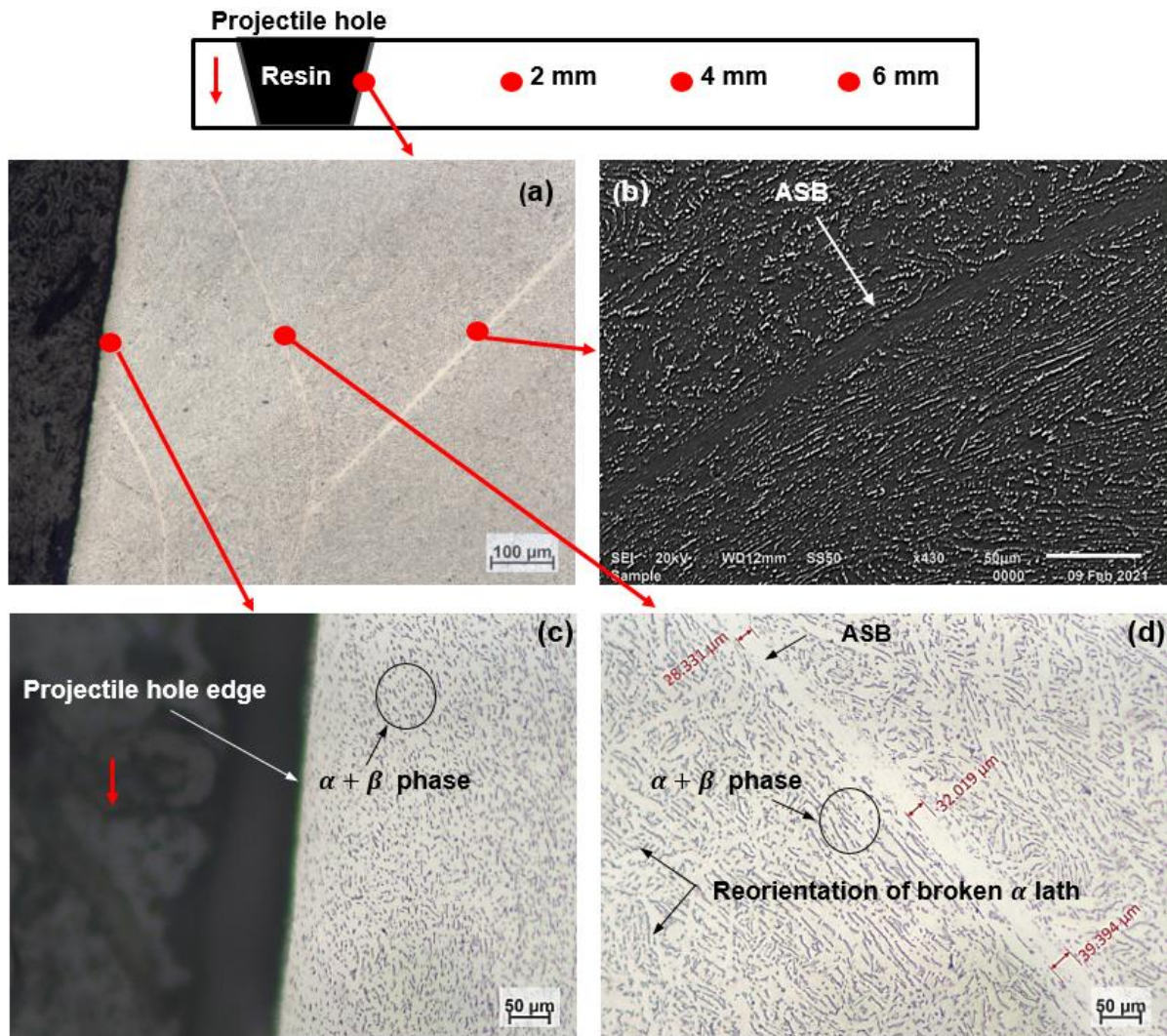


Figure 4.21: (a) Optical micrograph, (c) and (d) are higher magnification optical micrographs; (b) higher magnification SEM SEI micrograph of the indicated area on an ASB, all near the edge of the projectile hole through a 10 mm thick plate

It is seen from the diagram immediately above these micrographs that the projectile hole was filled with multifast resin ahead of scanning with an optical microscope. The red dots in this diagram show the locations at which observations were carried out on each specimen, with distances indicated relative to the edge of the projectile hole. The vertical arrow on the left end of this diagram shows the direction of penetration of the projectile.

In Figure 4.21(d) it can be seen that there are areas where there is a reorientation of the broken α laths [17, 18]. Moreover, adiabatic shear bands (ASBs) are evident in the same figure and Figure 4.21(b) [19, 20]. The thickness of the ASBs in this area fall within the range 28.3 μm - 39.39 μm as can be seen in Figure 4.21(d).

4.6.2. Microstructural analysis of wrought Ti6Al4V plates at a distance of 2 mm from the edge of projectile holes

Figures 4.22 (a), (b) and (c), 4.23(a), (b) and (c), 4.24(a), (b) and (c) and 4.25(a), (b) and (c) are optical micrographs at a distance of 2 mm from the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

Here as well, the delineations of ten α laths that were selected randomly on each micrograph are shown clearly, their widths measured and statistics of centrality and scatter of the widths calculated.

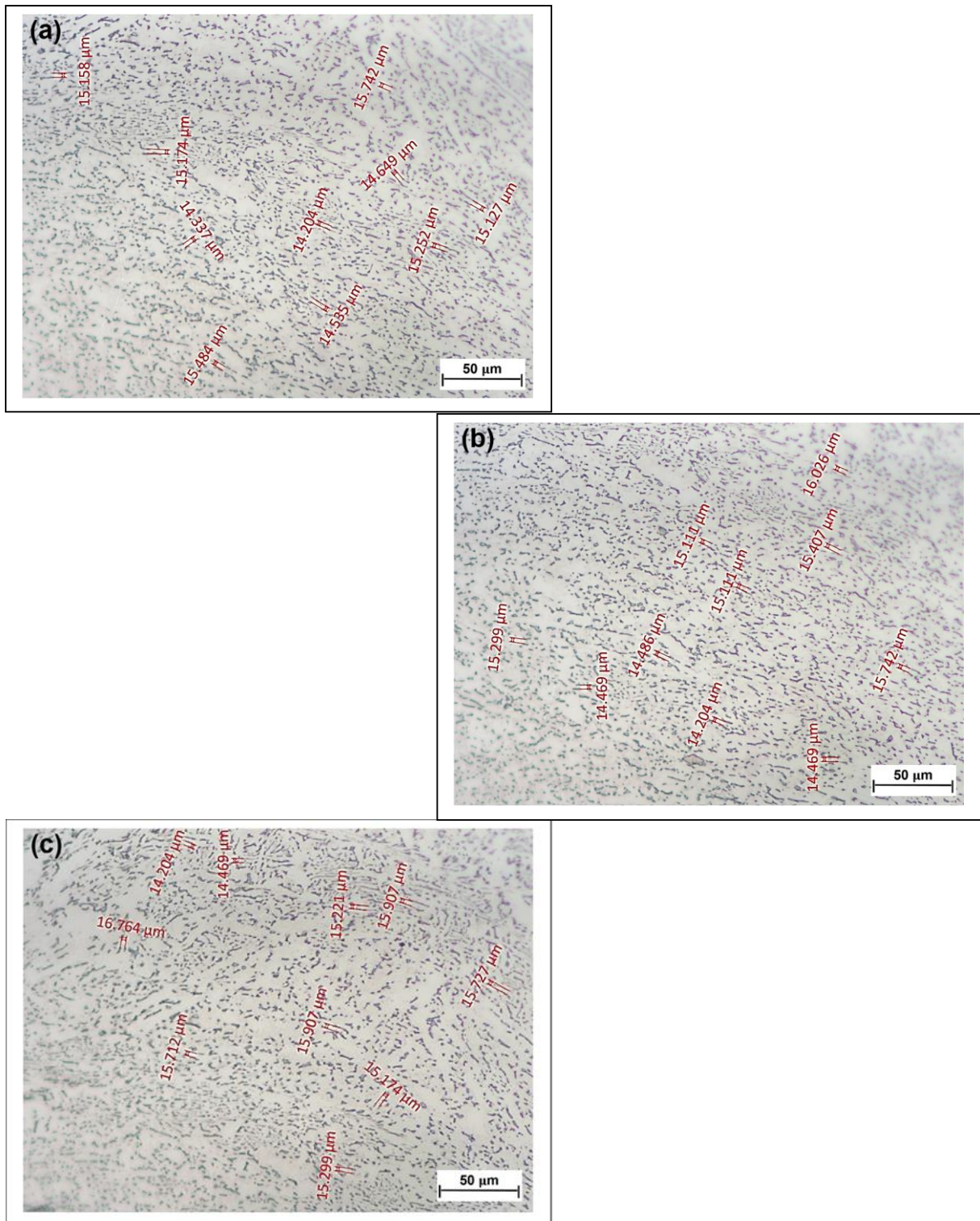


Figure 4.22: Optical micrographs at a distance of 2 mm from the edges of projectile holes through the 6 mm thick plates

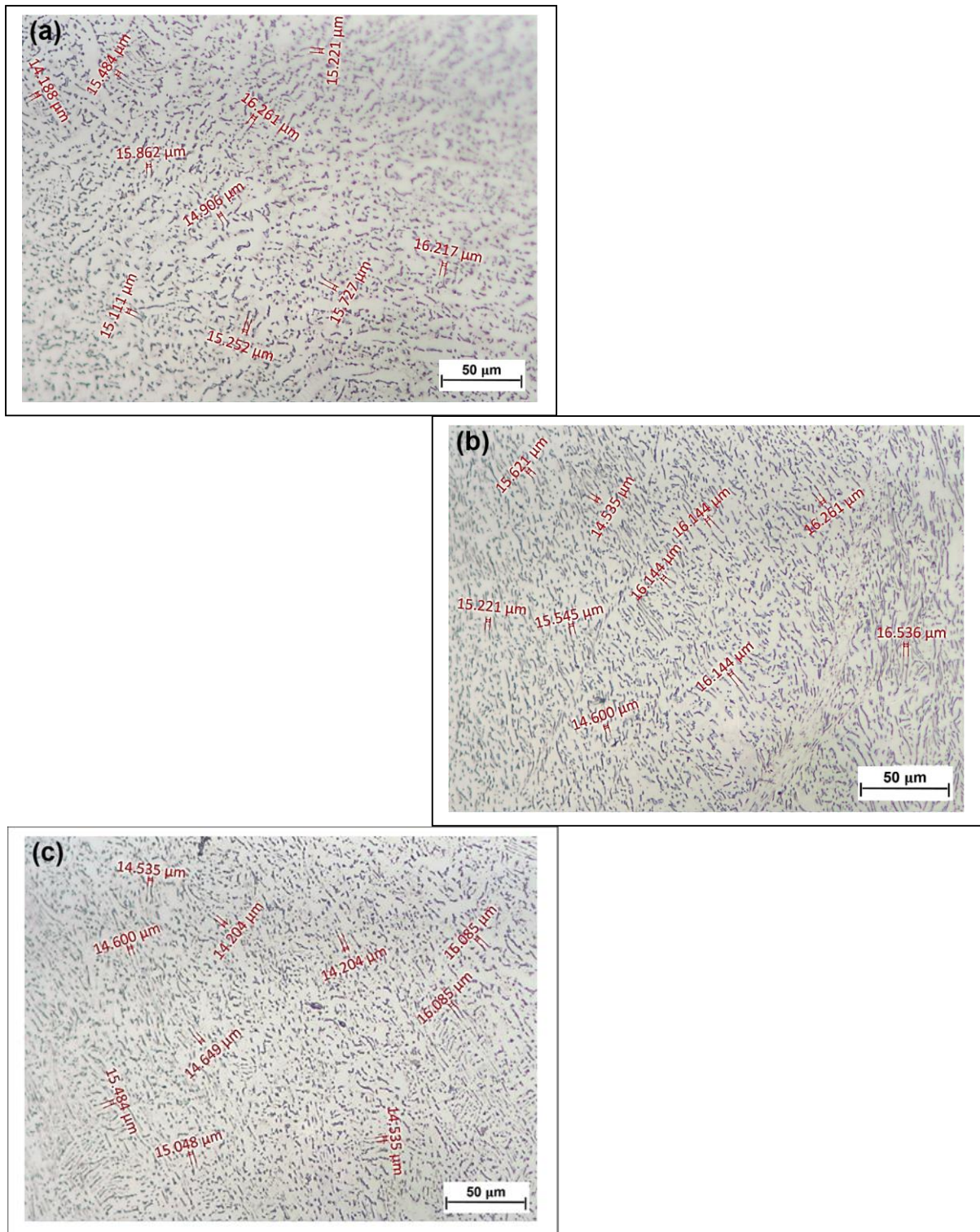


Figure 4.23: Optical micrographs at a distance of 2 mm from the edges of projectile holes through the 10 mm thick plates

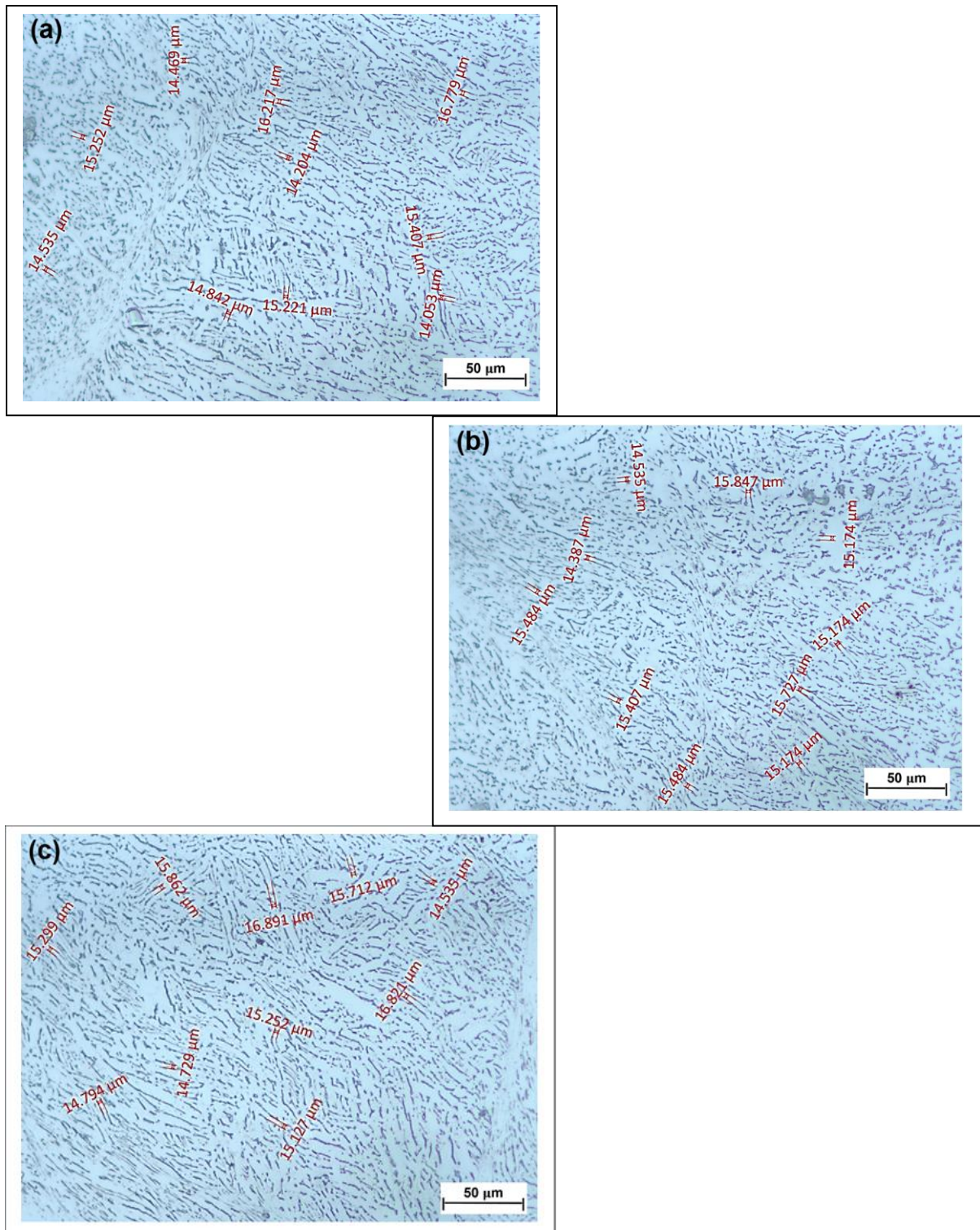


Figure 4.24: Optical micrographs at a distance of 2 mm from the edges of projectile holes through the 12 mm thick plates

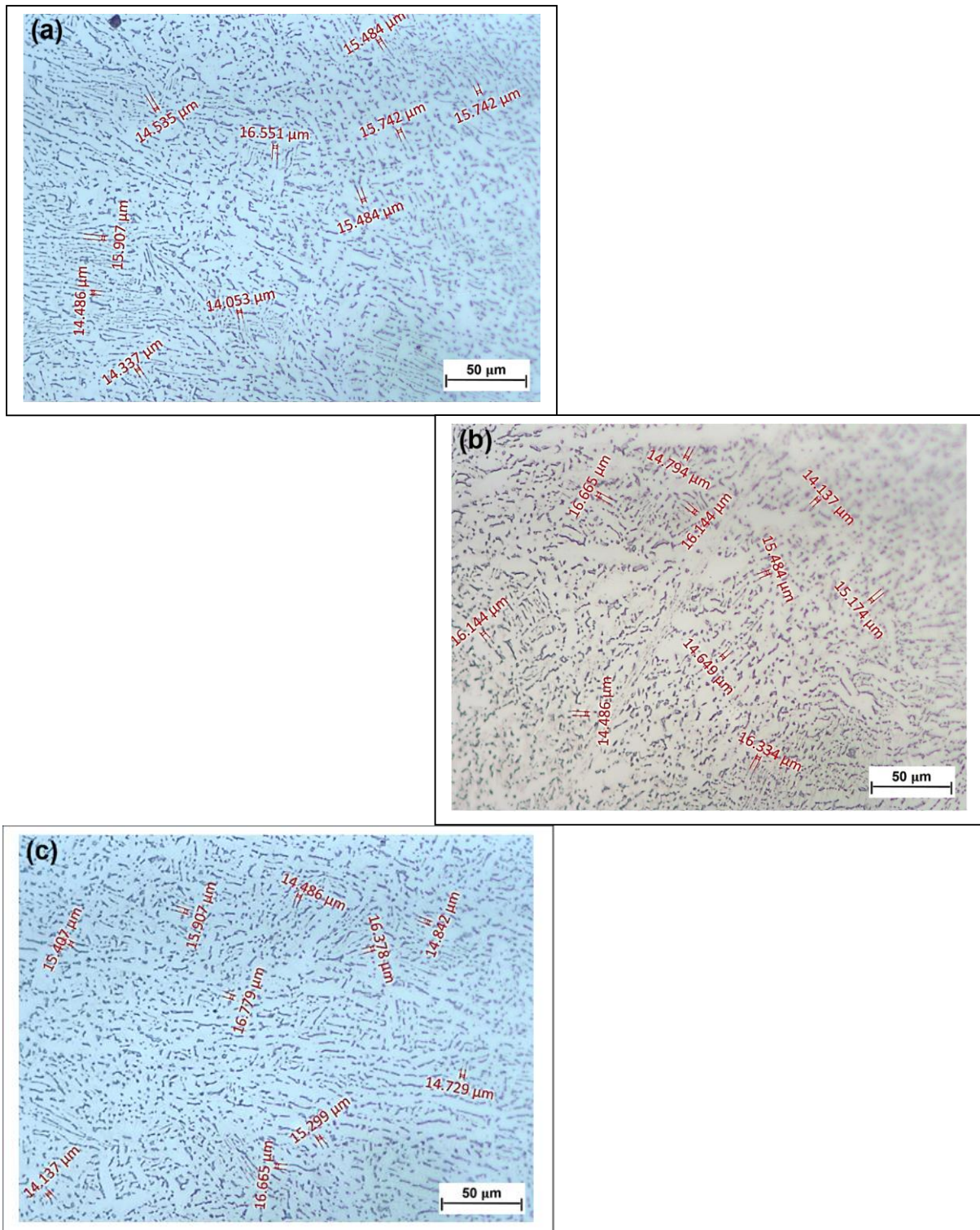


Figure 4.25: Optical micrographs at a distance of 2 mm from the edges of projectile holes through the 14 mm thick plates

Table 4.5 and Figure 4.20 show measurements of the thicknesses of α laths at a distance of 2 mm from the edges of projectile holes for each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates.

Table 4.5: Thickness of α laths at a distance of 2 mm from the edge of the projectile holes

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.22(a)	14.96	0.50
	Figure 4.22(b)	15.03	0.61
	Figure 4.22(c)	15.44	0.74
10 mm	Figure 4.23(a)	15.42	0.63
	Figure 4.23(b)	15.68	0.70
	Figure 4.23(c)	14.94	0.71
12 mm	Figure 4.24(a)	15.10	0.88
	Figure 4.24(b)	15.14	0.52
	Figure 4.24(c)	15.50	0.82
14 mm	Figure 4.25(a)	15.23	0.82
	Figure 4.25(b)	15.40	0.88
	Figure 4.25(c)	15.46	0.94

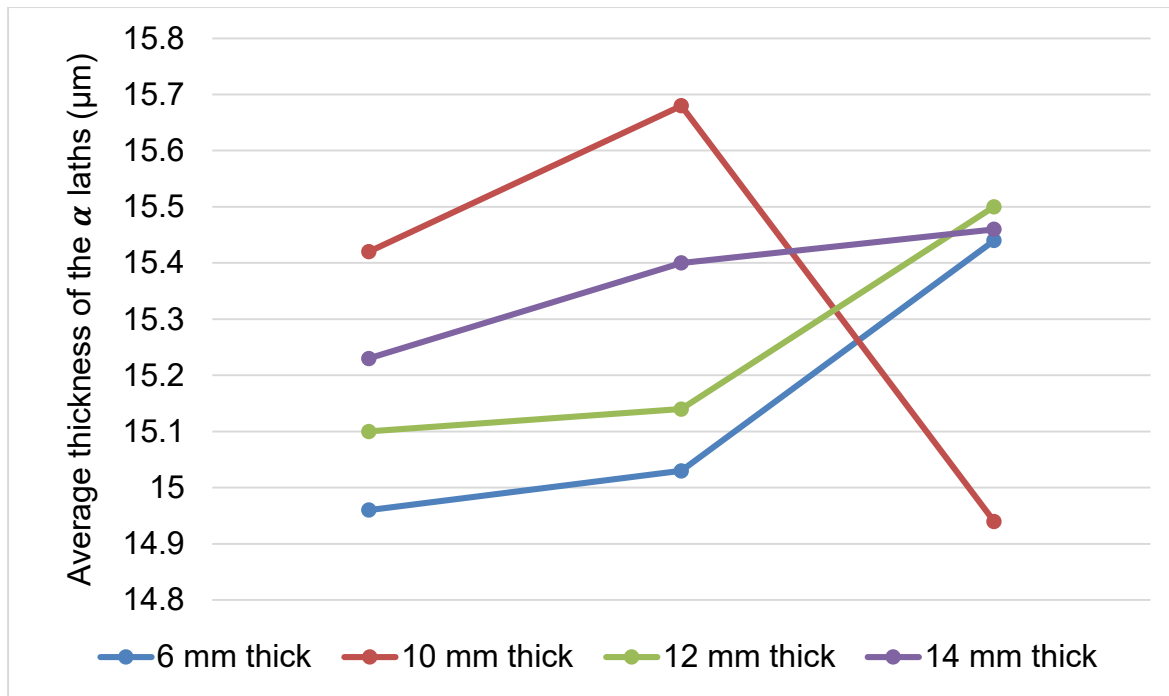


Figure 4.26: Average thickness of the α laths at a distance of 2 mm from the edge of the projectile holes for plates with different thicknesses

From Table 4.5 and Figure 4.26, it can be seen that the average thickness of the α laths at a distance of 2 mm from edge of the projectile holes through the 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range 14.96 μm - 15.68 μm . Additionally, the standard deviation of the thicknesses of the α laths falls within the range 0.50 - 0.94.

Based on the similarities of the microstructure of all the plate thicknesses at a distance of 2 mm from the edges of the projectile holes seen in Figure 4.22 up to Figure 4.25, the key features at this distance were, therefore, examined on a plate of 10 mm thickness, selected randomly.

Figure 4.27(a) is an optical micrograph and Figure 4.27(b) is a SEM micrograph, both at a distance of 2 mm from the edge of the projectile hole through a 10 mm thick plate.

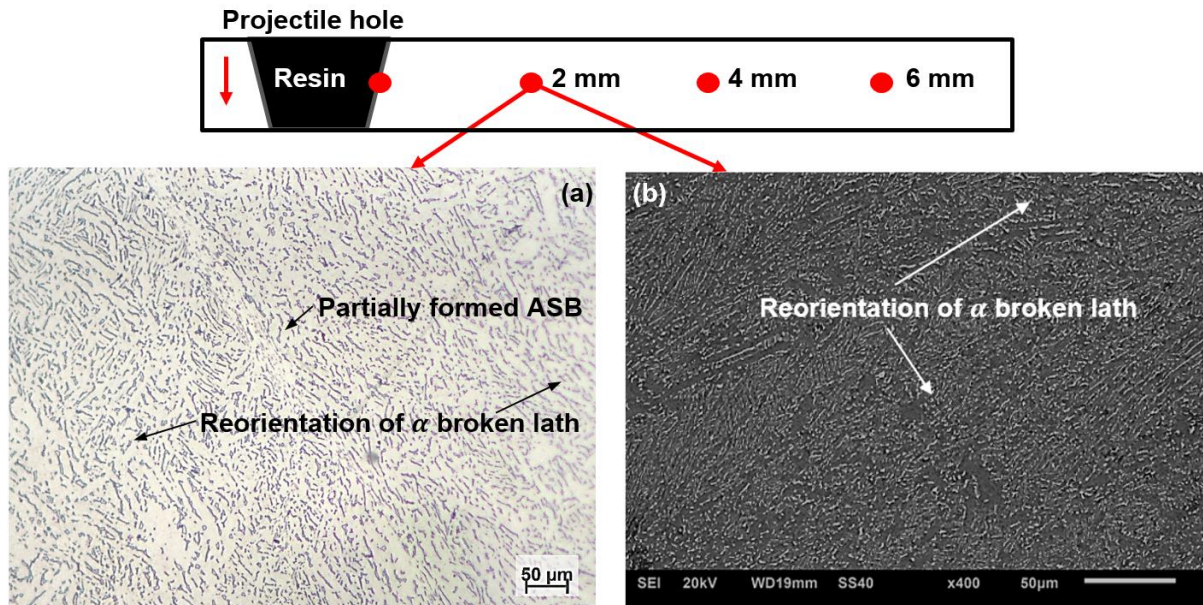


Figure 4.27: (a) Optical micrograph and (b) SEM SEI micrograph, both at a distance of 2 mm from the edge of the projectile hole through a 10 mm thick plate

Figure 4.27(a) shows that at a distance of 2 mm from the edge projectile of the projectile hole, the ASBs are not fully formed [21]. Furthermore, in both figures it is seen that there is an area where there is a reorientation of the broken α laths.

4.6.3. Microstructural analysis of the wrought Ti6Al4V plates at a distance of 4 mm from the edge of the projectile holes

Figures 4.28(a), (b) and (c), 4.29(a), (b) and (c), 4.30(a), (b) and (c) and 4.31(a), (b) and (c) are optical micrographs at a distance of 4 mm from the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

As in the previous two cases, the delineations of ten α laths that were selected randomly on each micrograph are shown, their widths measured and their statistics of centrality and scatter calculated.

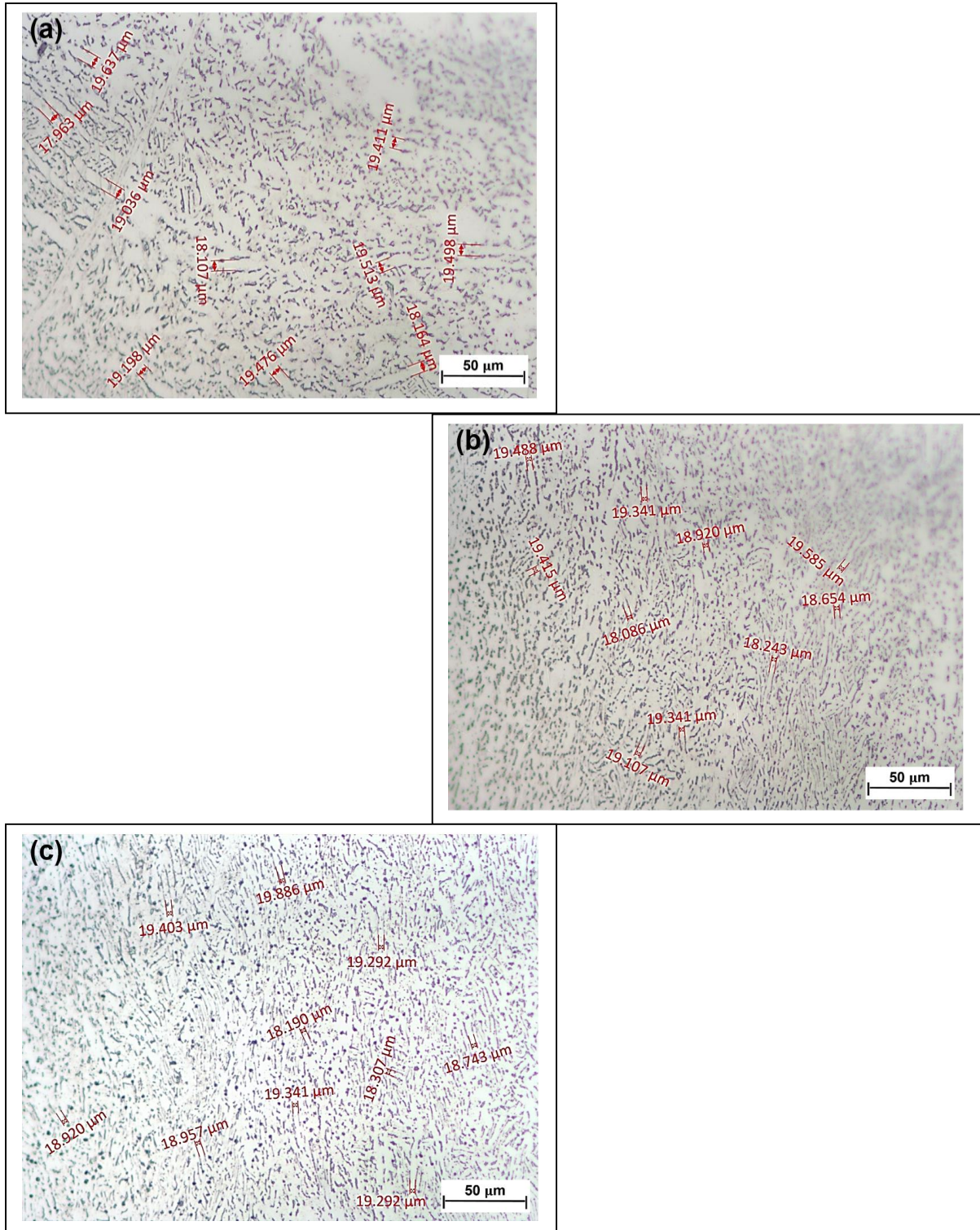


Figure 4.28: Optical micrographs at a distance of 4 mm from the edges of projectile holes through the 6 mm thick plates

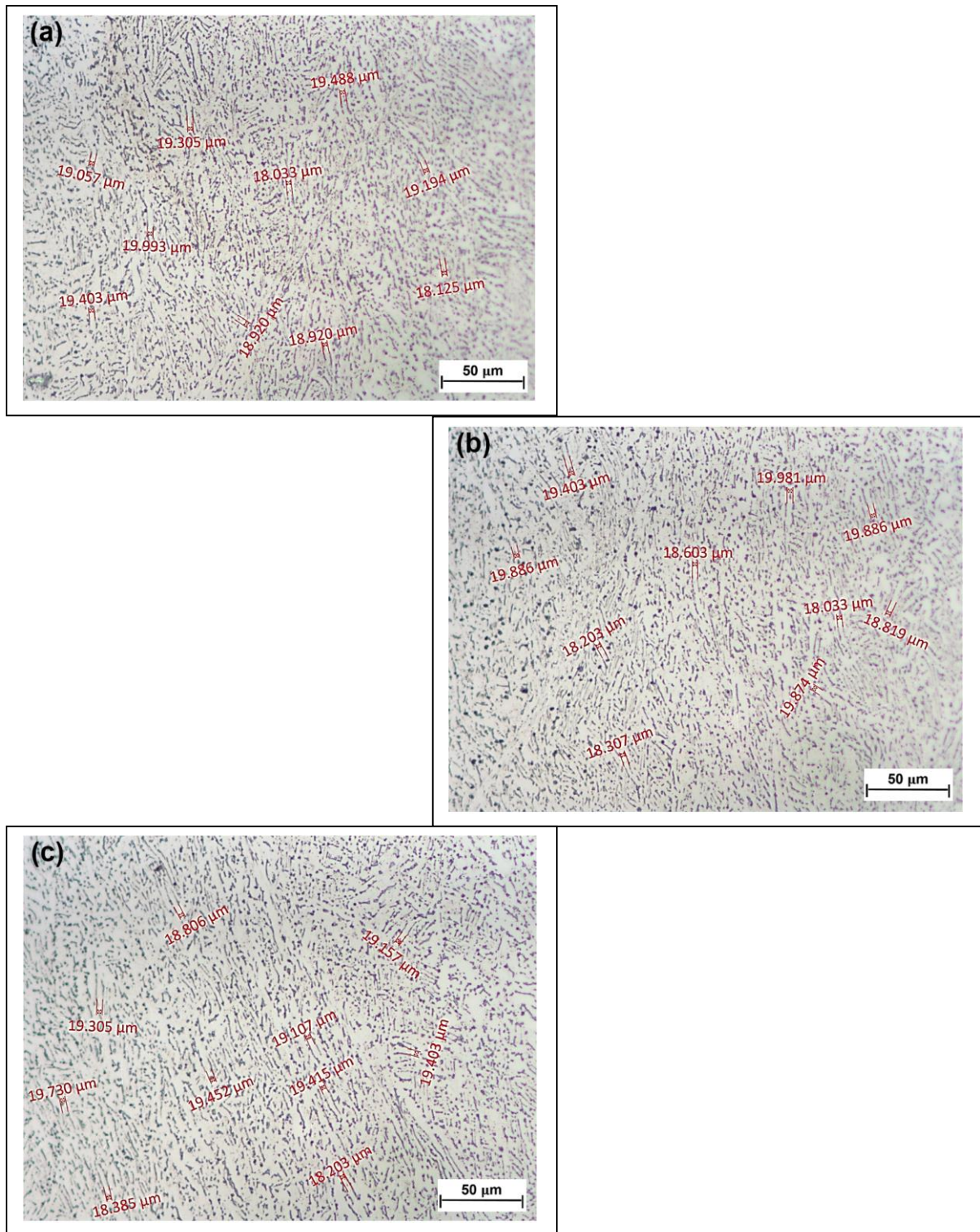


Figure 4.29: Optical micrographs at a distance of 4 mm from the edges of projectile holes through the 10 mm thick plates

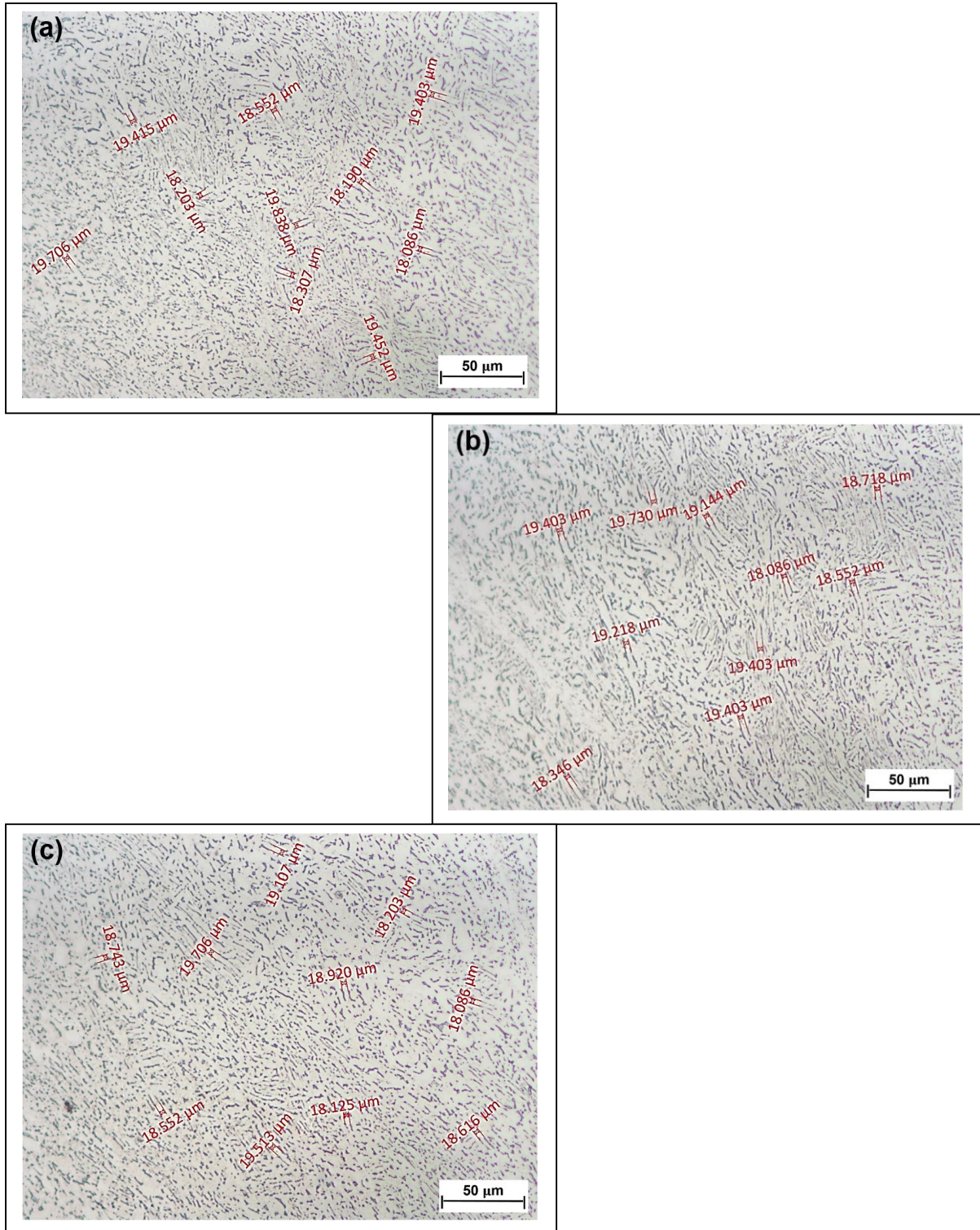


Figure 4.30: Optical micrographs at a distance of 4 mm from the edges of projectile holes through the 12 mm thick plates

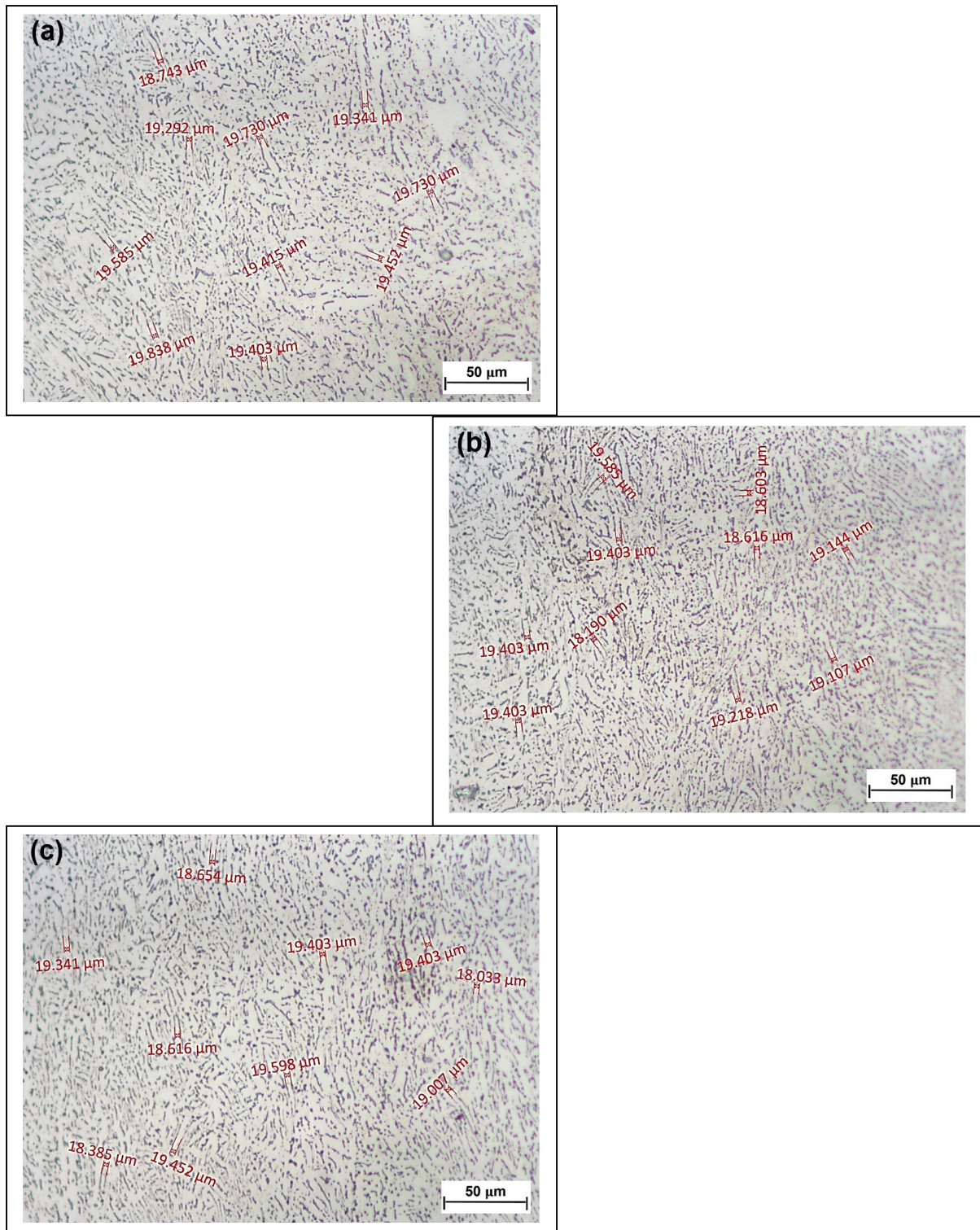


Figure 4.31: Optical micrographs at a distance of 4 mm from the edges of projectile holes through the 14 mm thick plates

Table 4.6 and Figure 4.32 show the measurements of the thickness of the α laths at a distance of 4 mm from the edges of projectile holes on each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates.

Table 4.6: Thickness of α laths at a distance of 4 mm from the edge of the projectile holes

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.28(a)	19.00	0.66
	Figure 4.28(b)	19.10	0.44
	Figure 4.28(c)	18.98	0.58
10 mm	Figure 4.29(a)	19.04	0.60
	Figure 4.29(b)	19.10	0.79
	Figure 4.29(c)	19.20	0.43
12 mm	Figure 4.30(a)	18.92	0.71
	Figure 4.30(b)	19.00	0.54
	Figure 4.30(c)	18.76	0.56
14 mm	Figure 4.31(a)	19.45	0.31
	Figure 4.31(b)	19.07	0.45
	Figure 4.31(c)	18.99	0.54

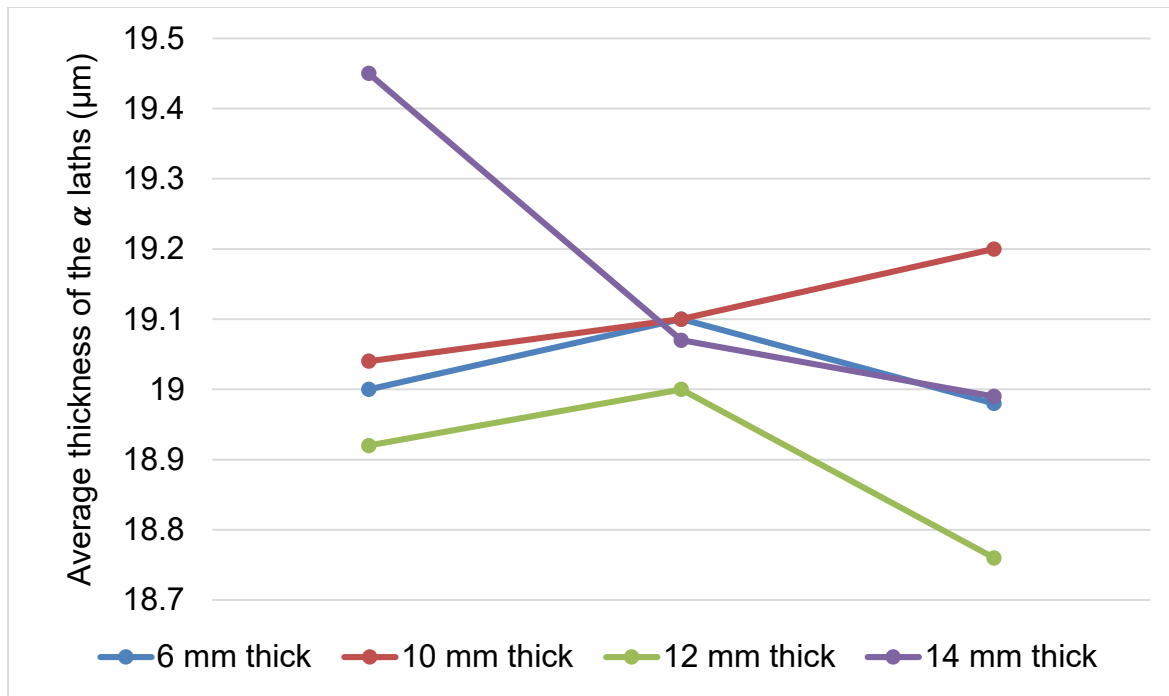


Figure 4.32: Average thickness of the α laths at a distance of 4 mm from the edge of the projectile holes for plates with different thicknesses

From Table 4.6 and Figure 4.32, it can be seen that the average thickness of the α laths at a distance of 4 mm from edge of projectile holes through the 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range 18.76 μm - 19.20 μm . Additionally, the standard deviation of the thicknesses of the α laths falls within the range 0.31 - 0.79.

Based on the similarities of the microstructure of all the plate thicknesses at a distance of 4 mm from the edges of the projectile holes seen in Figure 4.28 up to Figure 4.31, the key features at this distance were, therefore, examined on a plate of 10 mm thickness selected randomly.

Figure 4.33(a) is an optical micrograph and Figure 4.33(b) a SEM micrograph, both at a distance of 4 mm from the edge of the projectile hole through a 10 mm thick plate.

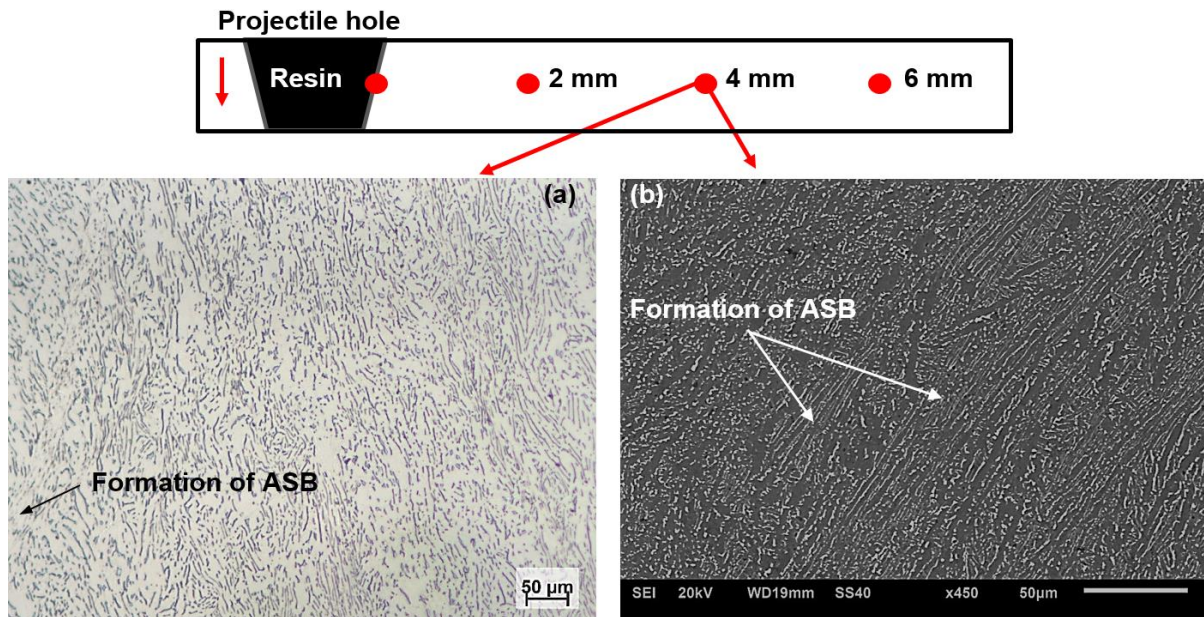


Figure 4.33: (a) Optical micrograph and (b) SEM SEI micrograph, both at a distance of 4 mm from the edge of the projectile hole through a 10 mm thick plate

In Figure 4.33(a) and (b) it is seen that at a distance of 4 mm from the edge of the projectile hole, the α phase fraction (lighter areas) is less than the β phase fraction (dark lines). This is a sharp contrast to the case of the micrograph shown in Figure 4.21(b) at the edge of a projectile hole, in which the α phase fraction is seen to be higher than the β phase fraction. The possible causes for this are discussed in more detail at the end of section 4.6.4.

4.6.4. Microstructural analysis of wrought Ti6Al4V plates at a distance of 6 mm from the edge of projectile holes

Figures 4.34(a), (b) and (c), 4.35(a), (b) and (c), 4.36(a), (b) and (c) and 4.37(a), (b) and (c) are optical micrographs at a distance of 6 mm from the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

Here also, the delineations of ten α laths that were selected randomly on each micrograph are shown, their widths measured and their statistics of centrality and scatter calculated.

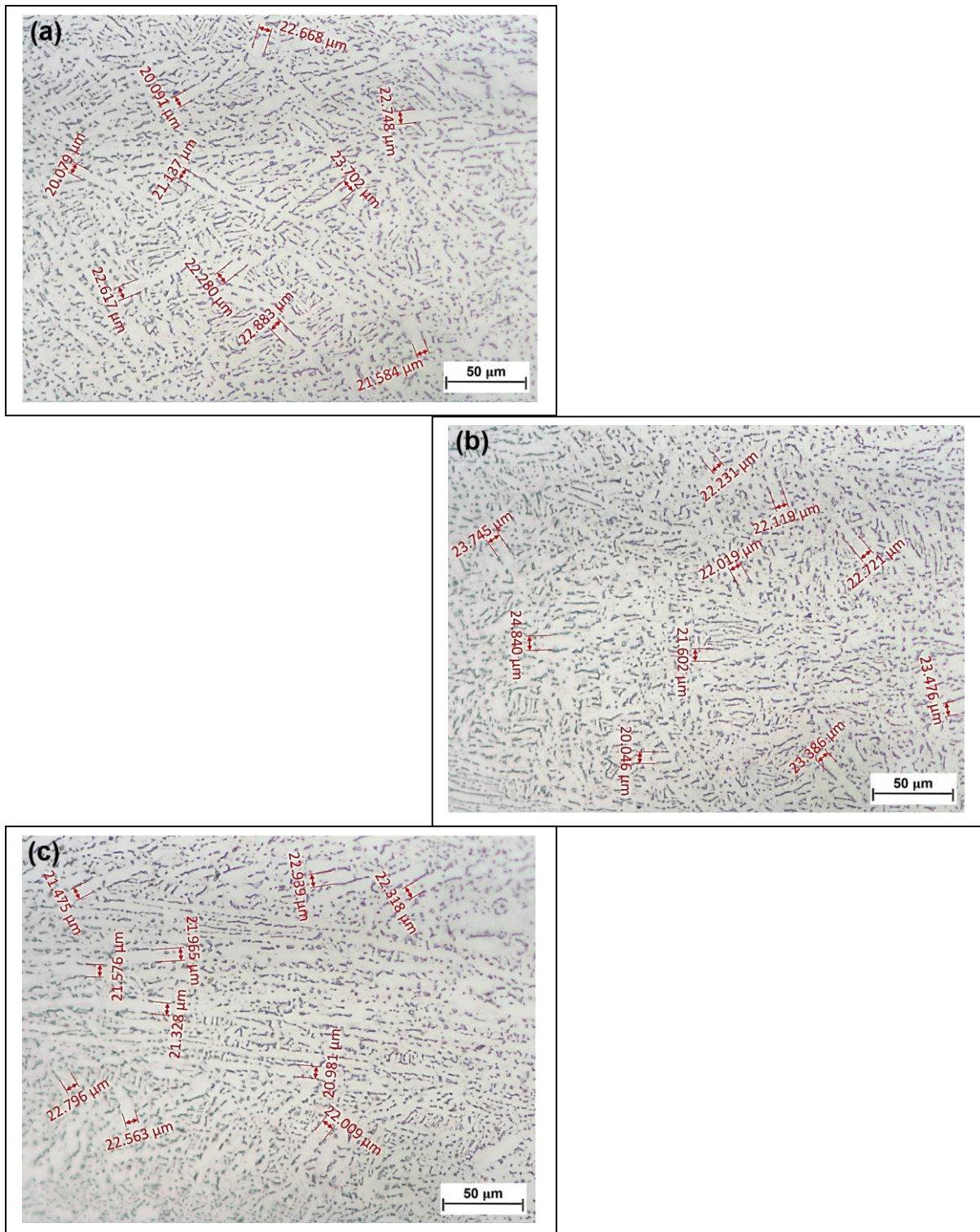


Figure 4.34: Optical micrographs at a distance of 6 mm from the edges of projectile holes through the 6 mm thick plates

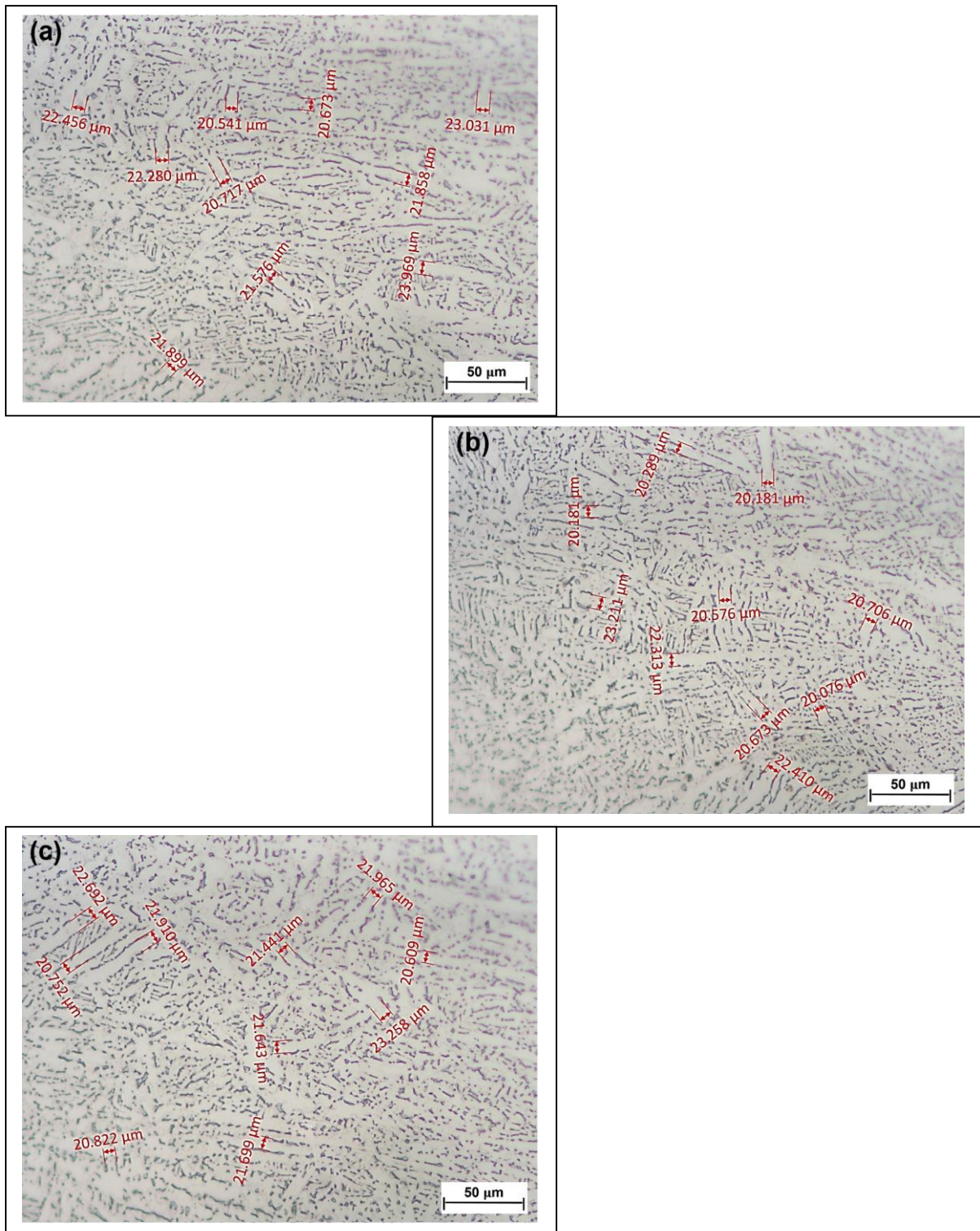


Figure 4.35: Optical micrographs at a distance of 6 mm from the edges of projectile holes through the 10 mm thick plates

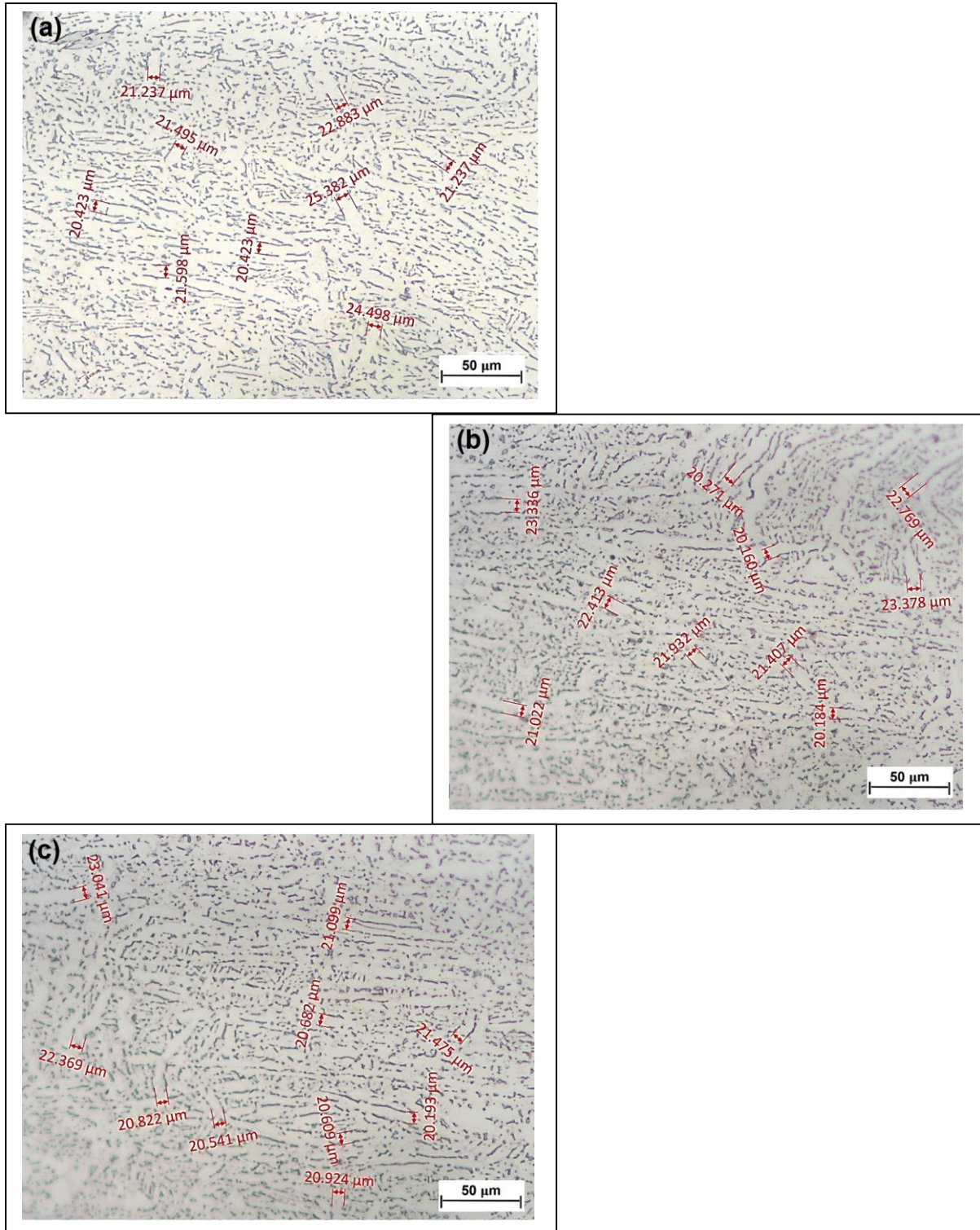


Figure 4.36: Optical micrographs at a distance of 6 mm from the edges of projectile holes through the 12 mm thick plates

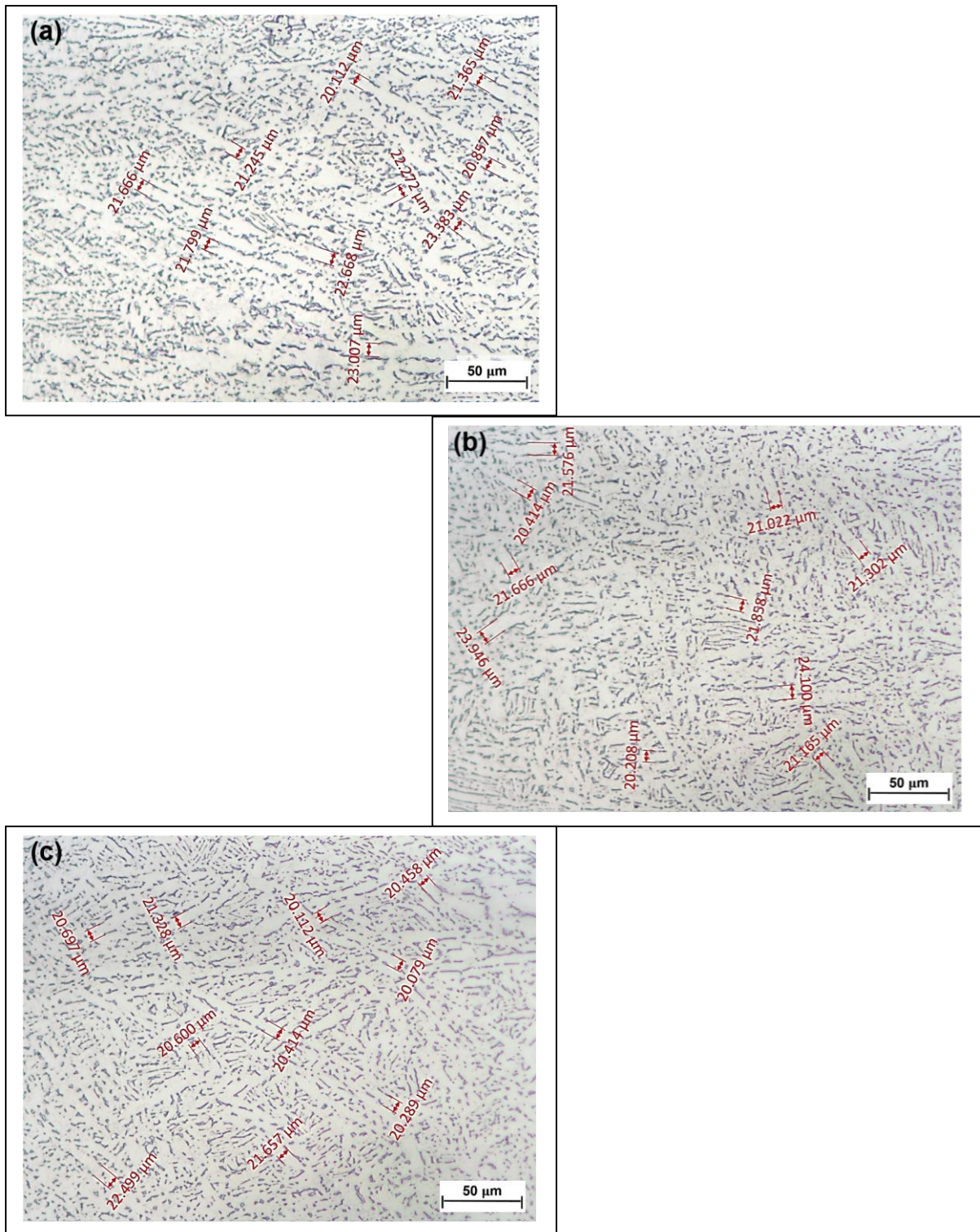


Figure 4.37: Optical micrographs at a distance of 6 mm from the edges of projectile holes through the 14 mm thick plates

Table 4.7 and Figure 4.38 show measurements of the thicknesses of the α laths at a distance of 6 mm from the edges of projectile holes through each one of the three the 6 mm, 10 mm, 12 mm and 14 mm thick plates.

Table 4.7: Thickness of α laths at a distance of 6 mm from the edge of the projectile holes

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.34(a)	21.98	1.22
	Figure 4.34(b)	22.51	1.41
	Figure 4.34(c)	22.00	0.66
10 mm	Figure 4.35(a)	21.94	1.11
	Figure 4.35(b)	20.87	1.06
	Figure 4.35(c)	21.68	0.85
12 mm	Figure 4.36(a)	22.04	1.69
	Figure 4.36(b)	21.69	1.27
	Figure 4.36(c)	21.22	0.84
14 mm	Figure 4.37(a)	21.84	1.01
	Figure 4.37(b)	21.73	1.32
	Figure 4.37(c)	20.81	0.78

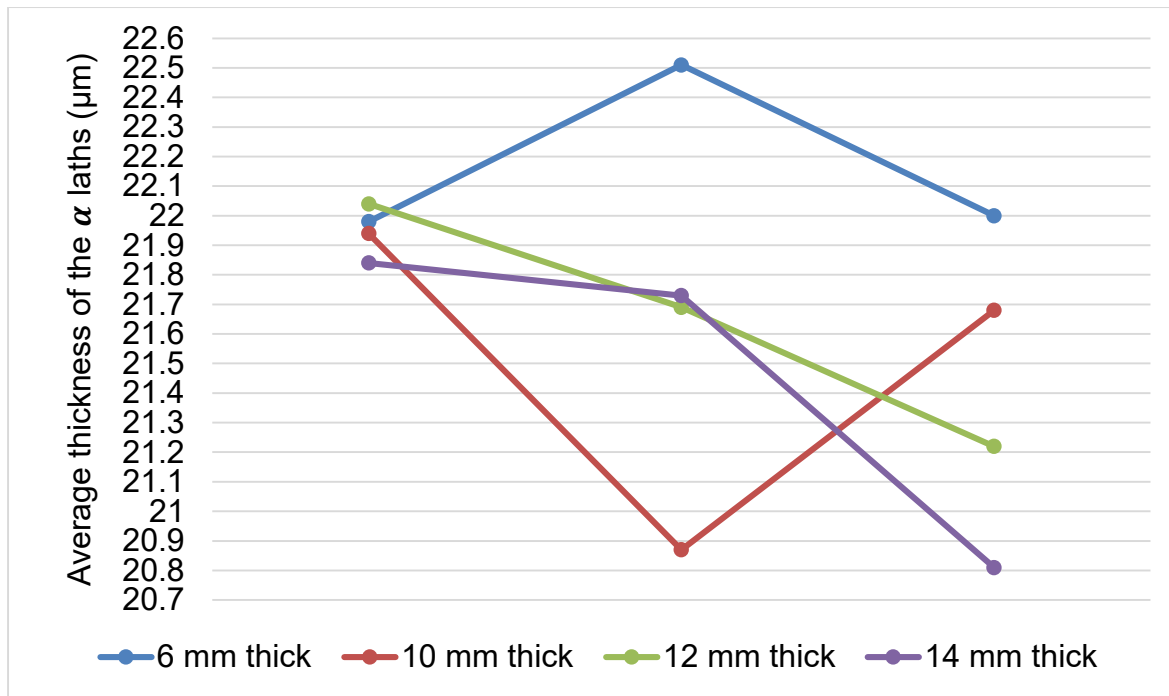


Figure 4.38: Average thickness of the α laths at a distance of 6 mm from the edge of the projectile holes for plates with different thicknesses

From Table 4.7 and Figure 4.38, it can be seen that the average thickness of the α laths at a distance of 6 mm from edge of the projectile holes through the 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range 20.81 μm - 22.51 μm . Additionally, the standard deviation of the thicknesses of the α laths falls within the range 0.66 - 1.69.

Based on the similarities of the microstructure of all the plate thicknesses at a distance of 6 mm from the edges of the projectile holes seen in Figure 4.34 up to Figure 4.37, the key features were thus examined on a plate of 10 mm thickness arrived at randomly.

Figure 4.39(a) is an optical micrograph and Figure 4.39(b) a SEM micrograph, both at a distance of 6 mm from the edge of the projectile hole through a 10 mm thick plate.

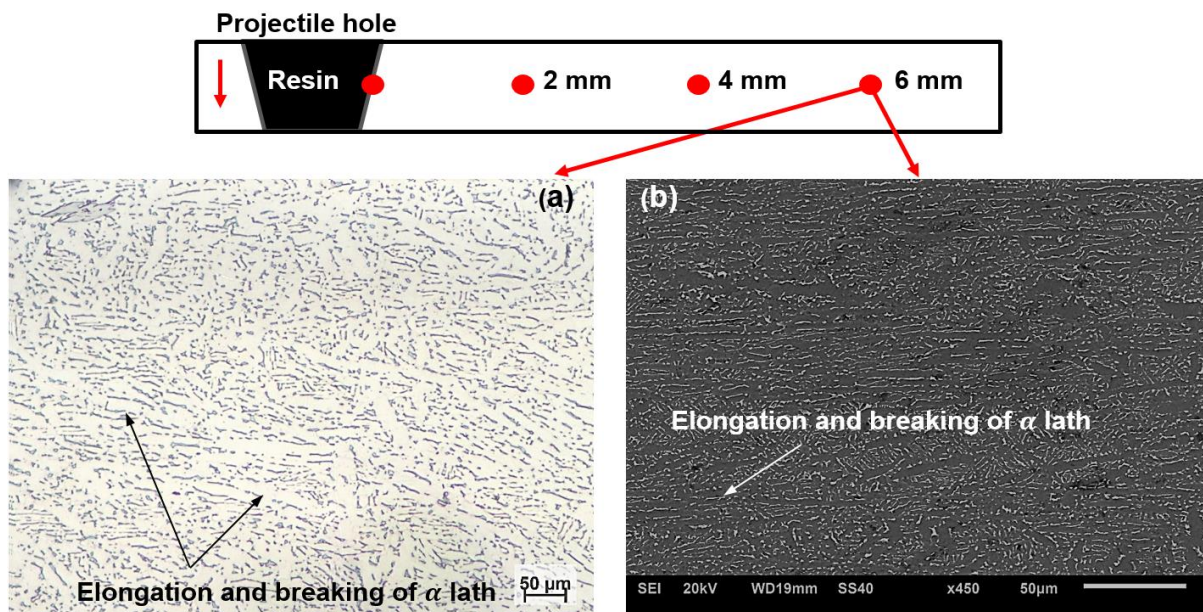


Figure 4.39: (a) Optical micrograph and (b) SEM SEI micrograph, both at a distance of 6 mm from the edge of the projectile hole through a 10 mm thick plate

In Figure 4.39(a) and (b), it can be seen that there is an elongation and fracture of the α laths [23]. The orientation of the longitudinal direction of the α laths in this micrograph is more or less horizontal.

At a distance of 6 mm from the edge of the projectile hole, the deformation of the alloy caused elongation, fracture and reorientation of the α and β phases [17, 18, 23]. The longer α laths in this area are thought to have been formed from the elongation of the globularized α phase along the direction of deformation induced by the tensile elastic stress wave [24].

At a distance of 4 mm from the projectile hole as seen in Table 4.6, there is a decrease in the size of the α laths to an average width ranging between 18.76 μm and 19.20 μm . At this distance, the α phase fraction is lower than the β phase fraction, in contrast to the case for the microstructure at a distance of 2 mm away from the edge of the projectile hole. The higher fraction of the β phase is thought to

be a result of the heating effect of impact. This also explains the occurrence of ASBs nearer than further away from the edge of the projectile hole [19, 20].

Moving closer to a distance of 2 mm from the projectile hole as seen in Table 4.5, there is a further decrease in the size of the α laths to an average width ranging between 14.96 μm and 15.68 μm . The smaller α laths in this area start to assume a random orientation apart from near the middle of the micrograph where an orientation appearing to be along an ill-defined ASB is seen [21]. At this point, the ASBs are not fully formed and this implies that strain rate and temperature rise in this area was not significant enough to bring about changes of microstructure [21].

At the edge of the projectile hole as seen in Table 4.4, there is a further decrease in the size of the α laths to an average width ranging between 7.76 μm and 8.61 μm . Furthermore, at this point, the smaller α laths are still randomly oriented apart from the areas adjacent to the ASBs, where the laths are oriented more or less parallel to the ASBs. The latter is likely to be the results of shear deformation along the direction of the ASBs [19, 20].

There is a visible gradual decrease in the size of the α and β phases with closer proximity towards the projectile hole, which leads to the formation of a finer microstructure. The finer microstructure is likely to have arisen due to heating above the beta transus temperature followed by cooling in air with the attendant formation of many sites of nucleation that then lead to this observed finer microstructure.

The gradual increase in size of the microstructure with distance from the projectile hole is not all together surprising, as the plates are expected to develop a temperature gradient away from the projectile hole, giving rise to lower temperature rises away from this point. The low coefficient of thermal conduction of the alloy is expected to steepen this temperature gradient. Near the penetration hole, there is also a visible network of ASBs.

The ASBs in this area are formed as a result of rapid deformation resulting in thermal softening of the material, due to the conversion of mechanical work into heat within the body and the attendant rise of temperature [19, 20]. The ASBs are seen in Figure 4.21 and Figure 4.27 to be inclined to the edge of the penetration hole. These

inclinations are consistent with shear failure of materials along the directions of maximum shear that are inclined to the directions of principal stresses.

The next phenomena that was studied on specimens a and b, was how cracks were formed in the material during high velocity impact. Figure 4.40(a) and (c) are optical micrographs showing bifurcation of ASBs and the formation of cracks along an ASB, respectively. The micrographs were all taken from a plate of 10 mm thickness.

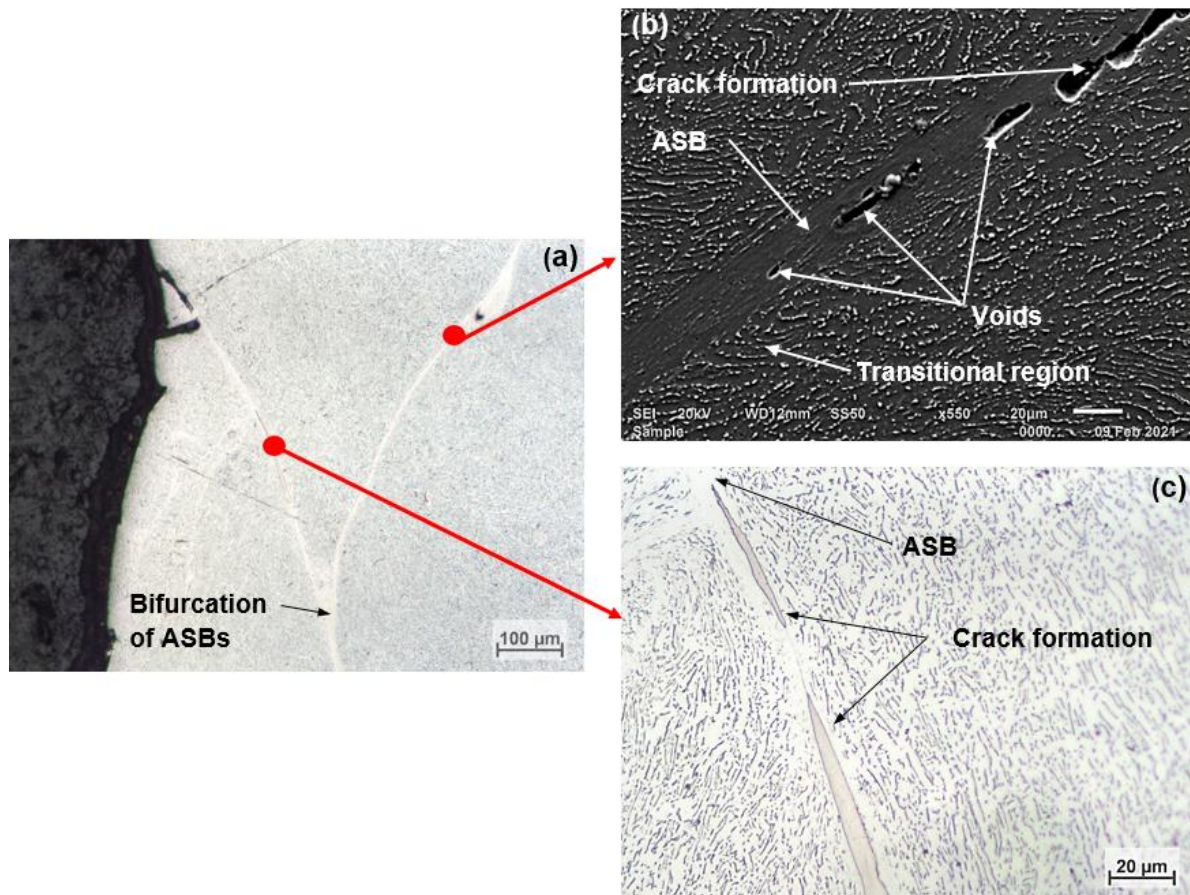


Figure 4.40: Optical micrographs showing (a) bifurcation of ASBs, (c) formation of a cracks along an ASB; (b) SEM SEI micrograph showing the formation of cracks along an ASB, all from a 10 mm thick plate

From Figure 4.40(c) it can be seen that cracks in the material were formed and propagated along the ASB during high velocity impact. Furthermore, it can be seen from the same figure and Figure 4.40(b) that crack formation was segmented, indicating that the nucleation as well as formation and aggregation of voids did not occur evenly throughout the ASBs [19, 25].

It is evident that the formation of ASBs occurred at specific points and not throughout the material as seen in Figure 4.40(a), Figure 4.21(a) and Figure 4.33(a), which is a clear sign of varying intensity of deformation of the material [25].

4.6.5. Microstructural analysis of wrought Ti6Al4V plates at a distance of 25 mm from the edge of projectile holes

The next set of micrographs were taken at mid span of specimens c and d, to investigate whether the impact of the high velocity projectile did also affect the microstructure of the alloy a distance of 25 mm away from the edge of the projectile hole.

Figures 4.41(a), (b) and (c), 4.42(a), (b) and (c), 4.43(a), (b) and (c) and 4.44(a), (b) and (c) are optical micrographs at a distance of 25 mm away from the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

As has been done in the previous cases, the delineations of ten α laths that were selected randomly on each micrograph are shown, their widths measured and their statistics of centrality and scatter calculated.

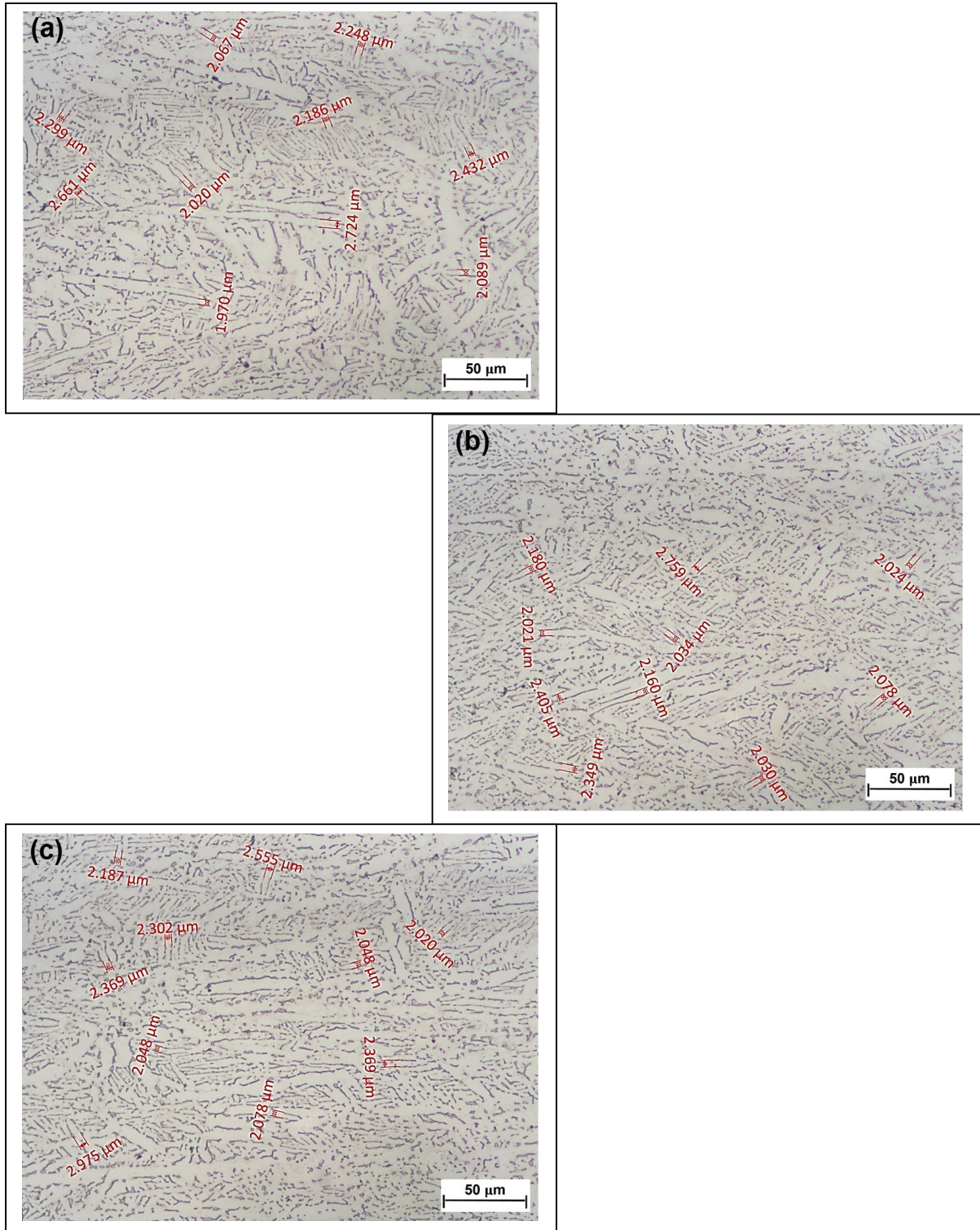


Figure 4.41: Optical micrographs at a distance of 25 mm from the edges of projectile holes through the 6 mm thick plates

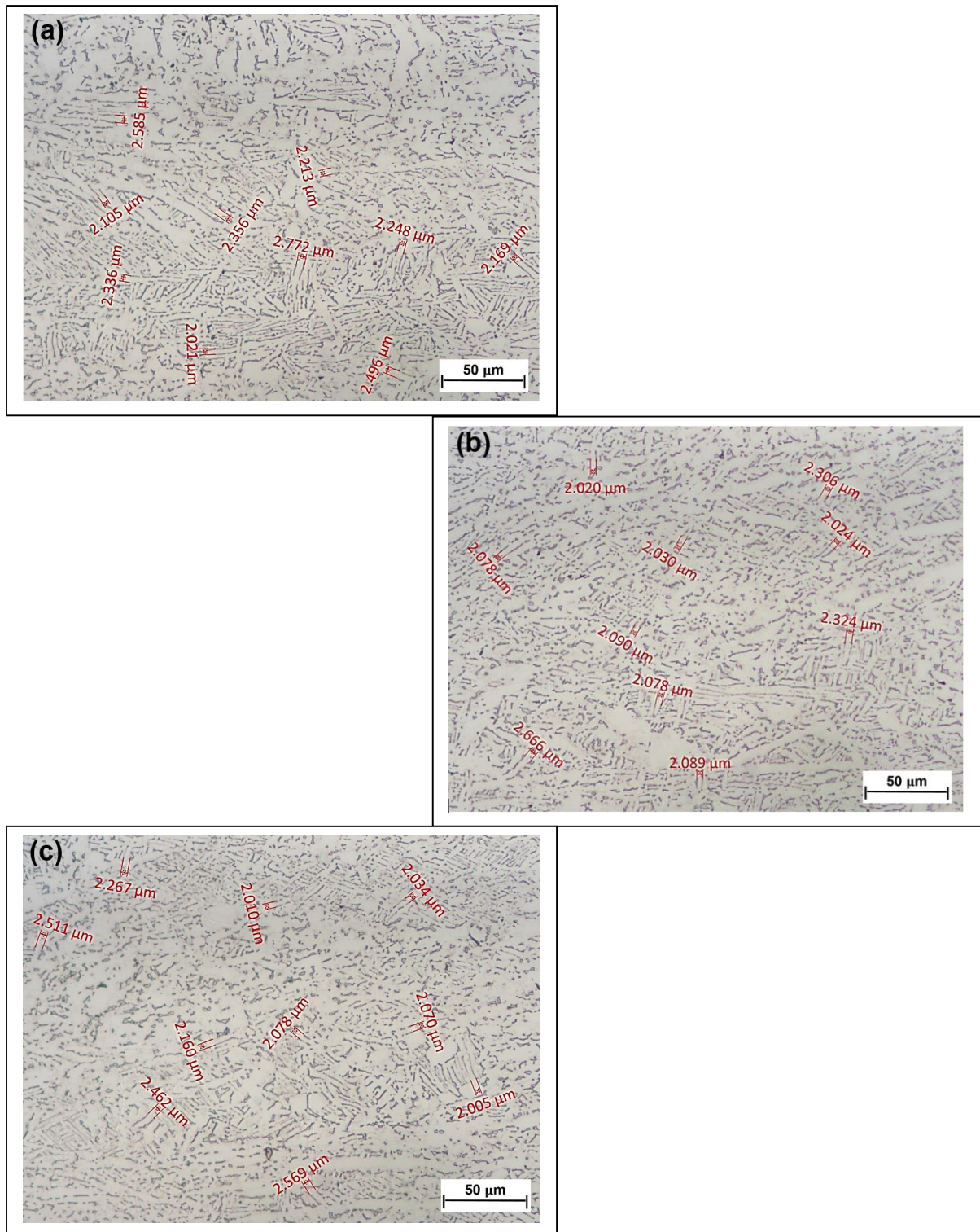


Figure 4.42: Optical micrographs at a distance of 25 mm from the edges of projectile holes through the 10 mm thick plates

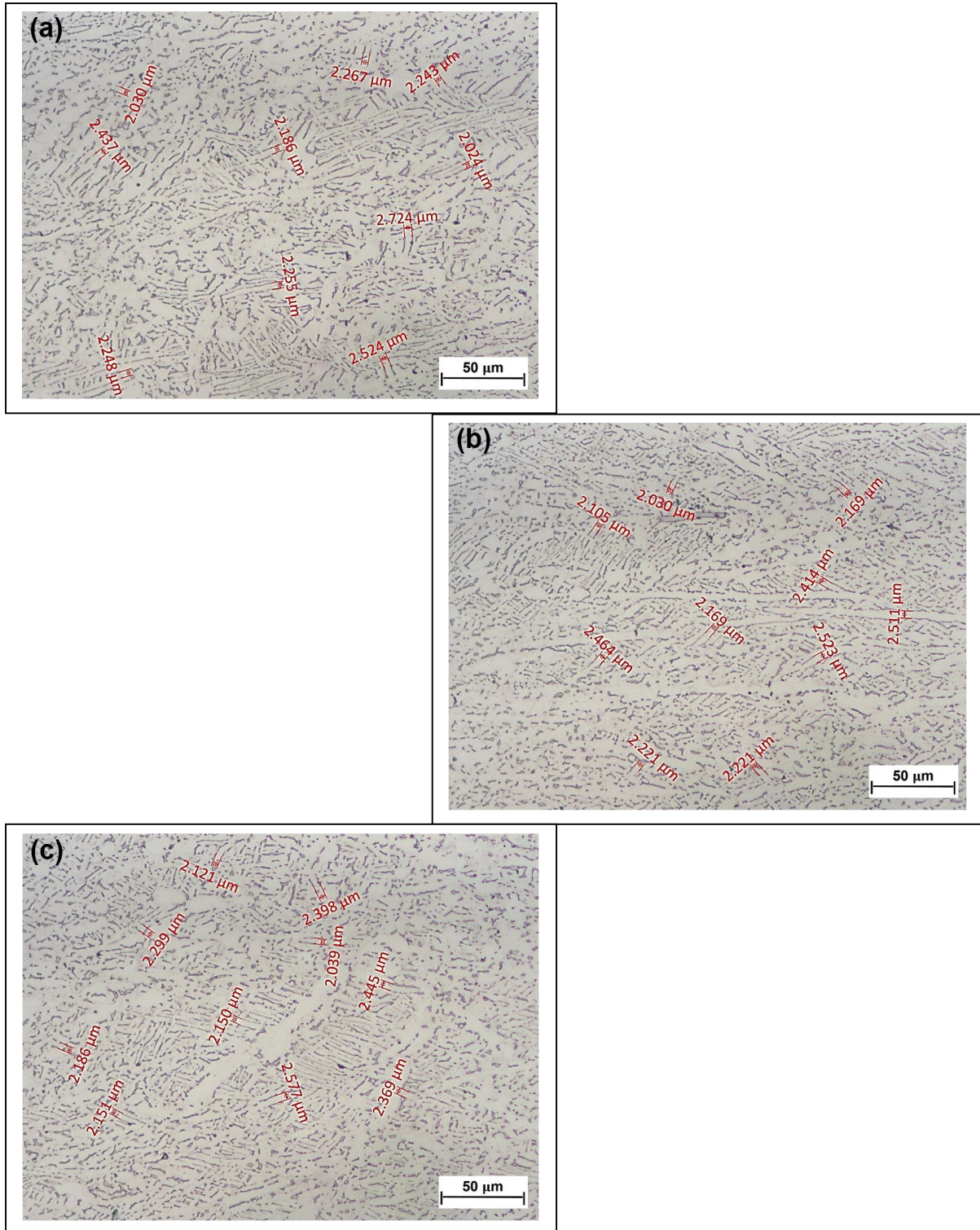


Figure 4.43: Optical micrographs at a distance of 25 mm from the edges of projectile holes through the 12 mm thick plates

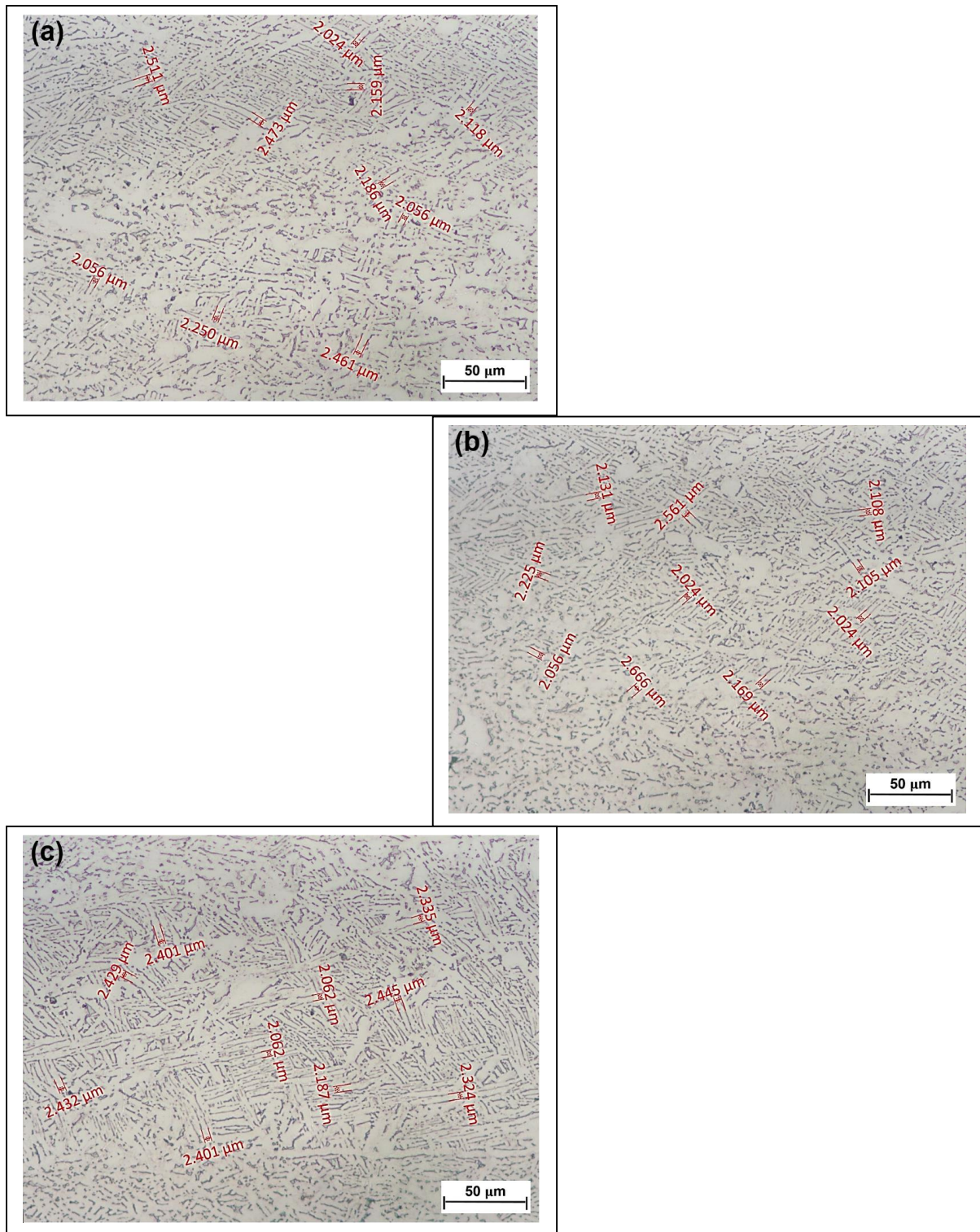


Figure 4.44 : Optical micrographs at a distance of 25 mm from the edges of projectile holes through the 14 mm thick plates

Figure 4.7 and Figure 4.45 shows the measurements of the thickness of the α laths at a distance of 25 mm from the edges of projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates.

Table 4.8: Thickness of α laths at a distance of 25 mm from the edge of the projectile holes

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.41(a)	2.27	0.26
	Figure 4.41(b)	2.17	0.23
	Figure 4.41(c)	2.30	0.30
10 mm	Figure 4.42(a)	2.33	0.23
	Figure 4.42(b)	2.17	0.21
	Figure 4.42(c)	2.22	0.22
12 mm	Figure 4.43(a)	2.29	0.22
	Figure 4.43(b)	2.28	0.18
	Figure 4.43(c)	2.27	0.17
14 mm	Figure 4.44(a)	2.23	0.19
	Figure 4.44(b)	2.21	0.22
	Figure 4.44(c)	2.31	0.15

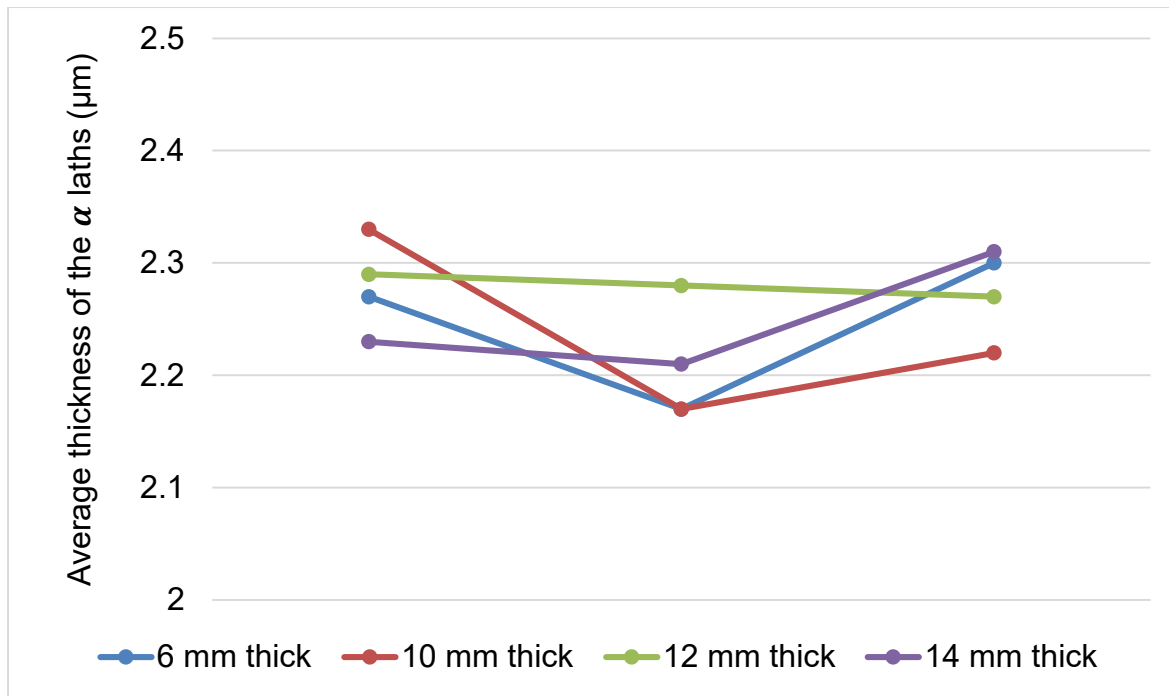


Figure 4.45: Average thickness of the α laths at 25 mm from the edge of the projectile holes for plates with different thicknesses

From Table 4.8 and Figure 4.45, it can be seen that the average thickness of the α laths at a distance of 25 mm from edges of the projectile holes through each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range of 2.17 μm - 2.33 μm . Additionally, the standard deviation of the thickness of the α laths falls within the range of 0.15 - 0.30.

Based on the similarities of the microstructure of all the plate thicknesses at 25 mm from the edge of the projectile hole seen in Figure 4.41 up to Figure 4.44, the key features were be examined on a plate of 10 mm thickness selected randomly.

Figure 4.46(a) is an optical micrograph, Figure 4.46(b) higher magnification micrograph and Figure 4.46(c) higher magnification SEM micrograph, all at a distance of 25 mm from the edge of a projectile hole through a 10 mm thick plate. It should be noted that micrographs (b) and (c) are higher magnification micrographs of (a).

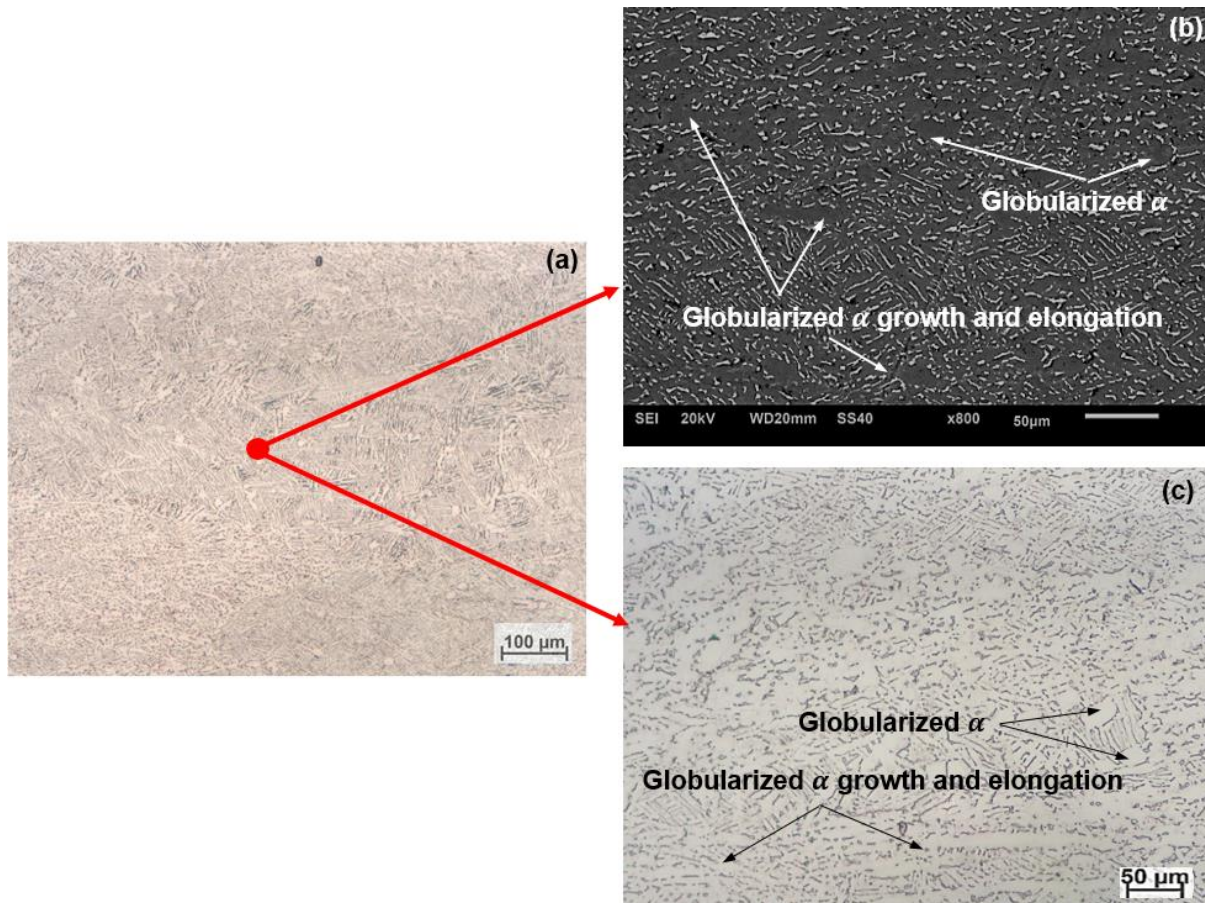


Figure 4.46: (a) Optical micrograph, (c) higher magnification optical micrograph and (b) higher magnification SEM SEI micrograph, all at a distance of 25 mm from the edge of the projectile hole through a 10 mm thick plate

In Figure 4.46(b) and (c), the microstructure is seen to be lamellar, with areas of globularized α phase. The globularized α grains appear elongated and thicker than those in the initial microstructure in Figure 4.46 [26].

4.6.6. Microstructural analysis of initial microstructure of wrought Ti6Al4V

The last set of micrographs was taken at mid span of specimens e and f, for all the plate thickness to view the microstructure of wrought Ti6Al4V prior to testing. The micrographs were taken at a distance 40 mm from the edges of projectile holes, far enough for the effects of impact not to be felt.

Figures 4.47(a), (b) and (c), 4.48(a), (b) and (c), 4.49(a), (b) and (c) and 4.50(a), (b) and (c) are optical micrographs of the initial microstructure of wrought Ti6Al4V from the 6 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

As has been done in the previous cases, the delineations of ten α laths that were selected randomly on each micrograph are shown, their widths measured and their statistics of centrality and scatter calculated.

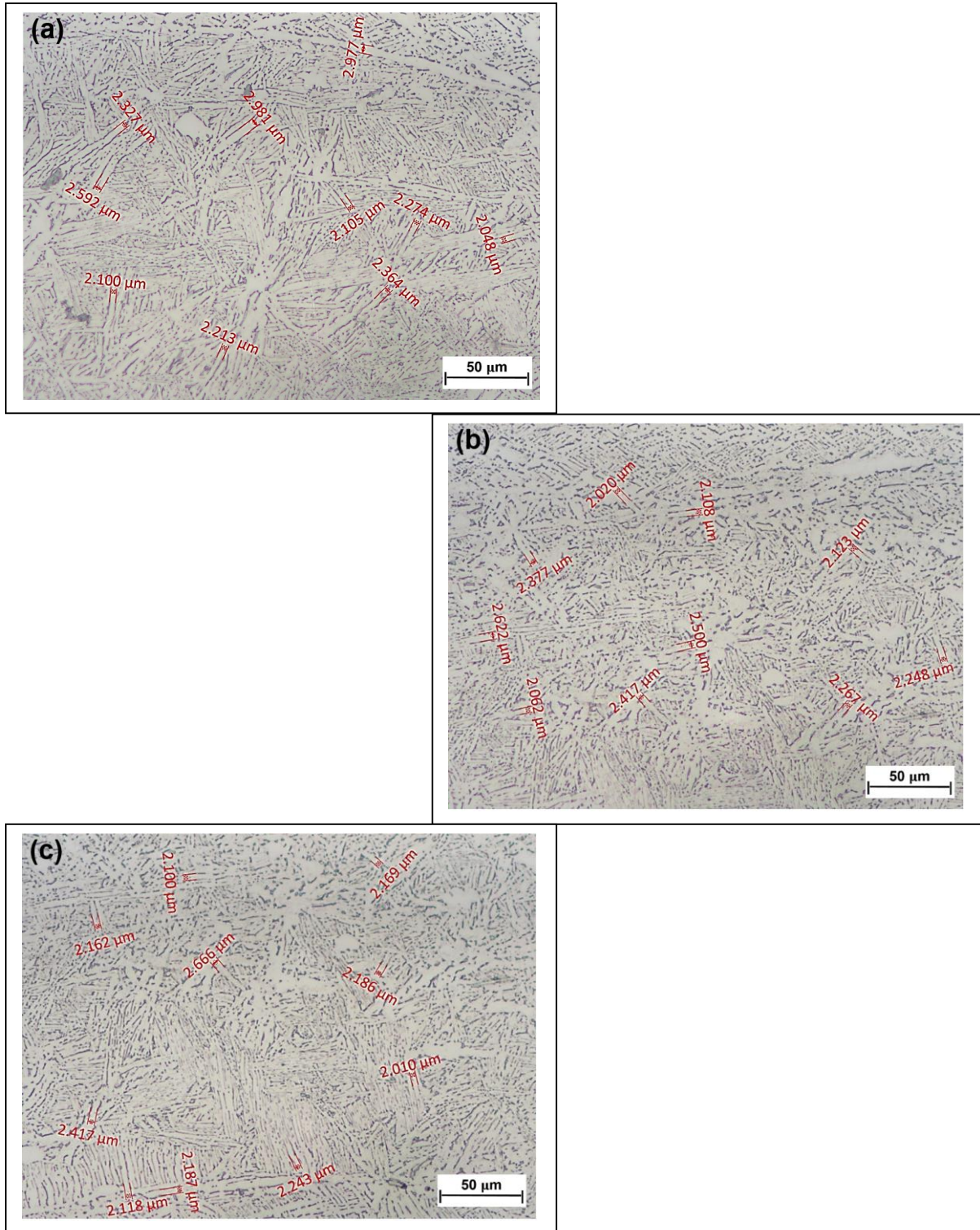


Figure 4.47: Optical micrographs of the initial microstructure of wrought Ti6Al4V (at a distance of 40 mm from the edges of projectile holes through the 6 mm thick plates)

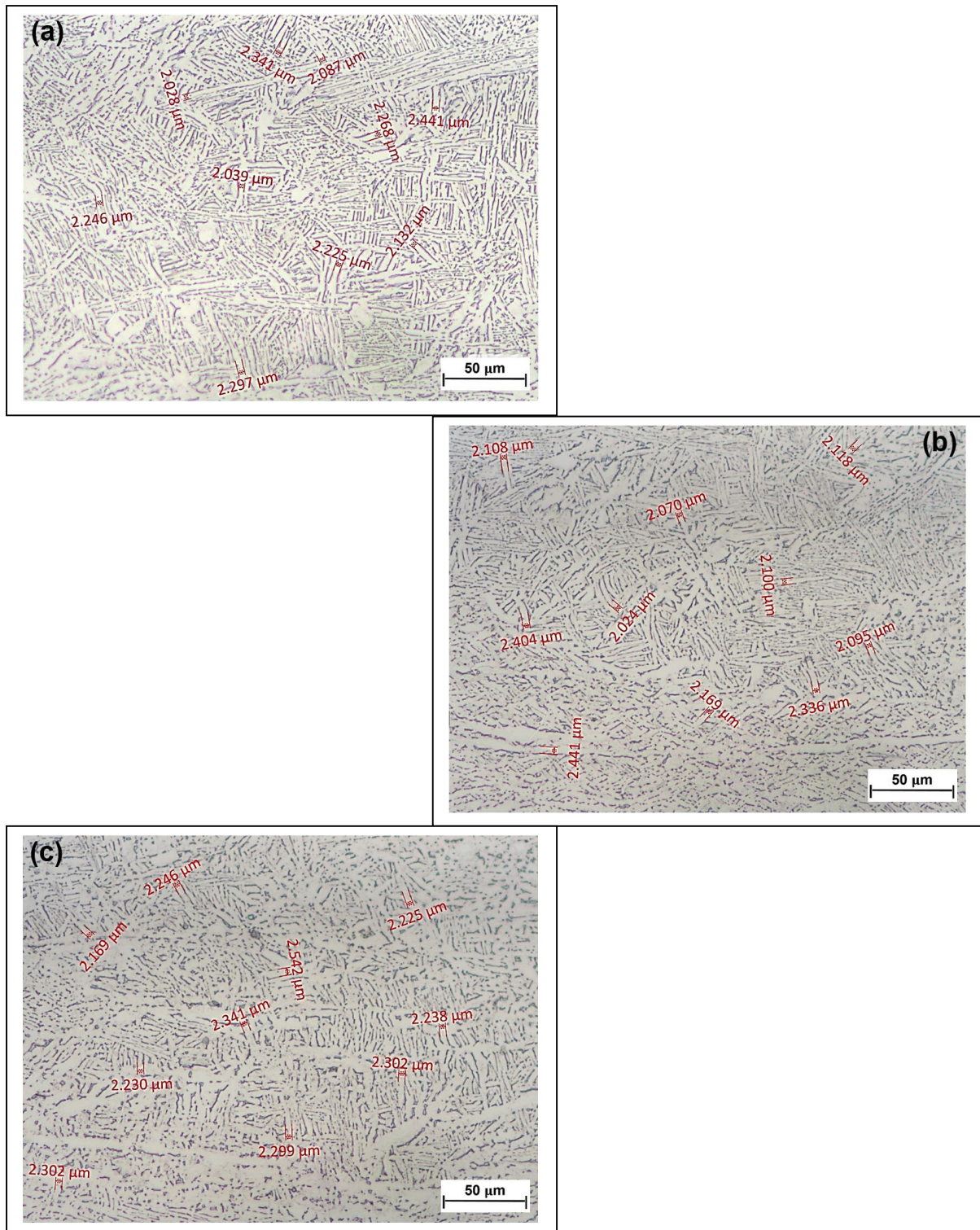


Figure 4.48: Optical micrographs of the initial microstructure of wrought Ti6Al4V (at a distance of 40 mm from the edges of projectile holes through the 10 mm thick plates)

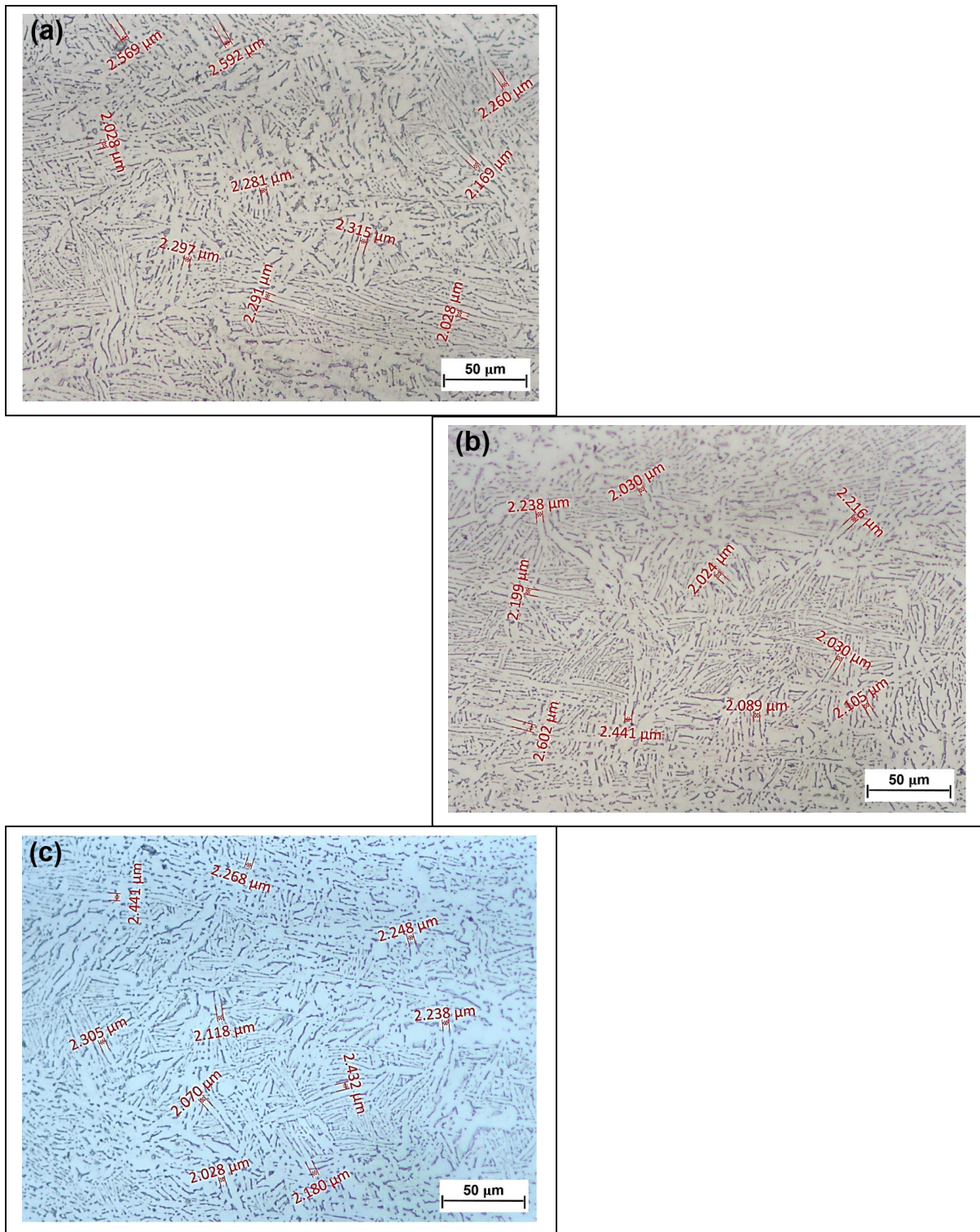


Figure 4.49: Optical micrographs of the initial microstructure of wrought Ti6Al4V (at a distance of 40 mm from the edges of projectile holes through the 12 mm thick plates)

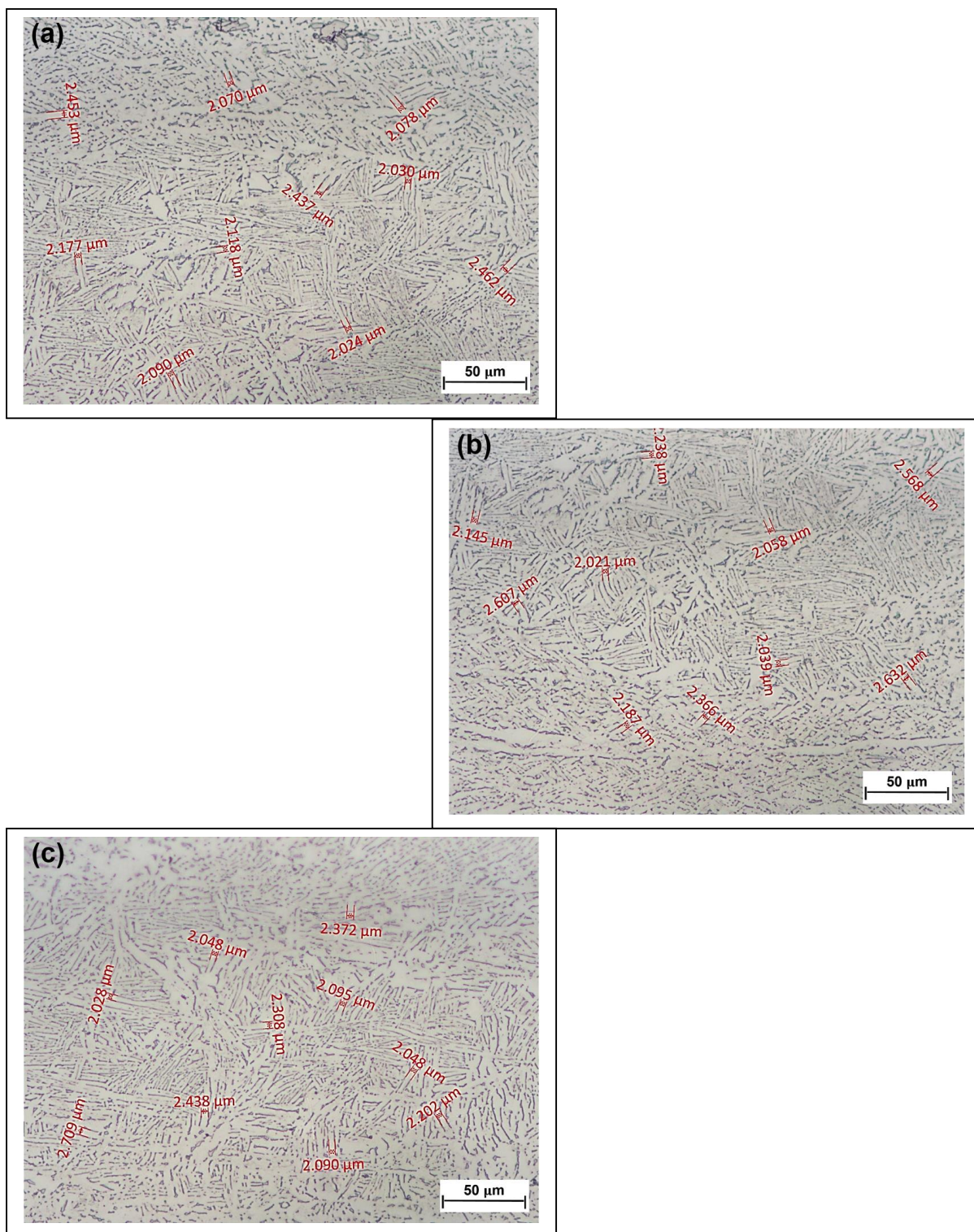


Figure 4.50: Optical micrographs of the initial microstructure of wrought Ti6Al4V (at a distance of 40 mm from the edges of projectile holes through the 14 mm thick plates)

Table 4.9 and Figure 4.51 shows the measurements of the thickness of the α laths on the initial microstructure of wrought Ti6Al4V from each one of the three 6 mm, 10 mm, 12 mm and 14 mm thick plates.

Table 4.9: Thickness of the α laths on the initial microstructure of wrought Ti6Al4V

Thickness of plate	Figure number	Average thickness of the α laths (μm)	Standard deviation
6 mm	Figure 4.47(a)	2.40	0.34
	Figure 4.47(b)	2.27	0.20
	Figure 4.47(c)	2.23	0.19
10 mm	Figure 4.48(a)	2.21	0.13
	Figure 4.48(b)	2.19	0.15
	Figure 4.48(c)	2.29	0.10
12 mm	Figure 4.49(a)	2.28	0.19
	Figure 4.49(b)	2.20	0.19
	Figure 4.49(c)	2.23	0.14
14 mm	Figure 4.50(a)	2.19	0.18
	Figure 4.50(b)	2.29	0.24
	Figure 4.50(c)	2.23	0.22

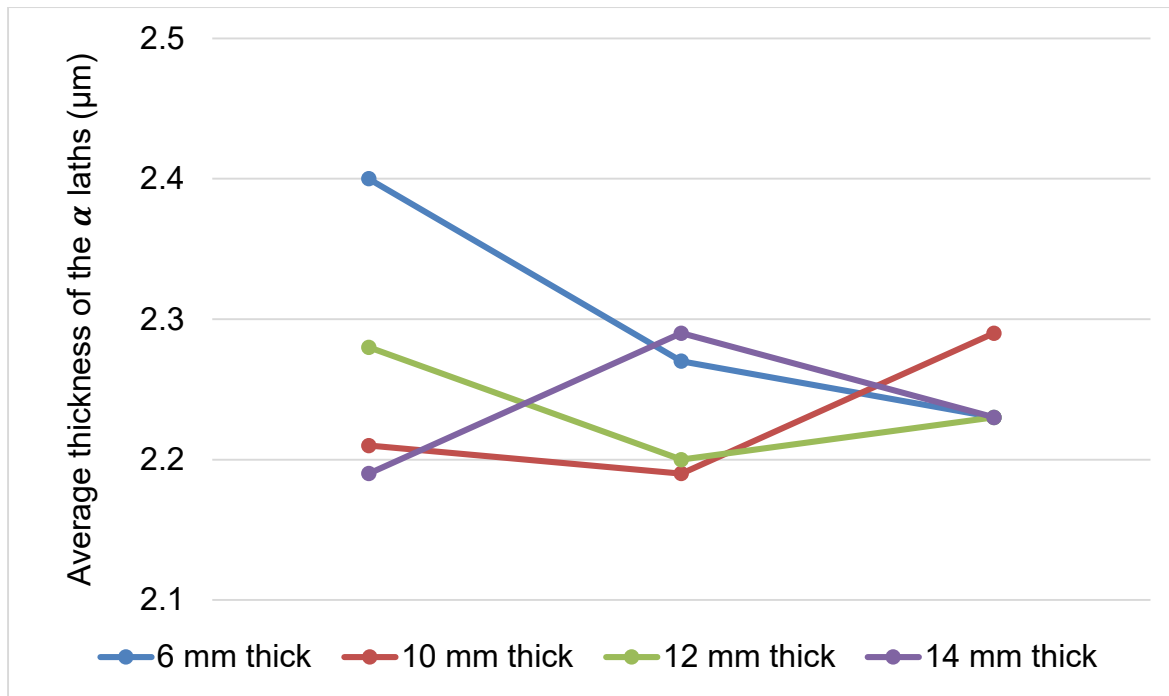


Figure 4.51: Average thickness of the α laths on the initial microstructure of wrought Ti6Al4V plates with different thicknesses

From Table 4.9 and Figure 4.51, it can be seen that the average thickness of the α laths in the initial microstructure of wrought Ti6Al4V from the 6 mm, 10 mm, 12 mm and 14 mm thick plates, falls within the range of 2.19 μm - 2.29 μm . Additionally, the standard deviation of the thickness of the α laths falls within the range of 0.10 - 0.34.

Based on the similarities of the initial microstructure of wrought Ti6Al4V seen in Figure 4.47 up to Figure 4.50, the key features were examined on a plate of 10 mm thickness selected randomly.

Figure 4.52(a) is an optical micrograph and Figure 4.52(b) a higher magnification micrograph, both of the initial microstructure of wrought Ti6Al4V from a 10 mm thick plate.

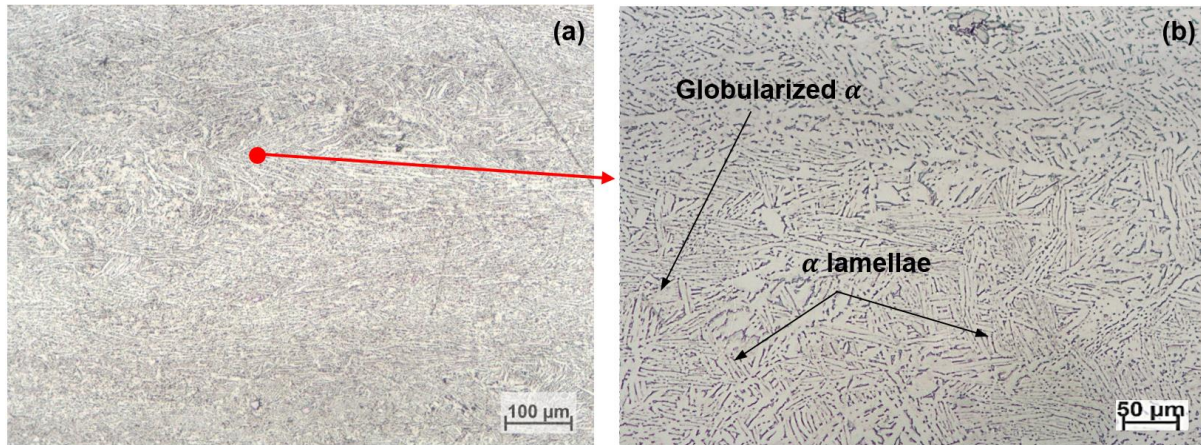


Figure 4.52: (a) Optical micrograph and (b) higher magnification optical micrograph, both of the initial microstructure of wrought Ti6Al4V from a 10 mm thick plate

In Figure 4.52(b), it can be seen that the initial microstructure of the wrought Ti6Al4V used for tests in this work had a lamellar microstructure, with incidences of globularisation as reported in [26]. Comparison of the micrographs in this subsection and those in the previous subsections for distances from the edges of projectile holes less than 25 mm, makes it clear that high velocity ballistic impact brings about microstructural changes in wrought Ti6Al4V. Moreover these changes are graded, varying for limited distances around the point of impact and penetration.

At the furthest points from the edges of projectile holes examined here, a distance of 40 mm, the average thickness of the α laths was observed to fall within the range 2.19 μm - 2.29 μm and the micrographs showed signs of globularization of the α phase that was spaced out in the alloy. Additionally, the standard deviation of the thickness of the α laths at this distance falls within the range of 0.10 - 0.34.

Moving closer to the projectile hole at a distance of 25 mm from it, the average thickness of the α laths was noted to fall within the range of 2.17 μm - 2.33 μm . The standard deviation of the thickness of the α laths at this distance falls within the range 0.15 - 0.30. At this distance from the projectile hole, the microstructure had spaced out areas of globularized α phase as at a distance of 40 mm from the edge of the projectile hole. The similarity between the micrographs taken at distances of 25 and 40 mm away from the edge of the projectile hole, demonstrate the limited distance around the projectile hole over which the effect of impact was felt.

4.7. Justification for Conducting High Velocity Ballistic Impact Studies Using As-built and Stress Relieved DMLS Ti6Al4V (ELI)

This section presents a summary of the justification for further high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI). It was found that the minimum thickness of wrought Ti6Al4V required to resist penetration by a bullet lies between that of RHA and AA 5083, and the added advantages of Ti6Al4V made this alloy attractive for ballistic armour. This and the advantages offered by AM made it necessary to consider the use of DMLS Ti6Al4V (ELI). A justification for further high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI) was thus developed to predict the performance of the alloy through theoretical modelling regarding the test results of wrought Ti6Al4V obtained here.

The justification used theoretical modelling to develop expressions for the V_{50} ballistic limit and absorbed strain energy of elastic and plastic deformation, both to estimate the optimum thickness of the material. Furthermore, the justification also used a comparison between the microstructure of wrought Ti6Al4V and as-built and stress relieved DMLS Ti6Al4V (ELI), as well as their mechanical properties, to predict the performance of the latter under the same conditions of applied load.

In the justification, the calculations conducted generated values of optimum penetration thickness of 13.41 mm and 10.40 mm for the alloy, for calculations based on the V_{50} ballistic limit and shear strain energy, respectively. These two values are lower than those of wrought Ti6Al4V of 15.38 mm and 14 mm, based on theoretical calculations of the V_{50} ballistic limit and experimental results. This decrease in optimum thickness of 12.81% and 25.71% was considered significant enough to generate interest in using DMLS Ti6Al4V (ELI) for ballistic impact over wrought Ti6Al4V.

The difference between the experimental and V_{50} ballistic limits for wrought Ti6Al4V can be attributed to the fact that the non-uniform plastic and elastic deformation of the material was not considered in the calculations. Taking this into account, the difference between the two was expressed as a correction factor of 8.97 % and then applied to the calculated V_{50} ballistic limit obtained for as-built and stress relieved

DMLS Ti6Al4V (ELI). This gave rise to a final value of expected experimental optimum thickness of 12.41 mm, a decrease of optimum thickness of 11.36% that is still attractive.

In the calculations based on shear strain energy, the comparatively much lower value of 10.41 mm obtained can be attributed to disregard of the non-uniform plastic deformation of the materials; wrought and as built and stress relieved DMLS Ti6Al4V (ELI).

The foregoing results from the theoretical modelling indicated that as-built and stress relieved DMLS Ti6Al4V (ELI) was expected to perform better under ballistic impact than the wrought Ti6Al4V. Therefore, ballistic impact testing of DMLS Ti6Al4 (ELI) was conducted to validate the theoretically determined values of optimum thickness, with anticipation that the material would yield better ballistic impact properties than wrought Ti6Al4V.

The rigorous analytical modelling which yielded the results discussed in this section is presented in the appendix.

4.8. High Velocity Ballistic Impact Testing of As-built and Stress Relieved DMLS Ti6Al4V (ELI)

Table 4.10 shows results from high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI). The symbols in the table have the same meaning as in Table 4.3.

Table 4.10: High velocity ballistic impact test results for as-built and stress relieved DMLS Ti6Al4V (ELI)

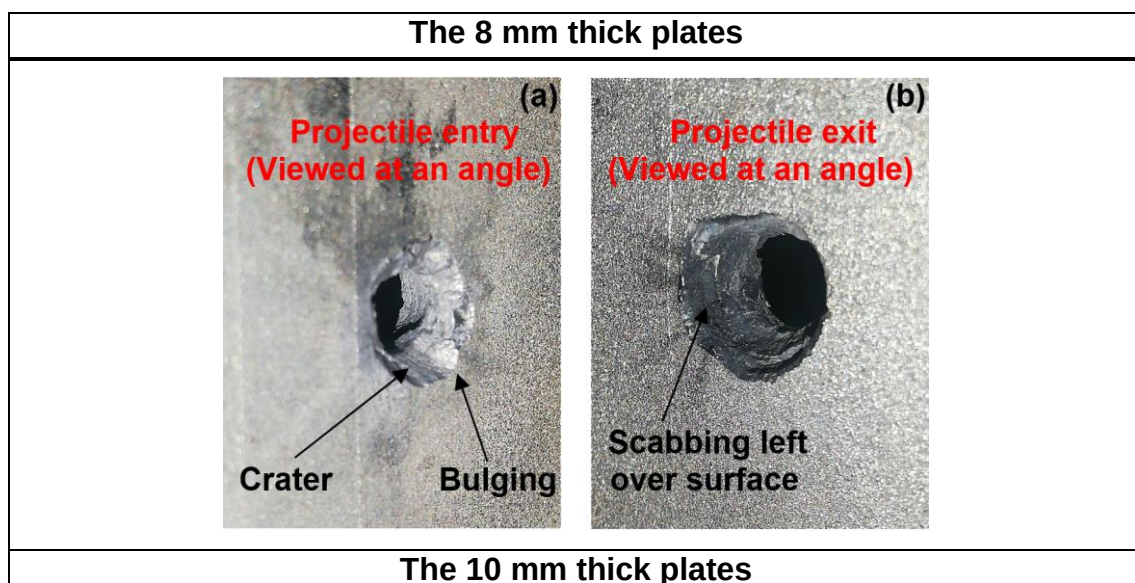
Material Type			Material Identification			Ammunition Type
DMLS titanium alloy			As-built and stress relieved DMLS Ti6Al4V (ELI)			7,62 x 39 mm API bullet, Type 56
Shot number	Actual Distance (m)	Angle Deg.	v_{chron} (m/s)	v_i (m/s)	t (m)	Results
1	30	0	712	710	14	Failed - CP core stuck
2	30	0	700	698	14	Failed - CP
3	30	0	700	698	14	Failed - CP + 1 x 1 mm MS
4	30	0	707	705	12	Failed - CP + 3 x 1 mm MS
5	30	0	698	696	12	Failed - CP + 6 x 1 mm MS
6	30	0	700	698	12	Failed - CP + 5 x 1 mm MS
7	30	0	706	704	10	Failed - CP + 11 x 1 mm MS
8	30	0	701	699	10	Failed - CP + 11 x 1 mm MS
9	30	0	707	705	10	Failed - CP + 6 x 1 mm MS
10	30	0	708	706	8	Failed - CP + 11 x 1 mm MS
11	30	0	711	709	8	Failed - CP + 15 x 1 mm MS
12	30	0	702	700	8	Failed - CP + 6 x 1 mm MS
Average			704	702		
Standard deviation			5	5		
Coefficient of variation (%)			0.7	0.7		

From Table 4.10, the average impact velocity for the tests was found to be 702 m/s, while the standard deviation of the impact velocity was 5 m/s, which gave rise to a coefficient of variation of 0.7% that is well below the limiting value of 6%. Similar to the preliminary testing of wrought Ti6Al4V, the impact angle of the projectile on the front face of the targets remained at 0° for all the tests. The variation between the minimum and maximum impact velocity v_i for the 14 mm, 12 mm, 10 mm and 8 mm thick plates of 12 m/s, 9 m/s, 6 m/s and 9 m/s, respectively, are small, with a coefficient of variation of 0.3%.

From Table 4.10 it can be seen that minimum thickness to prevent through penetration for as-built and stress relieved DMLS Ti6Al4V (ELI) during testing is above 14 mm. This value is higher than the value of 10.40 mm estimated in the justification for further testing of as-built and stress relieved DMLS Ti6Al4V (ELI), indicating deformation mechanisms different from those that were projected in the analytical models used in the justification.

4.9. Visual Inspection of As-built and Stress Relieved DMLS Ti6Al4V (ELI) Ballistically Impacted Plates

Visual inspection was conducted on the 8 mm, 10 mm, 12 mm and 14 mm thick plates, to investigate the type of failure that occurred due to high velocity ballistic impact. Figure 4.53 shows optical images of the visual inspection of the projectile penetration holes at the entry and exit points for all DMLS plate thicknesses.



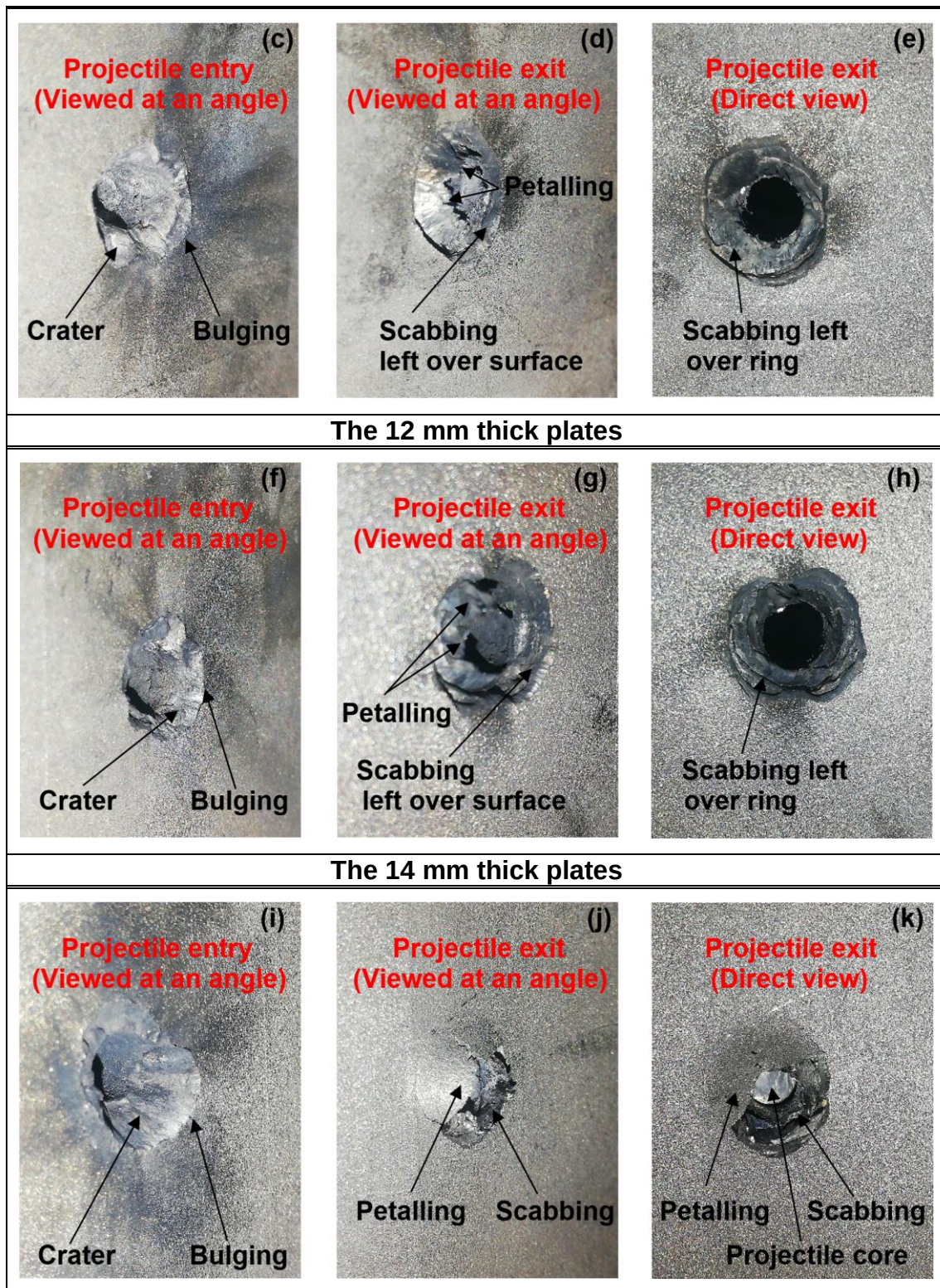


Figure 4.53: Visual inspection images of the projectile penetration holes at the entry and exit points for all the DMLS Ti6Al4V (ELI) plate thicknesses

Through visual inspection of all the plates, it can be deduced that all the plates showed bulging and formation of a crater (a sign of spalling) at the entry side of the

projectile penetration holes. Evidence of this is seen in Figure 4.53(a), (c), (f) and (i). Bulging on the sides of the projectile hole entrance suggests a ductile deformation on the edges of the projectile hole at the entry side of the projectile hole [26, 28, 29].

During high velocity impact, the target material cannot deform fast enough on the entry side in front of the projectile and, therefore, the generated compressive wave is propagated outward radially and backwards to form a bulge [26, 29]. Cratering arises from spalling failure of the material due to impact compressive stresses induced in the material at the point of impact of the projectile [26, 29, 30].

On the exit sides of the projectile penetration holes, the 8 mm thick plates showed signs of scabbing. Evidence of this can be seen through the scabbing left over surfaces shown in Figure 4.53(b) [26, 29]. On the other hand, the 10 mm, 12 mm and 14 mm thick plates showed signs of both scabbing and petalling on the exit side of the projectile penetration holes [26, 32]. Evidence of this can be seen through the scabbing left over surfaces and petalling shown in Figure 4.53(d) and (g), and also scabbing and petalling shown in Figure 4.53(j) [26, 29, 32]. Further evidence of this in the 10 mm and 12 mm thick plates can be seen from the scabbing left over rings shown in Figure 4.53(e) and (h) [26, 32].

Scabbing occurred from tensile fracture at the exit that ejected fractured pieces outwards from the exit side of the penetration holes [26, 30]. Petalling, on the other hand, occurred as a result of the compressive incident stress waves, which were reflected at the free ends (exit sides) of the plates as tensile waves. This caused layers of material to peel off at these ends, accompanied by internal failure and separation of material along a direction perpendicular to that of penetration of the projectile, leading to the formation of petals as the projectile exited the material [11, 30, 32]. Based on the foregoing explanation, it is clear that scabbing predates petalling.

The projectile core trapped in the 14 mm thick plate which can be seen in Figure 4.53(k) suggests significant slowing down of the projectile by this plate, which is peculiar since the impact velocity for this plate was higher than that of the other two plates of the same thickness.

4.10. Fractographic Analysis of As-built and Stress Relieved DMLS Ti6Al4V (ELI) Ballistically Impacted Plates

To understand the deformation behaviour along the surfaces of the penetration holes for the 8 mm, 10 mm, 12 mm and 14 mm thick plates, fractographic studies were carried out using a SEM on half sections 3 and 4, similar to the ones described in section 3.5 and also shown in Figure 3.9. For the 8 mm thick plates, SEI micrographs were taken at the projectile hole entrance and exit points based on their thickness compared to the other plates. Furthermore, for all the other plate thicknesses, SEI micrographs were taken at the projectile hole entrance, middle and exit points. As was the case for the ballistic impact studies on the wrought Ti6Al4V, the acronym DOP here stands for direction of penetration.

4.10.1. Fractography of DMLS 8 mm thick plates

Figure 4.54(a) is a SEI micrograph of the surface of a penetration hole through a typical 8 mm thick plate. Figure 4.54(b) is an enlarged area at the edge of the entry point of the projectile hole and Figure 4.54(c) an enlarged area at the edge of the exit point of the projectile hole through the same plate.

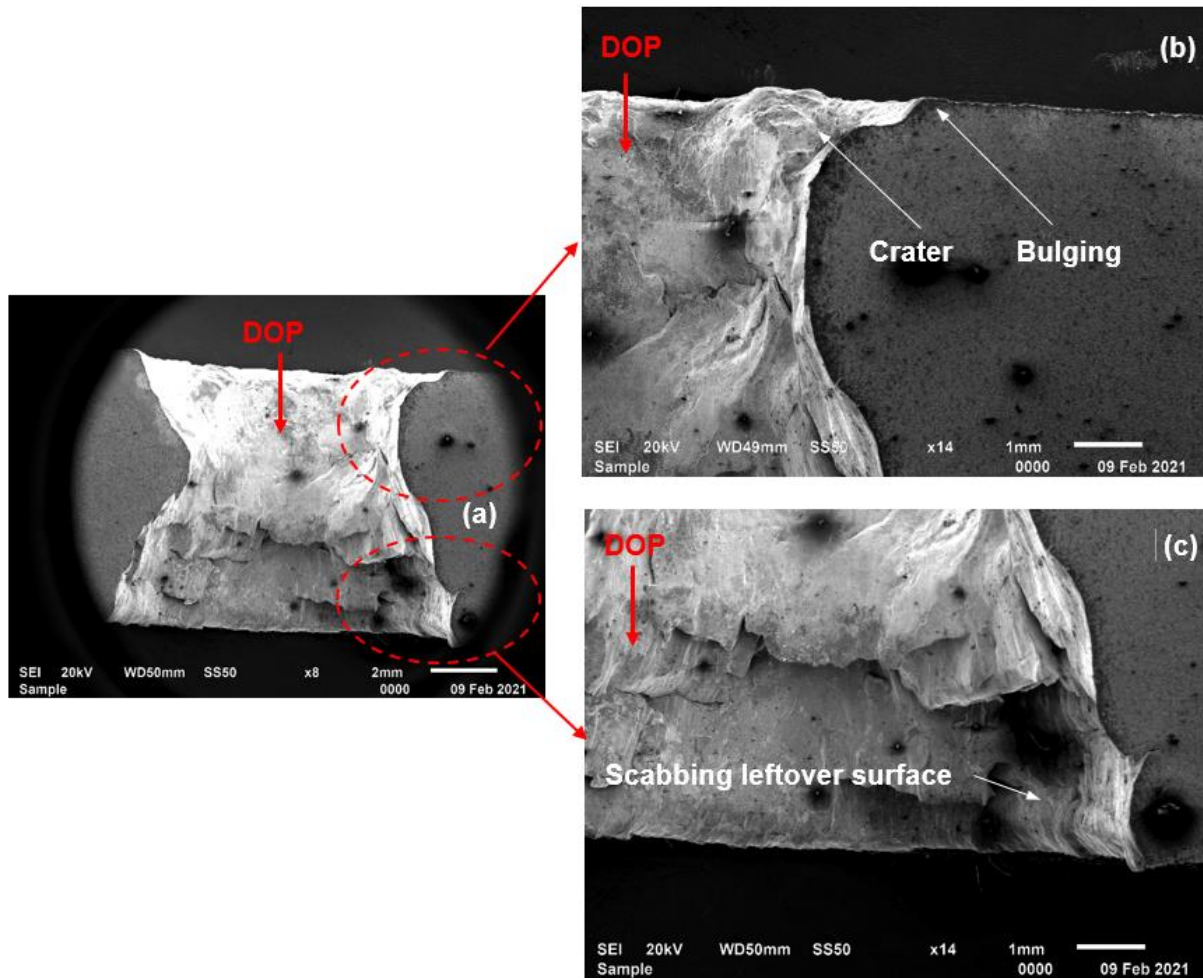


Figure 4.54: SEM SEI micrographs of an 8 mm thick plate projectile hole (a) along the depth; (b) at a magnified area at the edge of the entry point and (c) at a magnified area at the edge of the exit point

In Figure 4.54(b) there is evidence of bulging and formation of a crater at the entry point of the projectile hole [34, 35, 36]. Furthermore, it can be seen in Figure 4.54(c) that there is a scabbing left over surface at the exit point of the projectile hole [34]. Figure 4.54(a) exhibits an initial convergence at the entry side and divergence at the exit side of the projectile hole through the plates, that is typical of ballistic impact tests [34].

Figure 4.55(a) is an SEI micrograph of the same projectile hole shown in Figure 4.54(b), shown here with a circled area for magnification. Figure 4.55(b) is a magnified micrograph of the circled area in Figure 4.55(a).

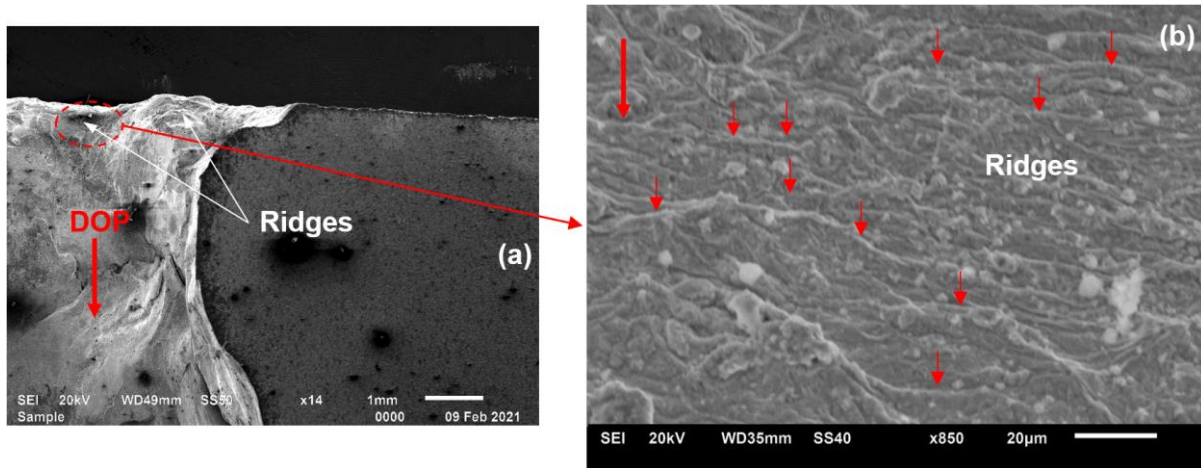


Figure 4.55: SEM SEI micrographs of an 8 mm thick plate projectile hole at (a) the entry point and (b) a magnified circled area at the entry point

Figure 4.55(b) shows a fracture surface with ridges at the entry point of the penetration hole. The ridges are consistent with brittle fracture and therefore denotes brittle failure at the entry point of the penetration hole [38, 39, 41].

Figure 4.56(a) is the same SEI micrograph as shown in Figure 4.54(c), shown here with a circled area for magnification. Figure 4.56(b) is a magnified micrograph of the circled area in Figure 4.56(a).

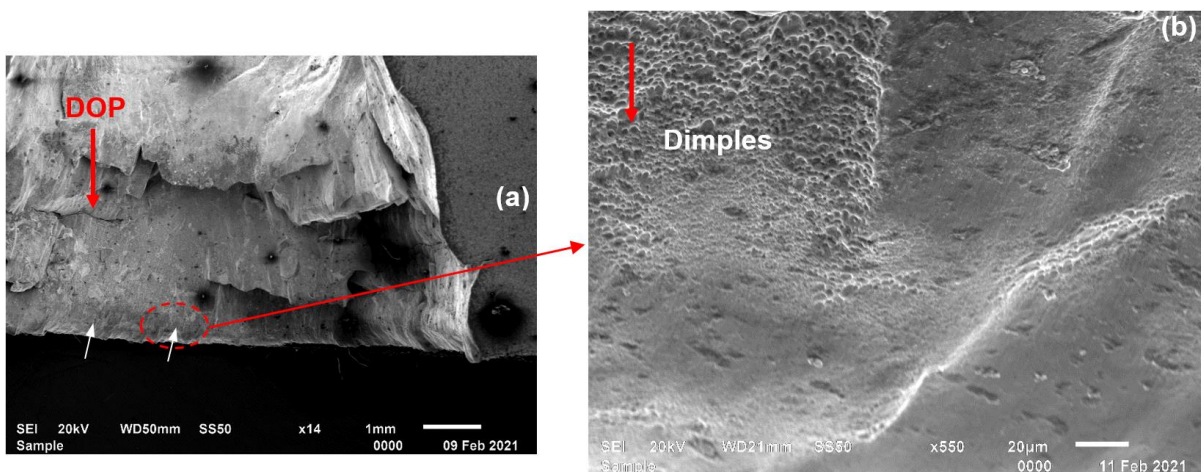


Figure 4.56: SEM SEI micrographs of an 8 mm thick plate projectile hole at (a) the exit point and (b) a magnified area at the exit point

Dimples are visible on the micrograph in Figure 4.56(b). The formation of dimples is an indication that the metal fractured in a ductile manner at the exit point of the projectile hole [39, 40, 42].

4.10.2. Fractography of DMLS 10 mm thick plates

Figure 4.57(a) is a SEI micrograph of the surface of a penetration hole through a typical 10 mm thick plate. Figure 4.57(b) is an enlarged area at the edge of the entry point of the projectile hole and Figure 4.57(c) an enlarged area at the edge of the exit point of the projectile hole through the same plate.

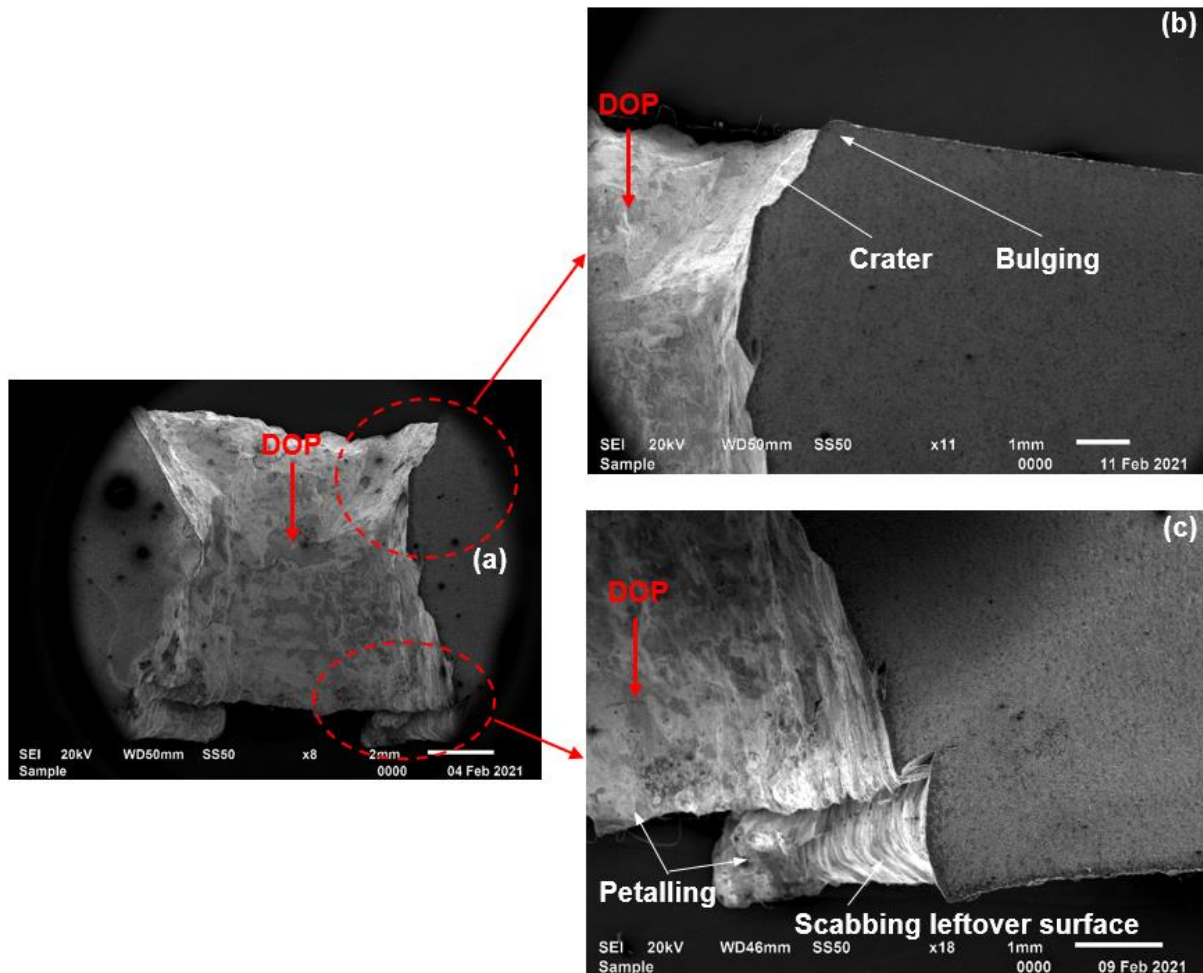


Figure 4.57: SEM SEI micrographs of a 10 mm thick plate projectile hole (a) along the depth; (b) at a magnified area at the edge of the entry point and (c) at a magnified area at the edge of the exit point

Similar to the 8 mm thick plates, the 10 mm thick plates show bulging and formation of a crater at the entry point of the projectile hole as can be seen in Figure 4.57(b) [34, 35, 36]. Moreover, in Figure 4.57(c) the plates also show signs of petalling and scabbing left-over surfaces at the exit point of the projectile hole [34]. The petalling at this point suggests a ductile mode of failure [34].

Figure 4.58(a) is the same SEI micrograph as shown in Figure 4.57(b) with a circled area for magnification. Figure 4.58(b) is a magnified micrograph of the circled area in Figure 4.58(a).

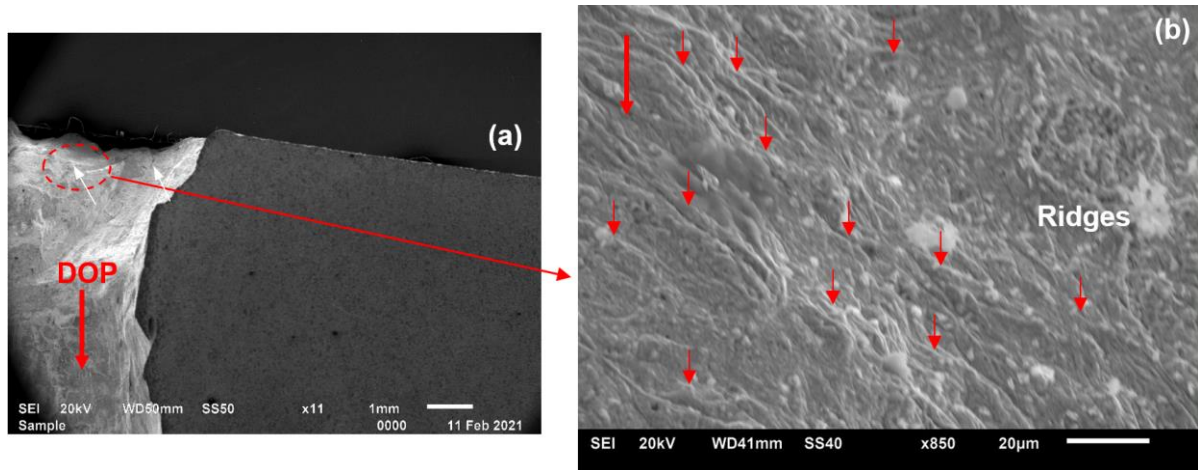


Figure 4.58: SEM SEI micrographs of a 10 mm thick plate projectile hole at (a) the entry point and (b) a magnified area at the entry point

From Figure 4.58(b), it can be seen that there are ridges at the entry point of the penetration hole. The ridges are a distinctive feature of brittle fracture and therefore suggests a brittle mode of failure at the entry point of the penetration hole [38, 39, 41].

Figure 4.59 is a SEI micrograph of the surface at the middle point of the penetration hole through a 10 mm thick plate.

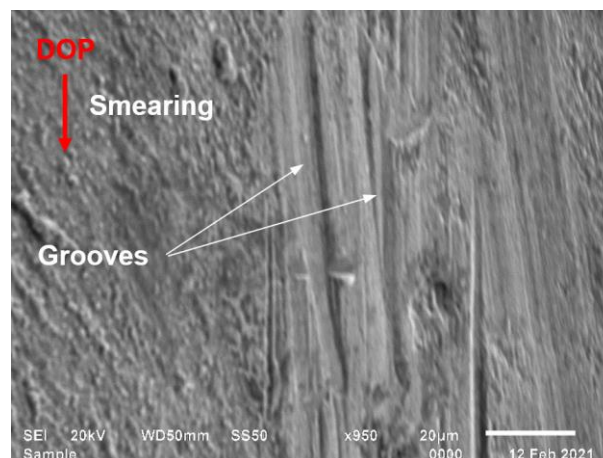


Figure 4.59: SEM SEI micrograph at the middle point of the penetration hole through a typical 10 mm thick plate

The fracture surface at the middle point of the penetration hole shows grooves and signs of smearing, both caused by the movement of the projectile through the metal, as can be seen in Figure 4.59 [42]. In such a case the lack of clear fracture features makes it impossible to identify the fracture mode [43, 44].

Figure 4.60(a) is the same SEI micrograph shown in Figure 4.57(c) with a circled area for magnification. Figure 4.60(b) is a magnified micrograph of the circled area in Figure 4.59(a).

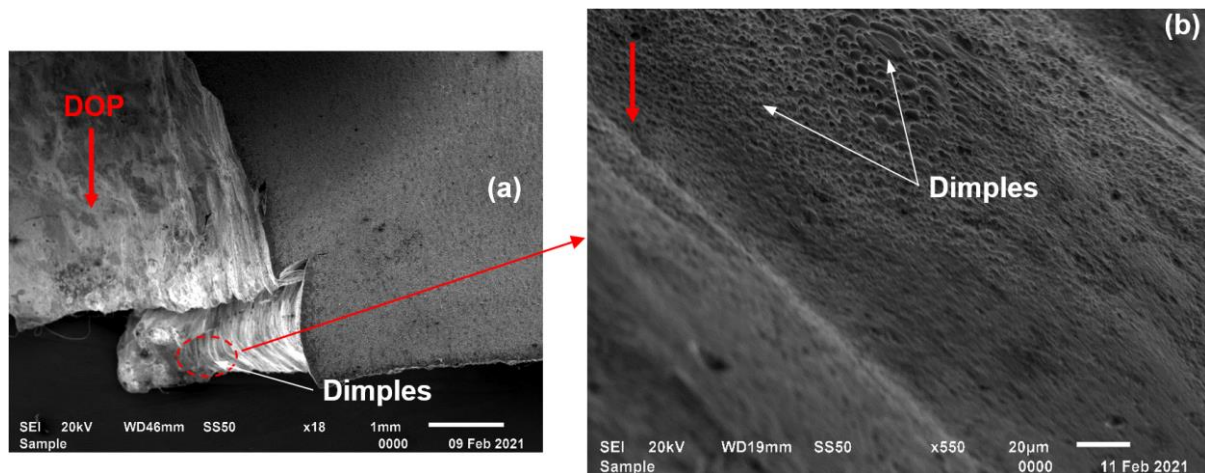


Figure 4.60: SEM SEI micrographs of a 10 mm thick plate projectile hole at (a) the exit point and (b) a magnified area at the exit point

Similar to the 8 mm thick plates, the fracture surface at the exit point of the projectile hole through the 12 mm thick plate primarily showed dimples as can be seen in Figure 4.60(b). The dimples here, together with clear signs of petalling are both an indication of a ductile mode of failure [39, 40, 42].

4.10.3. Fractography of DMLS 12 mm thick plates

Figure 4.61(a) and (c) are SEI micrographs of the surfaces at the entry and exit points of a penetration hole through a 12 mm thick plate, respectively. Figure 4.61(b) and (d) are higher magnification areas at the edge of the entry and exit points of the projectile hole, respectively.

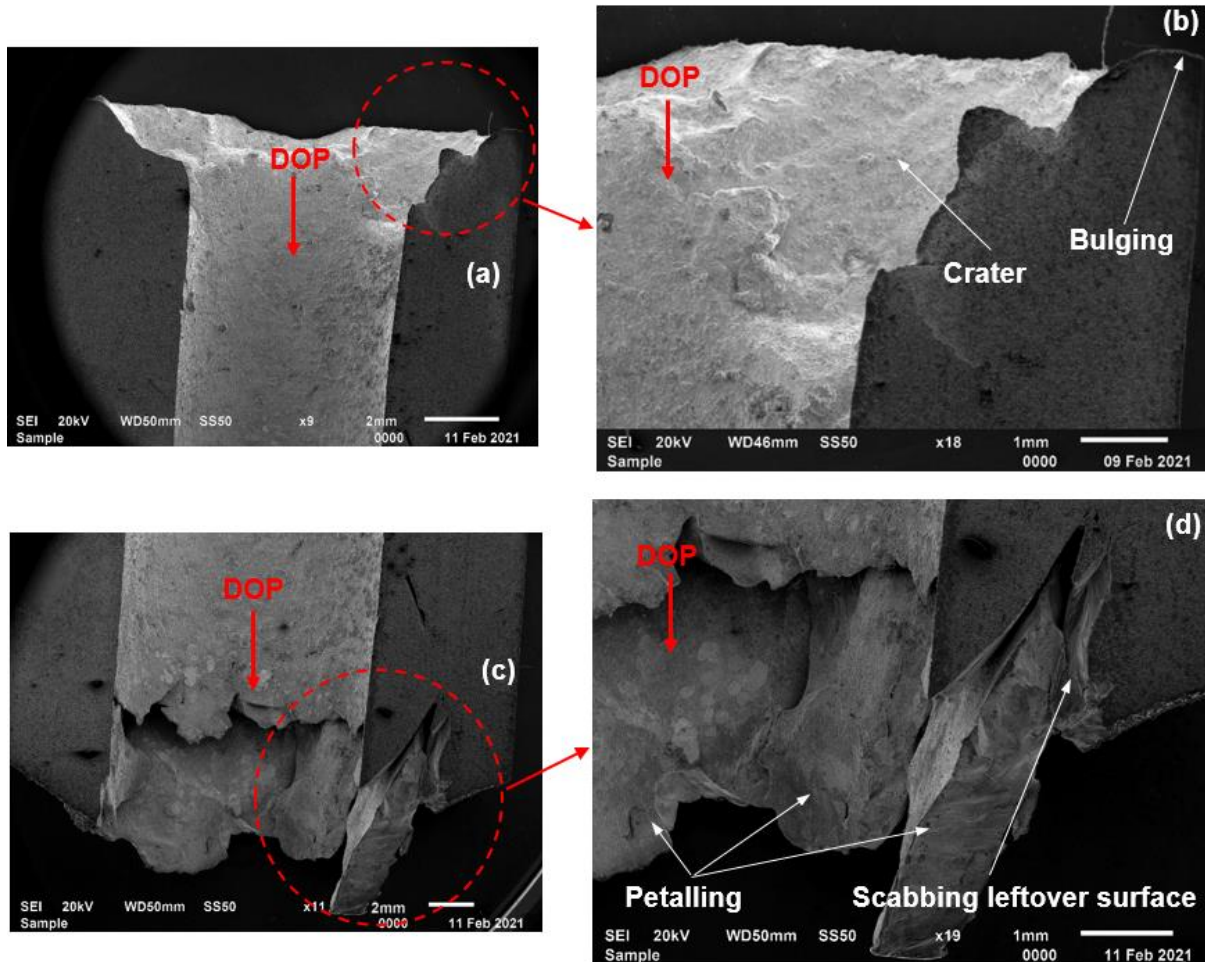


Figure 4.61: SEM SEI micrographs of a 12 mm thick plate projectile hole at (a) the entry point; (b) a magnified area at the edge of the entry point; (c) the exit point and (d) a magnified area at the edge of the exit point

Similar to the 8 mm and 10 mm thick plates, the 12 mm thick plates show bulging and formation of a crater at the entry point of the projectile hole as can be seen in Figure 4.61(b) [34, 35, 36]. Additionally, in Figure 4.61(d) the plates show petalling and a scabbing left over surface at the exit point of the projectile hole [34].

Figure 4.62(a) is the same SEI micrograph as shown in Figure 4.61(b) with a circled area for magnification. Figure 4.62(b) is a magnified micrograph of the circled area in Figure 4.62(a).

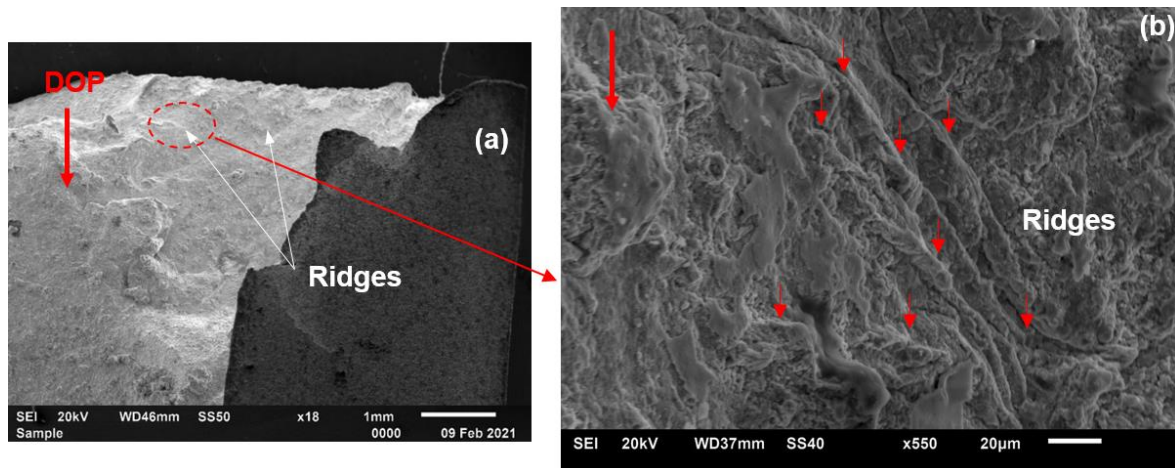


Figure 4.62: SEM SEI micrographs of a 12 mm thick plate projectile hole at (a) the exit point and (b) a magnified area at the exit point

Figure 4.62(b) shows a fracture surface with ridges at the entry point of the penetration hole. The ridges are consistent with brittle fracture and therefore confirms a brittle failure at the entry point of the penetration hole [38, 39, 41].

Figure 4.63 is a SEI micrograph of the surface at the middle point of the penetration hole through a 12 mm thick plate.

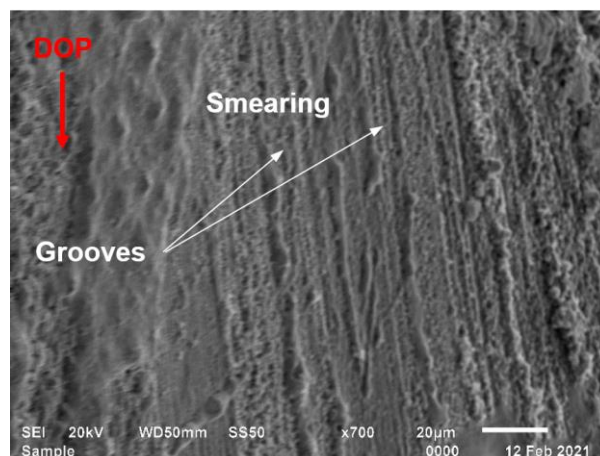


Figure 4.63: SEM SEI micrograph at the middle point of the penetration hole through a 12 mm thick plate

Similar to the 10 mm thick plates, the surface at the middle point of the penetration hole through the 12 mm thick plates shows grooves and signs of smearing as can be seen in Figure 4.63 [42]. In such a case the lack of clear fracture features makes it impossible to identify the mode of failure [43, 44].

Figure 4.64(a) is the same SEI micrograph as shown in Figure 4.61(d) with a circled area for magnification. Figure 4.64(b) is a magnified micrograph of the circled area in Figure 4.64(a).

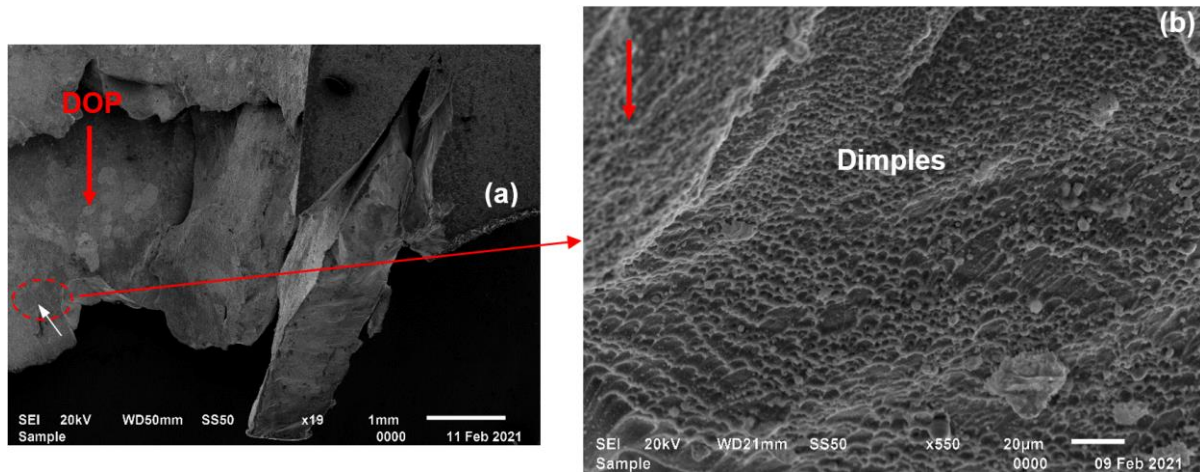


Figure 4.64: SEM SEI micrographs of a 12 mm thick plate projectile hole at (a) the exit point and (b) a magnified area at the exit point

The 12 mm thick plates also exhibit ductile fracture at the exit point of the projectile hole. This observation is substantiated by the dimples and petals seen on the micrographs in Figure 4.64(b) and Figure 4.61(d), respectively [39, 40, 42].

4.10.4. Fractography of DMLS 14 mm thick plates

Figure 4.65(a) and (c) are SEI micrographs of the surfaces at the entry and exit points of a penetration hole through a 14 mm thick plate, respectively. Figure 4.65(b) and (d) are enlarged areas at the edge of the entry and exit points of the projectile hole, respectively.

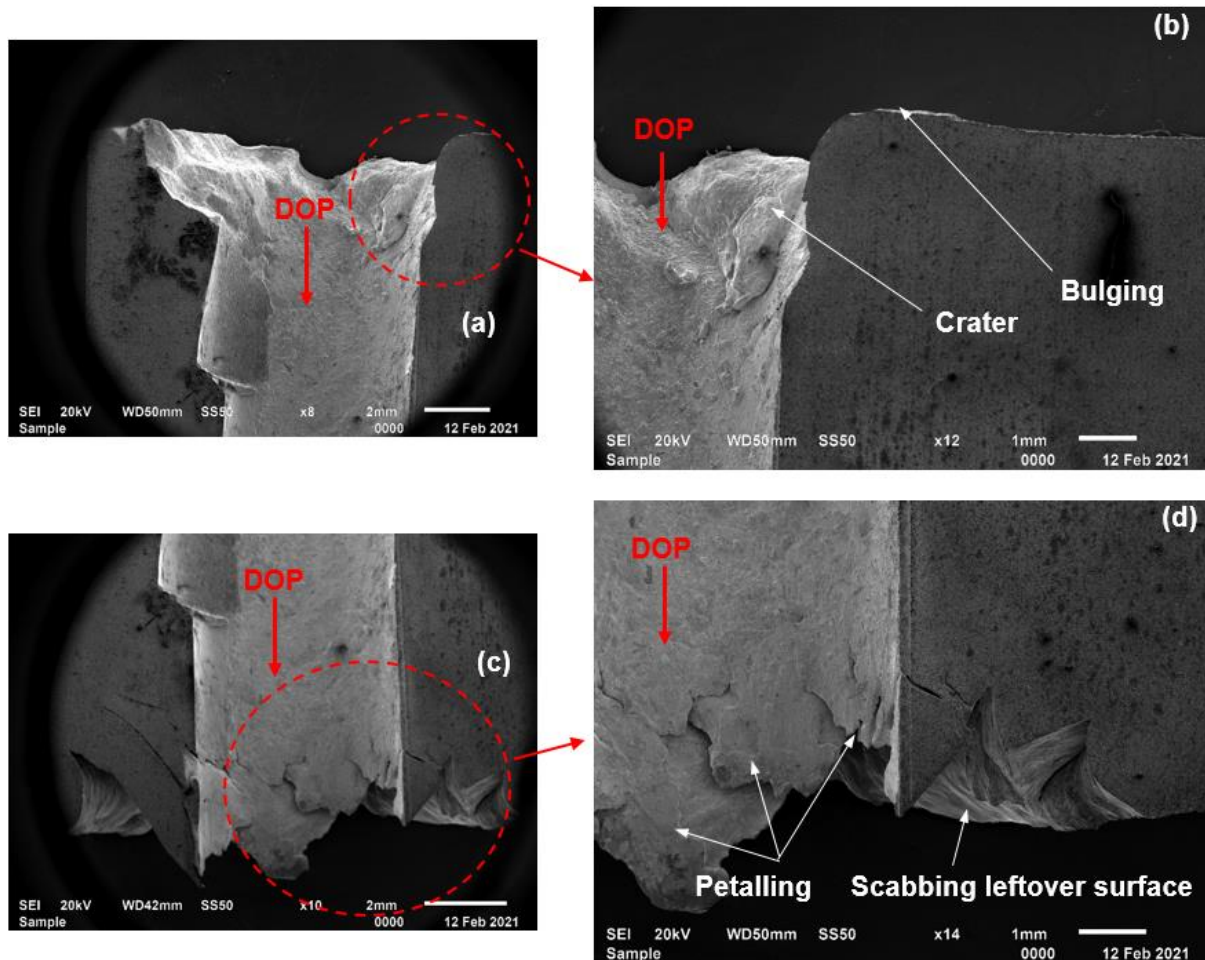


Figure 4.65: SEM SEI micrographs of a 14 mm thick plate projectile hole at (a) the entry point; (b) a magnified area at the edge of the entry point; (c) the exit point and (d) a magnified area at the edge of the exit point

The 14 mm thick plates also show bulging and formation of a crater at the entry point of the projectile hole as can be seen in Figure 4.65(b) [34, 35, 36]. In addition, the plates also show petalling and scabbing left-over surfaces at the exit point of the projectile hole as can be seen in Figure 4.65(d) [34].

Figure 4.66(a) is the same SEI micrograph as shown in Figure 4.65(a) with a circled area for magnification. Figure 4.66(b) is a magnified micrograph of the circled area in Figure 4.66(a).

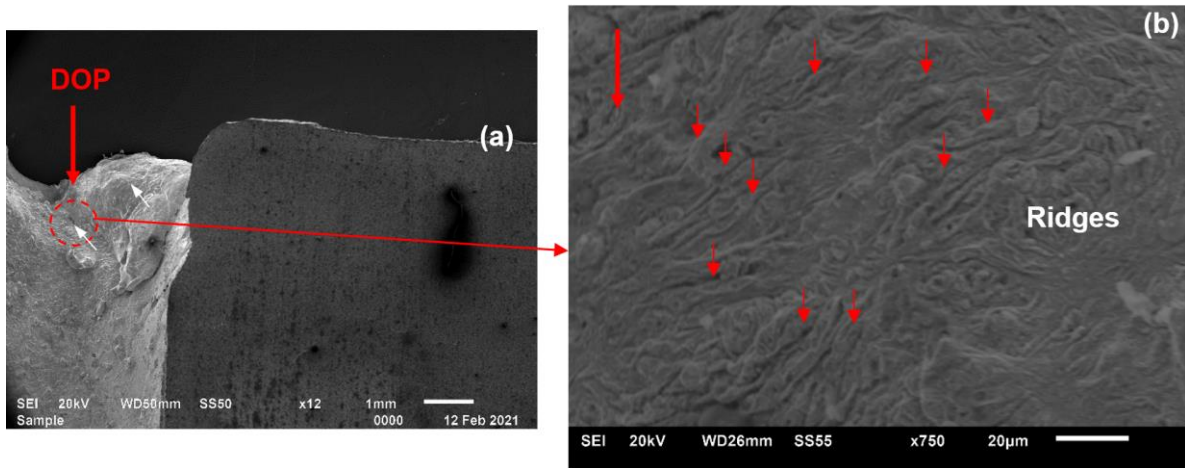


Figure 4.66: SEM SEI micrographs of a 14 mm thick plate projectile hole at (a) the entry point and (b) a magnified area at the entry point

The ridges noticed on the fracture surface at the entry point of the projectile hole shown in Figure 4.66(b) is evidence of a brittle fracture [38, 39, 41].

Figure 4.67 is a SEI micrograph of the surface at the middle point of the penetration hole through a 14 mm thick plate.

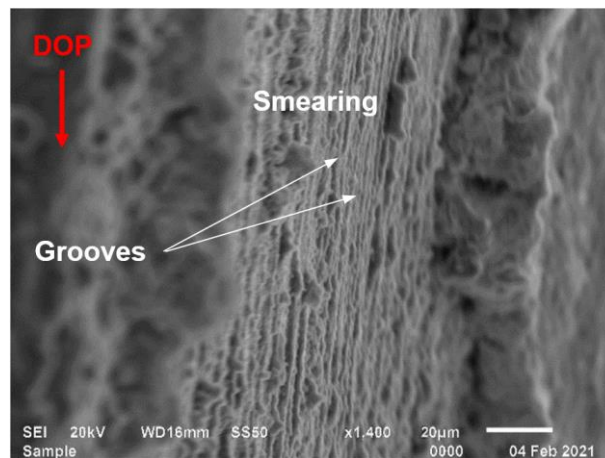


Figure 4.67: SEM SEI micrograph at the middle point of the penetration hole through a 14 mm thick plate

At the middle point of the penetration hole through the 14 mm thick plates the fracture surface shows grooves and signs of smearing as can be seen in Figure 4.67 [42].

Figure 4.68(a) is the same micrograph shown in Figure 4.65(c) with a circled area for magnification. Figure 4.68(b) is a higher magnification micrograph of the circled area in Figure 4.68(a).

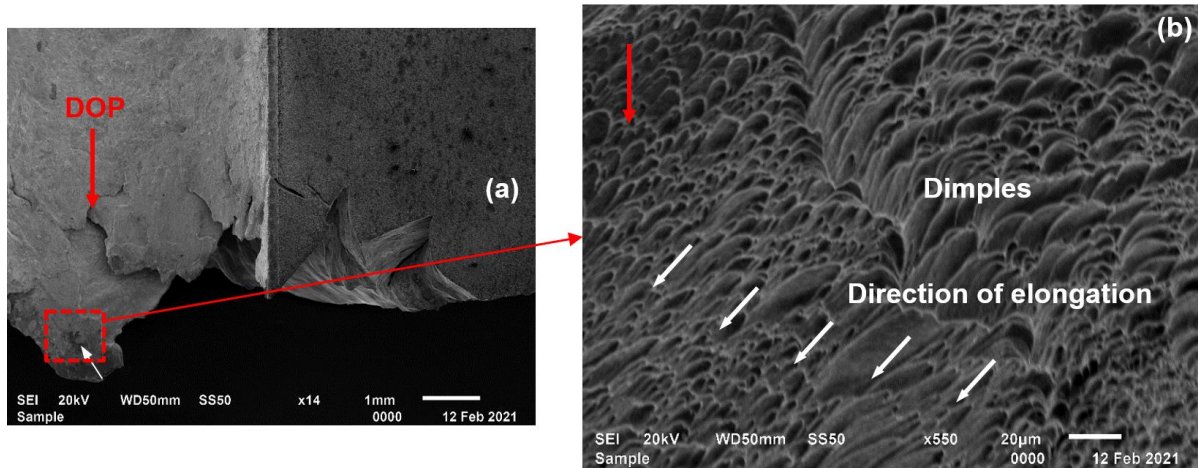


Figure 4.68: SEM SEI micrographs a 14 mm thick plate projectile hole at (a) the exit point and (b) a magnified area at the exit point

The 14 mm thick plates show a surface fracture with elongated dimples at the exit point of the projectile hole. The direction of elongation of the dimples, points to the direction of shear failure of the material in this area. The surface fracture with dimples coupled together with the formation of petals noted in Figure 4.65(d) suggest a ductile mode of failure [39, 40, 42].

All the micrographs at the entry points of the penetration holes through all the plate thicknesses exhibit a predominance of ridges, which indicates/confirms brittle fracture [38, 39, 41].

Similar to the tested wrought Ti6Al4V, at the middle points of the penetration holes through all the DMLS plates, the fracture surfaces lacked clearly defined fracture features. It is not possible in such a case to determine the prevailing mode of fracture of the material in these areas. The fracture surfaces show grooves and smearing, which can be attributed to the friction effect of the projectile as it moves through the material [38, 43, 44].

At the exit points of the penetration holes through all the plate thicknesses, the micrographs exhibited a predominance of dimples. The dimples, together with the observed petalling of the 10 mm, 12 mm and 14 mm thick plates are an indication of

ductile failure [38, 39, 41]. Similar to the wrought Ti6Al4V, it is evident from Figure 4.56(b), Figure 4.60(b), Figure 4.64(b) and Figure 4.68(b), for the as-built and stress relieved DMLS Ti6Al4V (ELI) plates, that the dimples also become more pronounced with an increase in plate thickness. This is an indication of increased plastic deformation of the plates before failure with an increase in plate thickness.

4.11. Microstructural Analysis of High Velocity Ballistic Impacted As-built and Stress Relieved DMLS Ti6Al4V (ELI)

This section focuses on microstructural analyses of as-built and stress relieved DMLS Ti6Al4V (ELI) specimens a, b, c, d, e and f extracted from 8 mm, 10 mm, 12 mm and 14 mm thick plates as shown in Figure 3.11.

Similar to the wrought Ti6Al4V, the first set of micrographs were obtained for specimens a and b for all the plate thicknesses. The micrographs were obtained from the edge of the projectile hole and at distances of 2 mm, 4 mm and 6 mm from it, moving radially outwards, in order to investigate the change in microstructure with distance away from the penetration hole during impact. In this section, analysis of the micrographs was done visually. The visual analysis was done by comparing the α phase fraction (lighter areas) to the β phase fraction (dark lines) in the micrographs presented.

4.11.1. Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates near the edge of the projectile holes

Figures 4.69(a), (b) and (c), 4.70(a), (b) and (c), 4.71(a), (b) and (c) and 4.72(a), (b) and (c) are optical micrographs near the edge of the projectile holes through 8 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

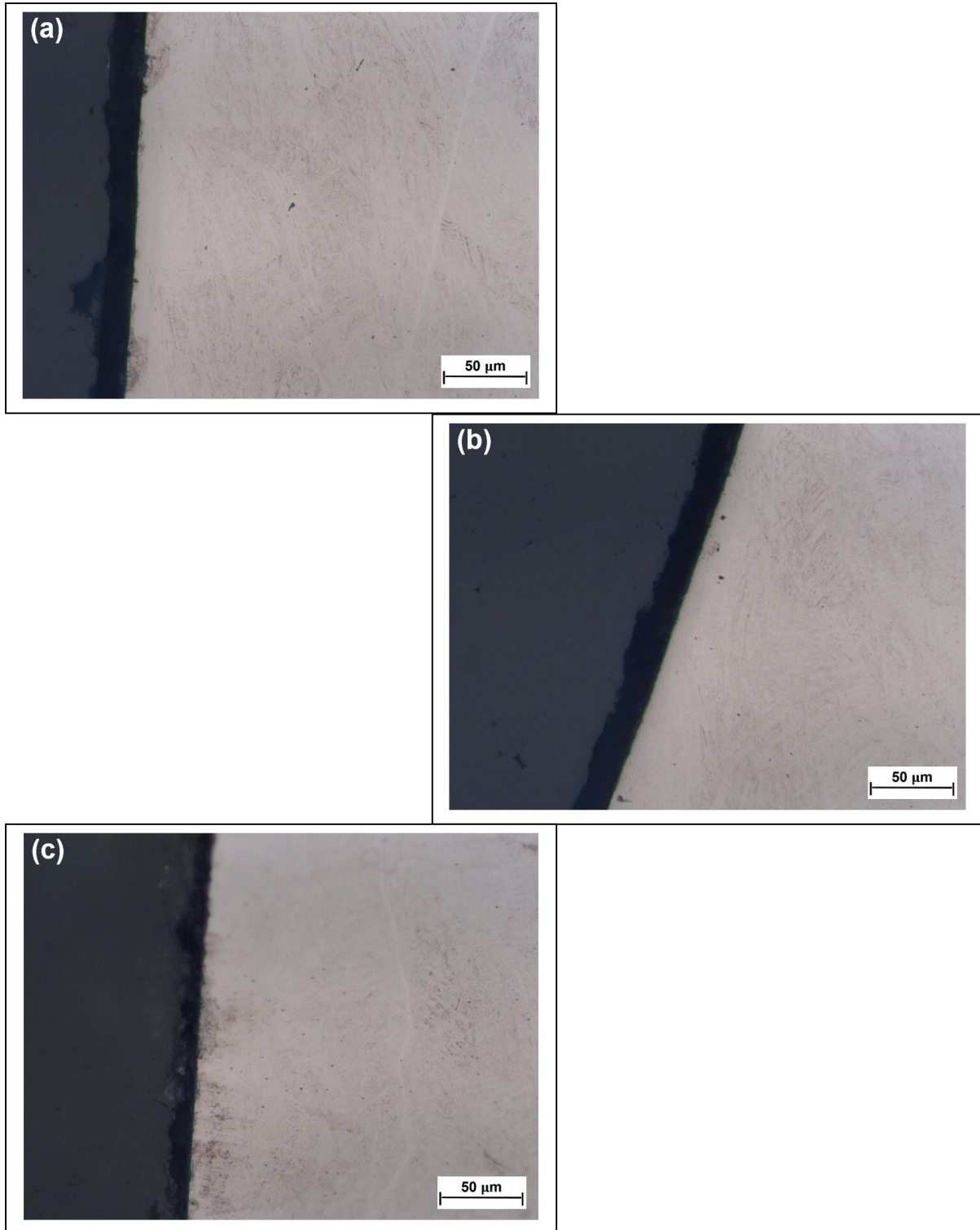


Figure 4.69: Optical micrographs near the edge of the projectile holes through the 8 mm thick as-built and stress relieved plates

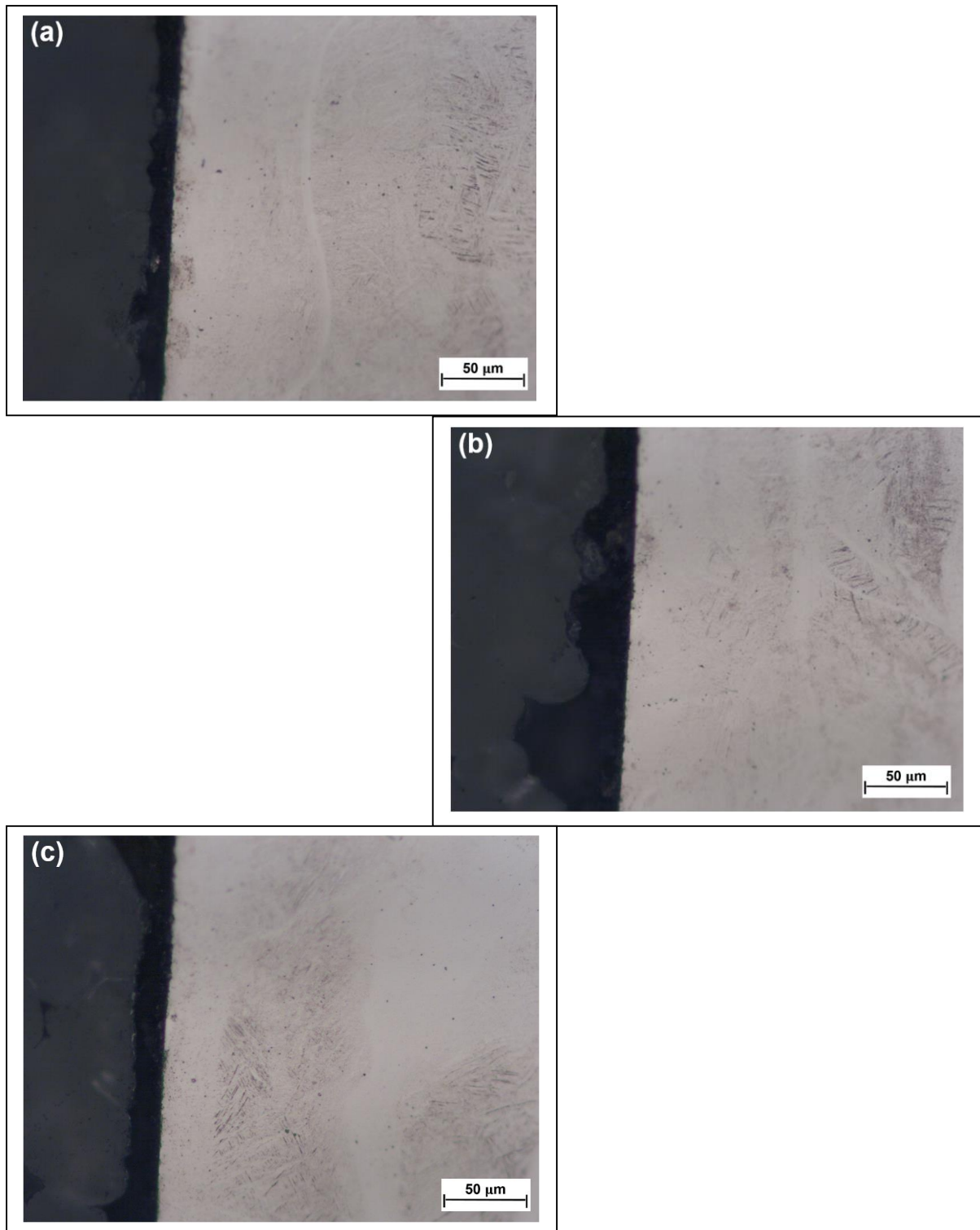


Figure 4.70: Optical micrographs near the edge of the projectile holes through the 10 mm thick as-built and stress relieved plates

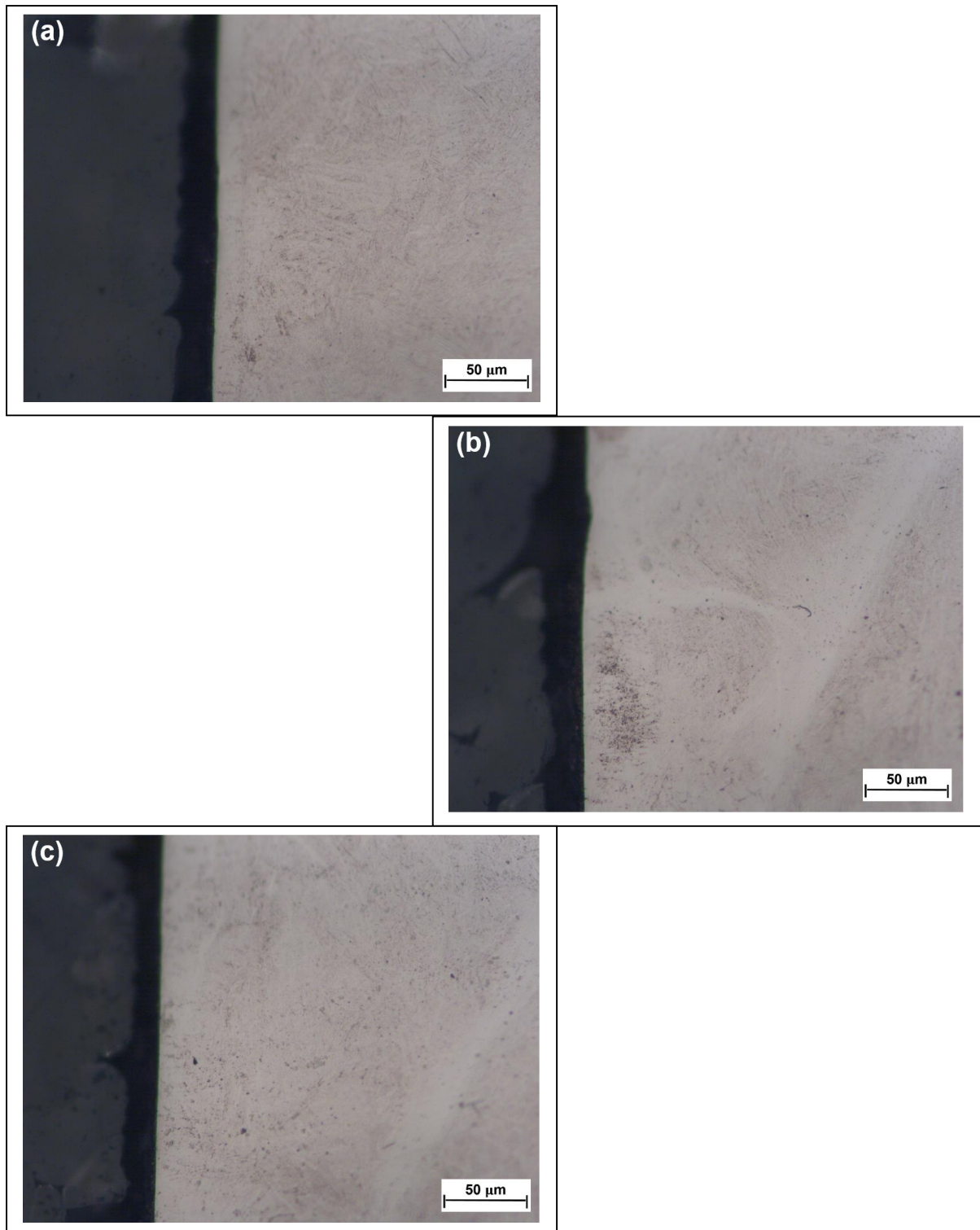


Figure 4.71: Optical micrographs near the edge of the projectile holes through the 12 mm thick as-built and stress relieved plates

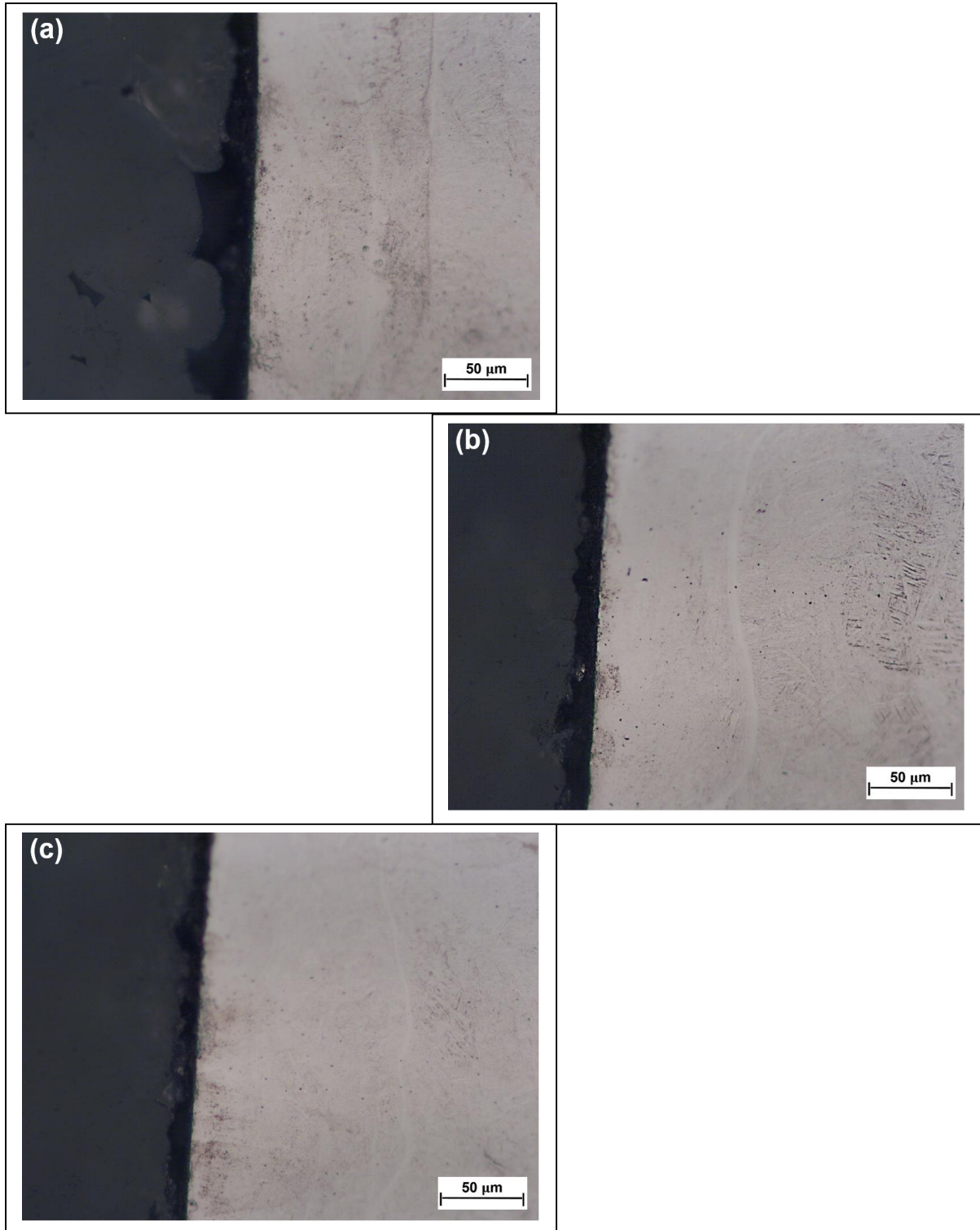


Figure 4.72: Optical micrographs near the edge of the projectile holes through the 14 mm thick as-built and stress relieved plates

Based on the similarities of the microstructure of all the plate thicknesses in Figure 4.69 up to Figure 4.72, their key features were examined based on a plate of 10 mm thickness, selected randomly.

Figure 4.73(a) is an optical micrograph, (b) and (c) are higher magnification optical micrographs, all near the edge of the projectile hole through a plate of 10 mm thickness. It should be noted that (b) and (c) are higher magnification micrographs of (a). It is seen from the diagram immediately above these micrographs that the projectile hole was filled with multifast resin ahead of scanning with an optical microscope. The red dots in this diagram show the locations at which observations were carried out on each specimen, with distances indicated relative to the edge of the projectile hole.

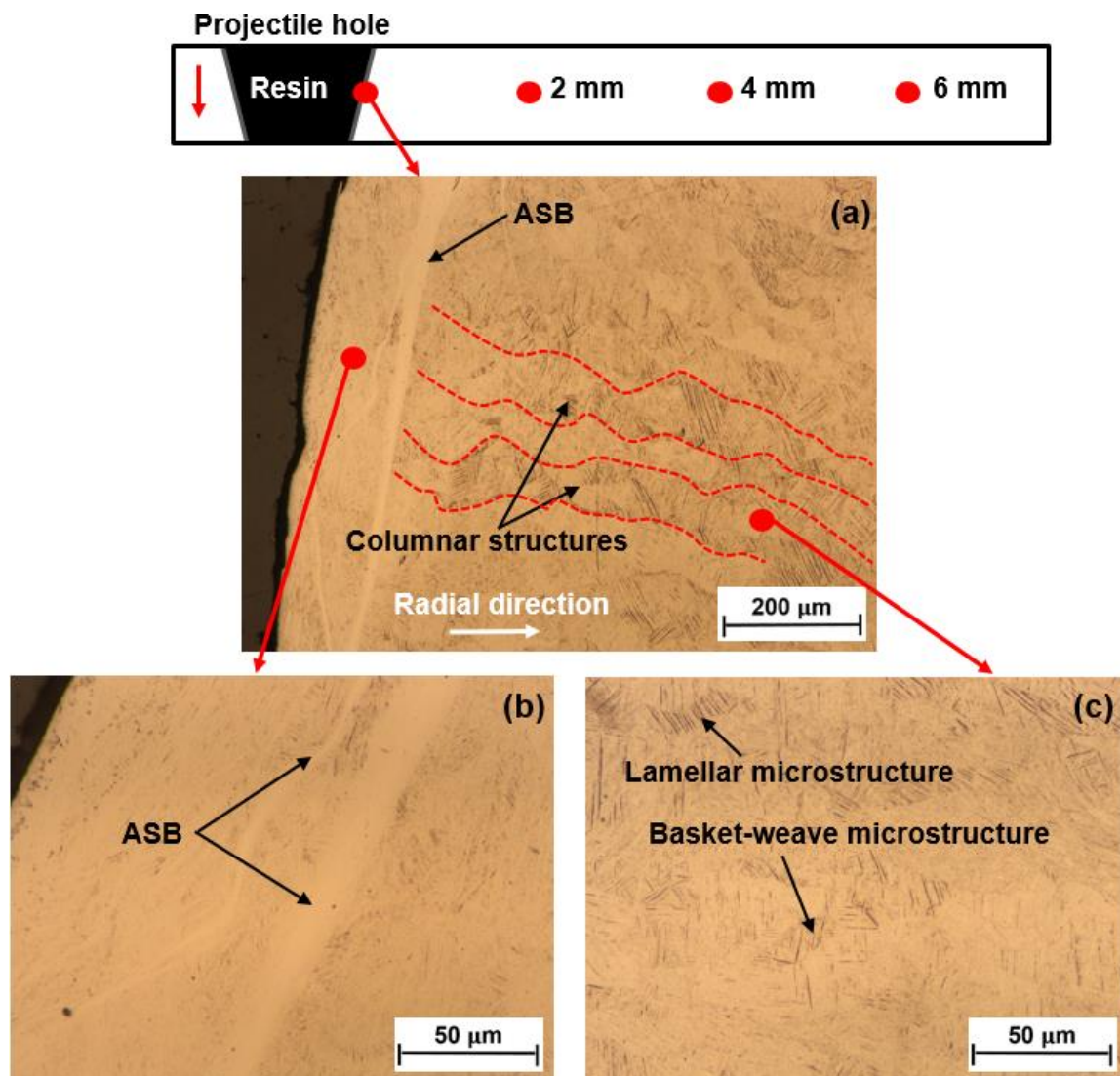


Figure 4.73: (a) Optical micrograph, (b) and (c) magnified optical micrographs, all near the edge of the projectile hole through a 10 mm thick plate

From Figure 4.73(a) and (b) it can be seen that near the edge of the projectile hole, there is a network of adiabatic shear bands (ASBs) [47, 48].

The ASBs appear to run more or less along the edge of penetration hole. There is a narrow ASB that is nearer the edge of the penetration hole and runs at angle to the edge of the penetration hole for part of its length and then joins the large ASB located further away from the edge of the penetration hole. The inclined ASB is consistent with shear failure of materials along the directions of maximum shear that are inclined to the directions of principal stresses [47, 54]. On the other hand, the ABS that is parallel to the direction of penetration can be attributed to tensile fracture as a function of induced circumferential tensile stress parallel to the circumference of the penetration hole, hence this orientation [47, 54].

In Figure 4.73(a) and (c), on the right of the large ASB, it can be seen that the microstructure is comprised of a combination of lamellae and basket-weave microstructure within columnar structures [49, 50]. The columnar structures are aligned in the radial direction, which is the direction of induced tensile stress waves [50, 51].

4.11.2. Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates at a distance of 2 mm from the edge of the projectile holes

Figures 4.74(a), (b) and (c), 4.75(a), (b) and (c), 4.76(a), (b) and (c) and 4.77(a), (b) and (c) are optical micrographs at a distance of 2 mm from the edge of projectile holes through each one of the three 8 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

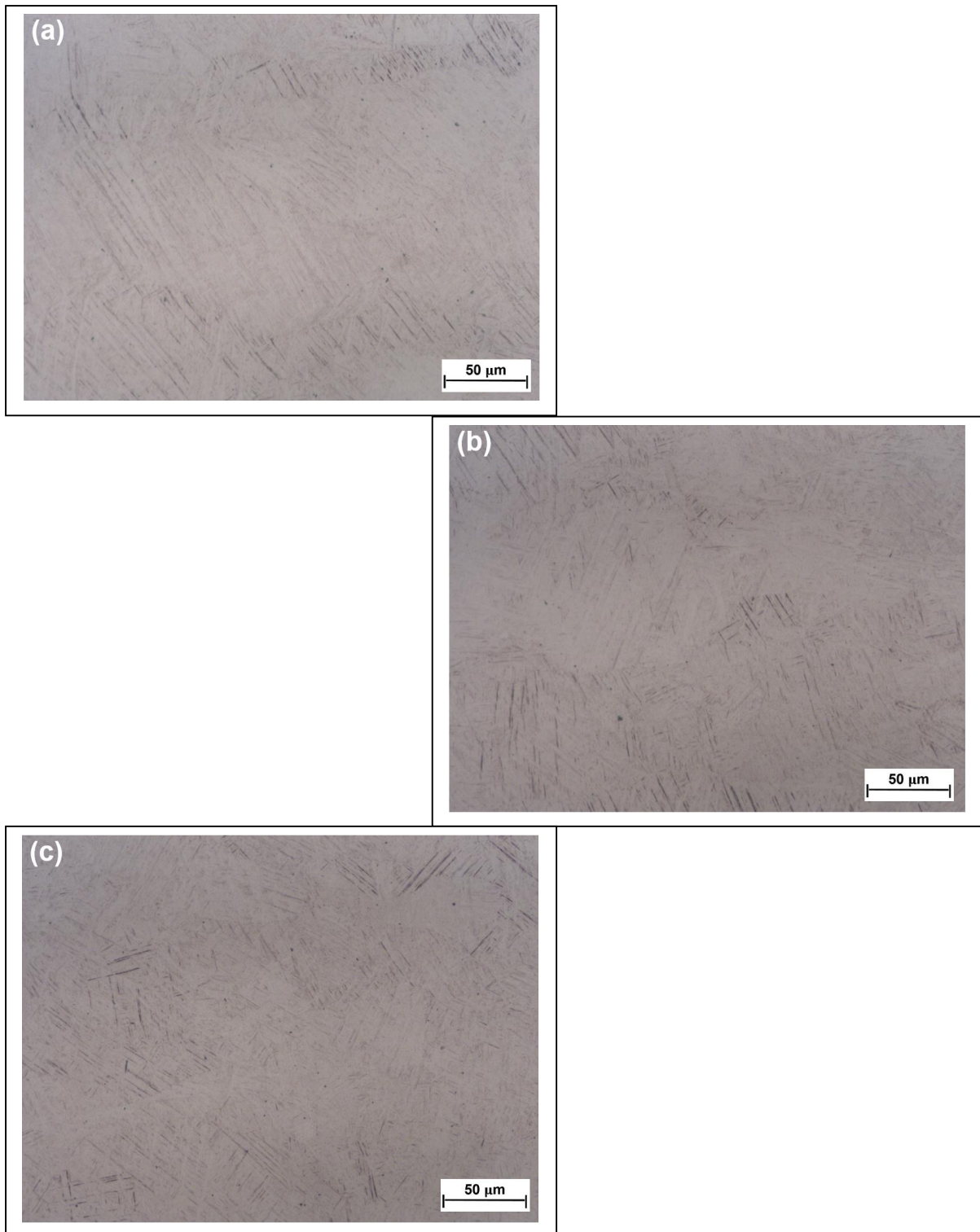


Figure 4.74: Optical micrographs at a distance of 2 mm from the edge of the projectile holes through the 6 mm thick plates

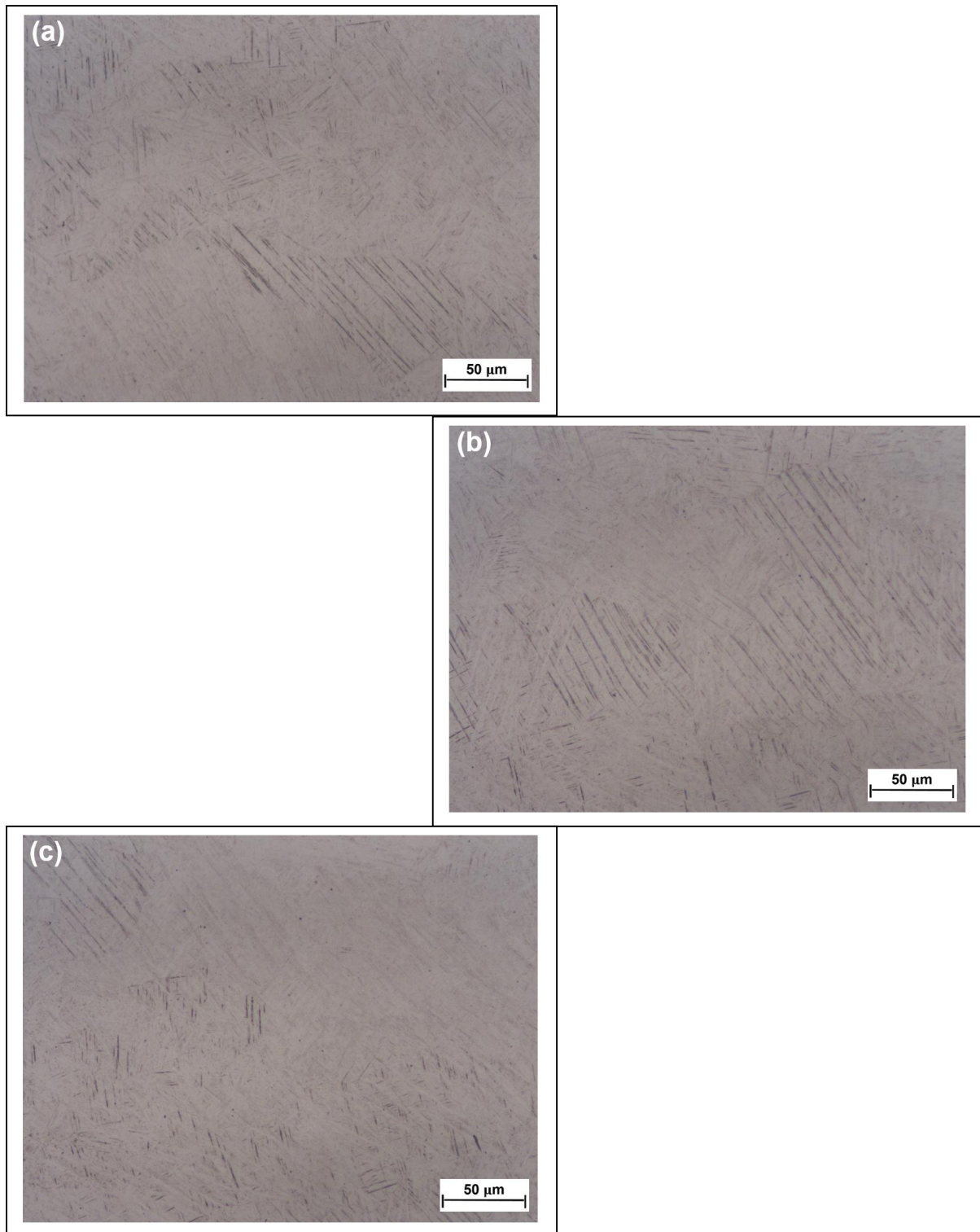


Figure 4.75: Optical micrographs at a distance of 2 mm from the edge of the projectile holes through the 10 mm thick plates

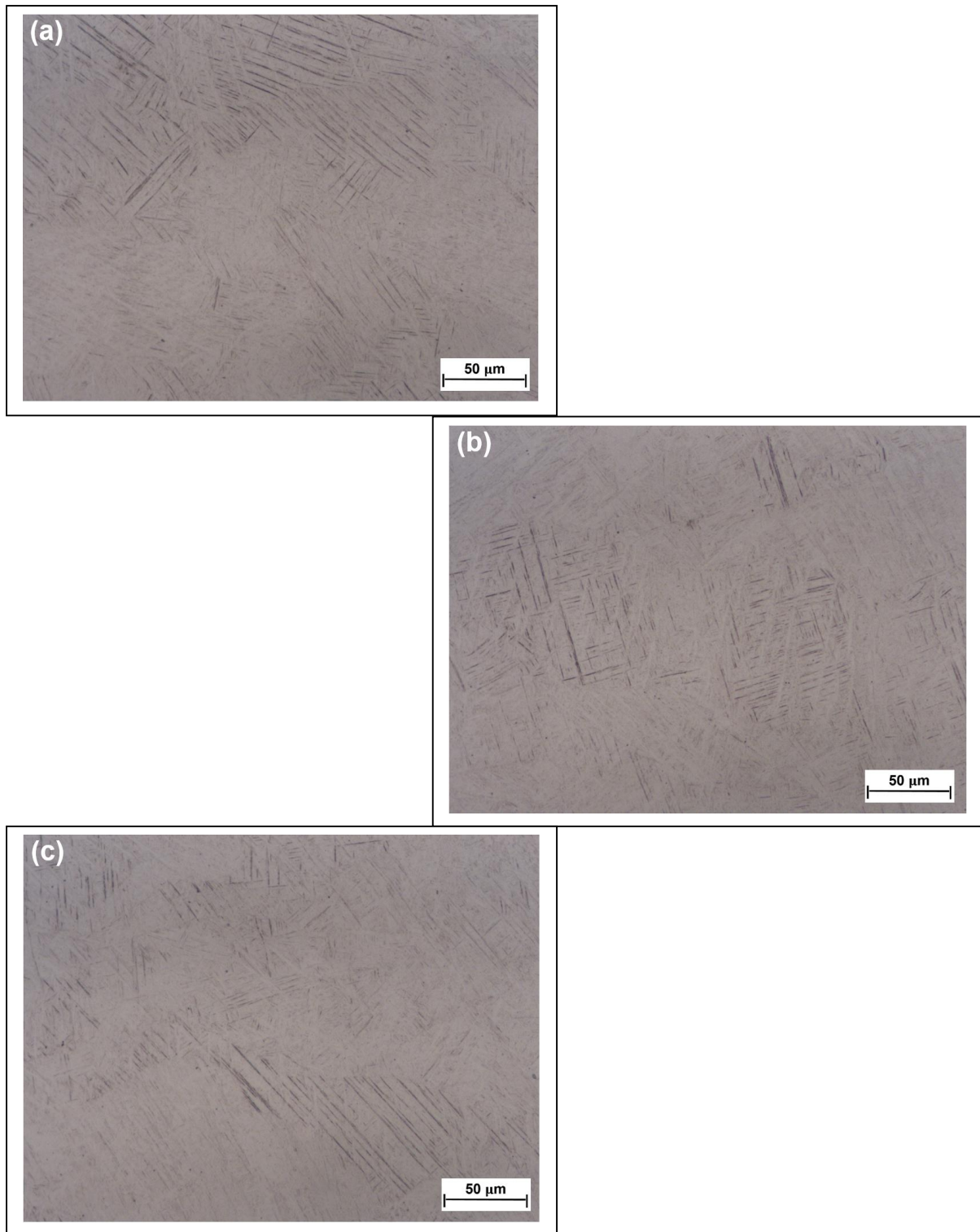


Figure 4.76: Optical micrographs at a distance of 2 mm from the edge of the projectile holes through the 12 mm thick plates

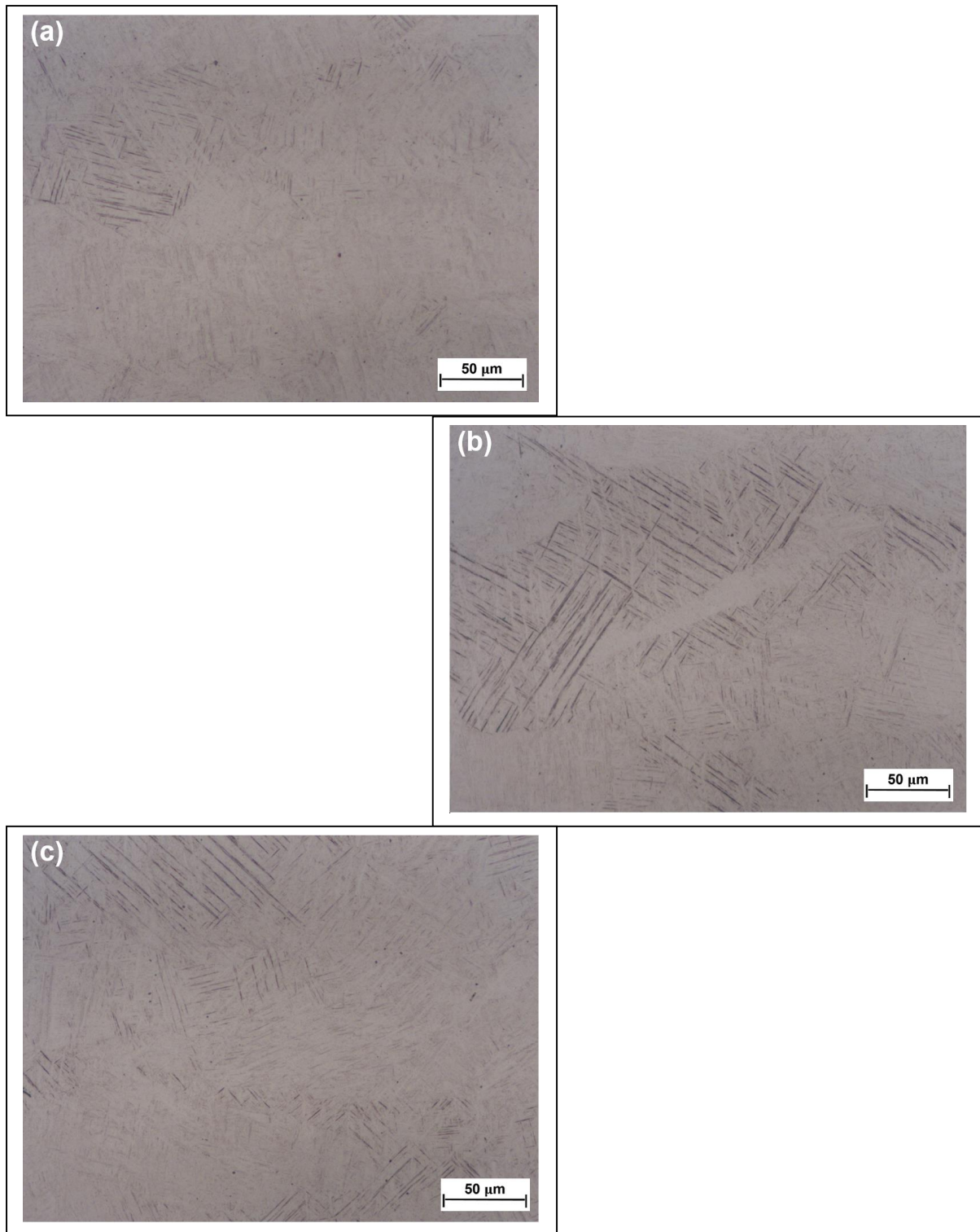


Figure 4.77: Optical micrographs at a distance of 2 mm from the edge of the projectile holes through the 14 mm thick plates

Based on similarities of the microstructure of all the plate thicknesses at a distance of 2 mm from the edge of the projectile hole seen in Figure 4.74 up to Figure 4.77,

the key features here were be examined based on a plate of 10 mm thickness, selected randomly.

Figure 4.78(a) is an optical micrograph and (b) a magnified optical micrograph, both at a distance of 2 mm from the edge of the projectile hole through a plate of 10 mm thickness.

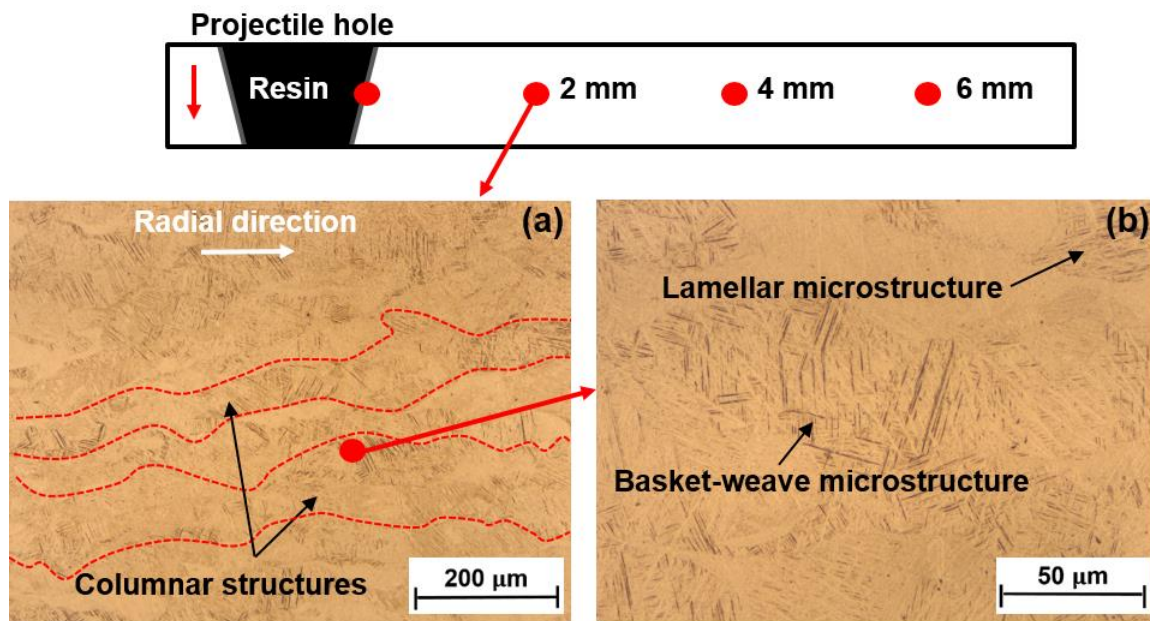


Figure 4.78: (a) Optical micrograph and (b) magnified optical micrograph, both at a distance of 2 mm from the edge of the projectile hole through a 10 mm thick plate

From Figure 4.78(a) and (b), it can be seen that at a distance of 2 mm from the edge of the projectile hole, the microstructure is also comprised of a combination of lamellae and basket-weave microstructure within columnar structures [49, 50].

4.11.3. Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates at a distance of 4 mm from the edge of the projectile holes

Figures 4.79(a), (b) and (c), 4.80(a), (b) and (c), 4.81(a), (b) and (c) and 4.82(a), (b) and (c) are optical micrographs at a distance of 4 mm from the edge of projectile holes through each one of the three 8 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.



Figure 4.79: Optical micrographs at a distance of 4 mm from the edge of the projectile holes through the 8 mm thick plates

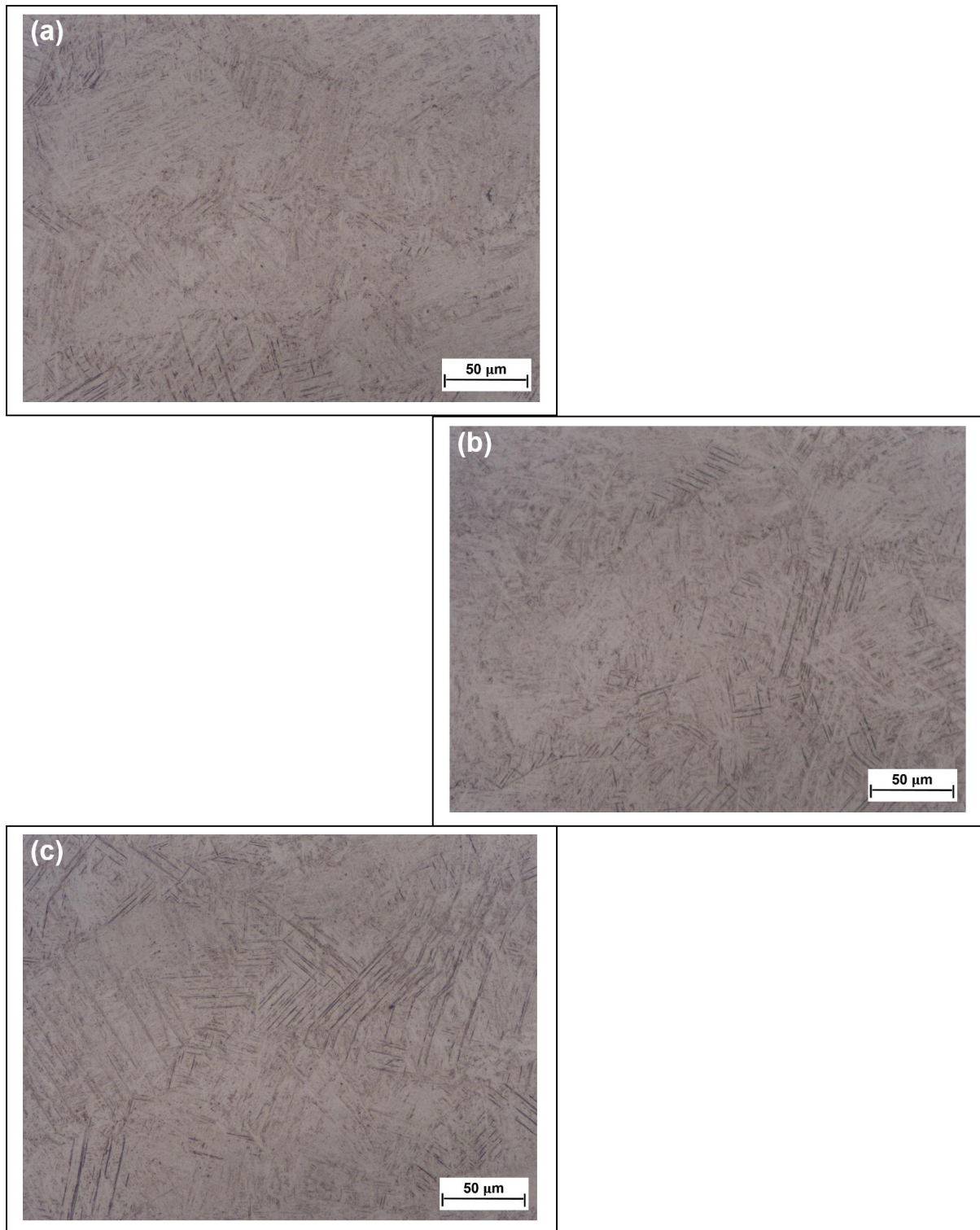


Figure 4.80: Optical micrographs at a distance of 4 mm from the edge of the projectile holes through the 10 mm thick plates

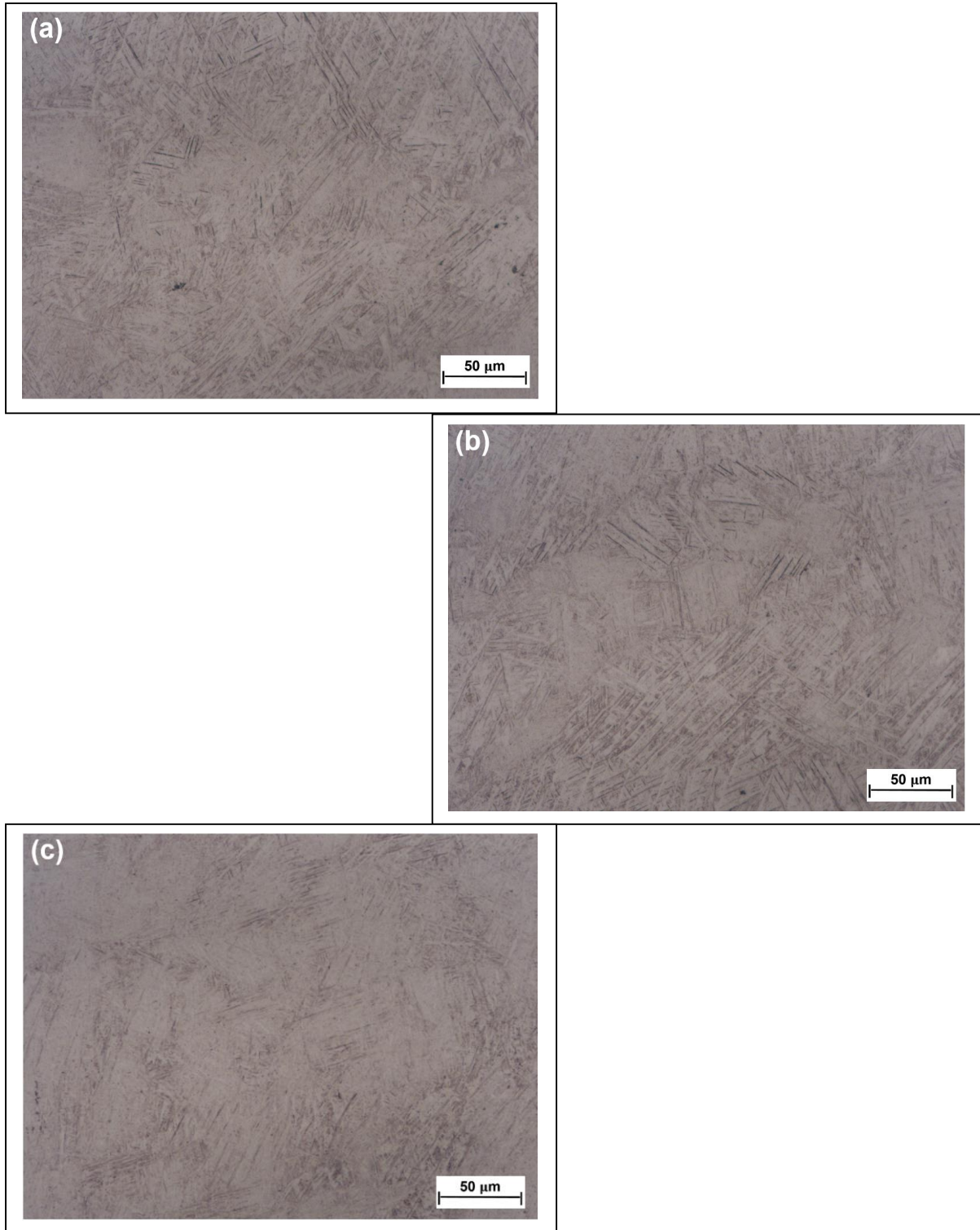


Figure 4.81: Optical micrographs at a distance of 4 mm from the edge of the projectile holes through the 12 mm thick plates

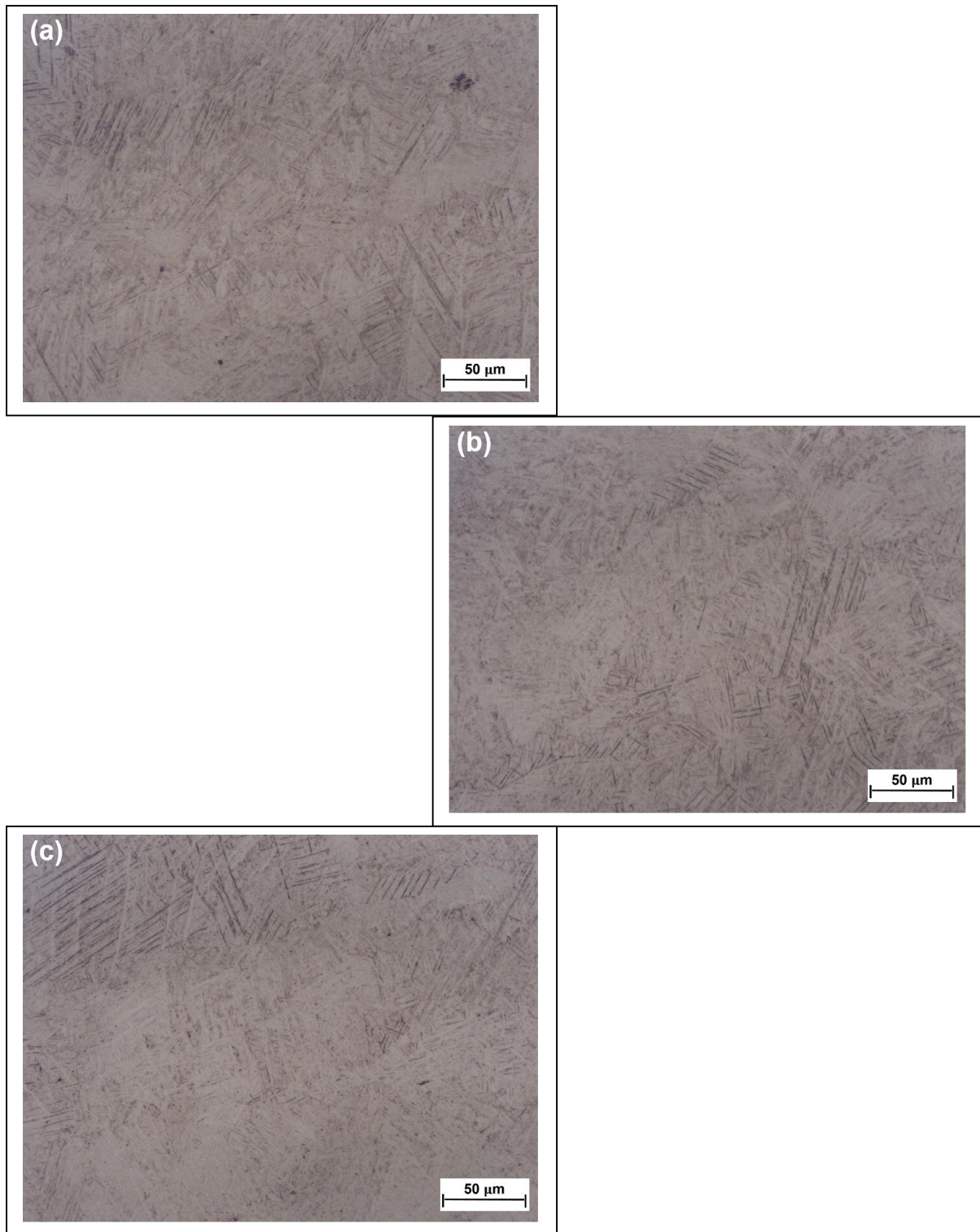


Figure 4.82: Optical micrographs at a distance of 4 mm from the edge of the projectile holes through the 14 mm thick plates

Based on similarities of the microstructure of all the plate thicknesses at a distance of 4 mm from the edge of the projectile holes seen in Figure 4.79 up to Figure 4.82, the key features here were be examined based on a plate of 10 mm thickness,

selected randomly. Figure 4.83(a) is an optical micrograph and (b) a magnified optical micrograph, both at a distance of 4 mm from the edge of the projectile hole through a plate of 10 mm thickness.

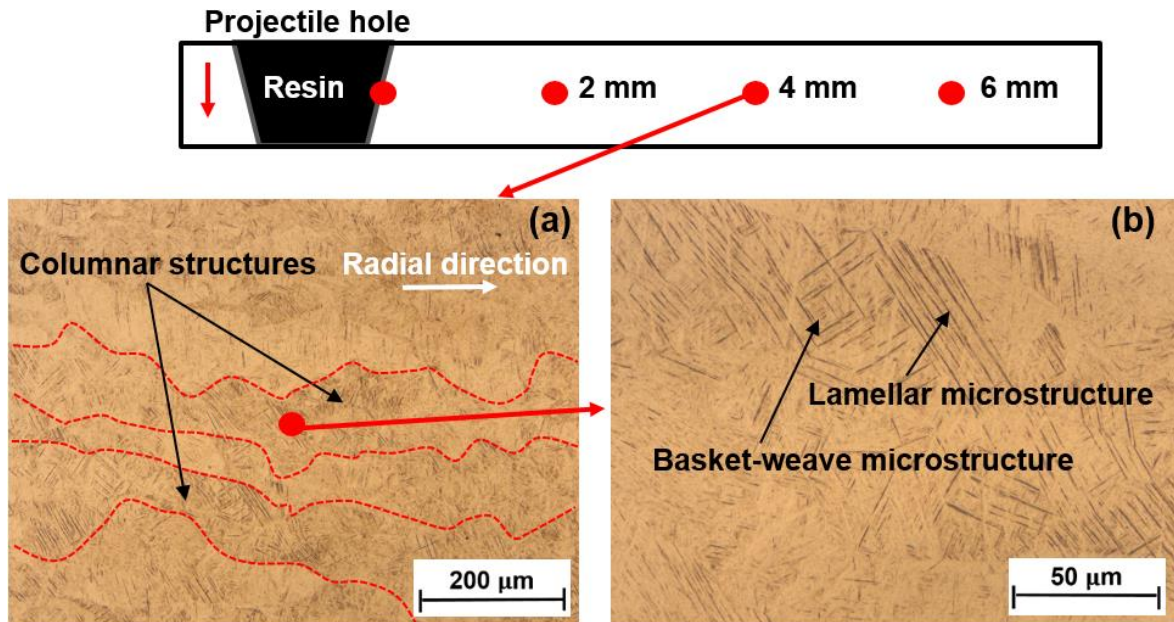


Figure 4.83: (a) Optical micrograph and (b) magnified optical micrograph, both at a distance of 4 mm from the edge of the projectile hole through a 10 mm thick plate

From Figure 4.83(a) and (b), it can be seen that at a distance of 4 mm from the edge of the projectile hole, the microstructure is comprised of a combination of lamellae and basket-weave microstructure within columnar structures [49, 50].

The α phase here is more in content than in the previous micrographs at a distance of 2 mm from and near the edge of the projectile hole. The reason for this is the lower heating effect with distance radially away from the edge of the projectile hole.

4.11.4. Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates at a distance of 6 mm from the edge of the projectile holes

Figures 4.84(a), (b) and (c), 4.85(a), (b) and (c), 4.86(a), (b) and (c) and 4.87(a), (b) and (c) are optical micrographs at a distance of 6 mm from the edge of the projectile holes through each one of the three 8 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

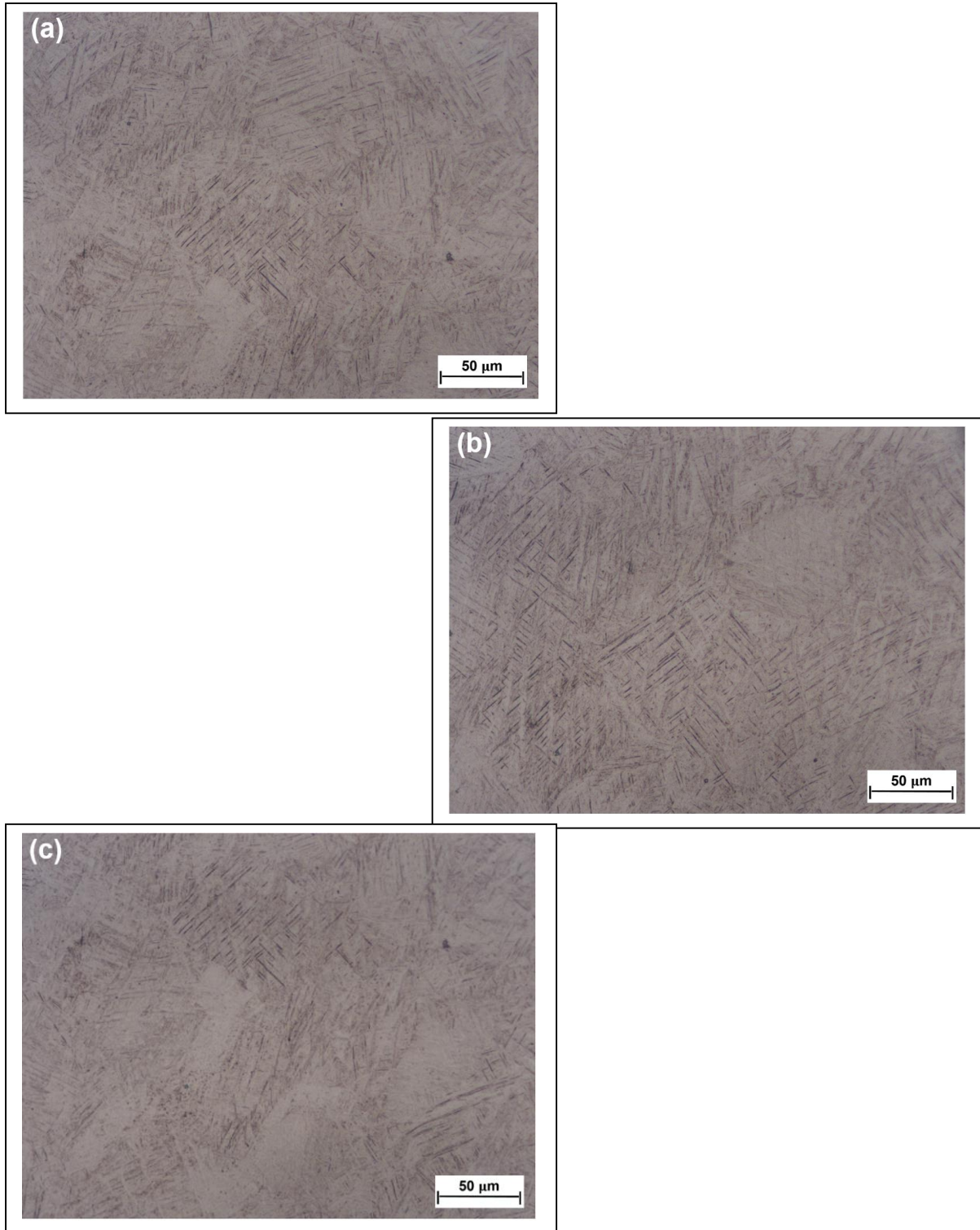


Figure 4.84: Optical micrographs at a distance of 6 mm from the edge of the projectile holes through the 8 mm thick plates

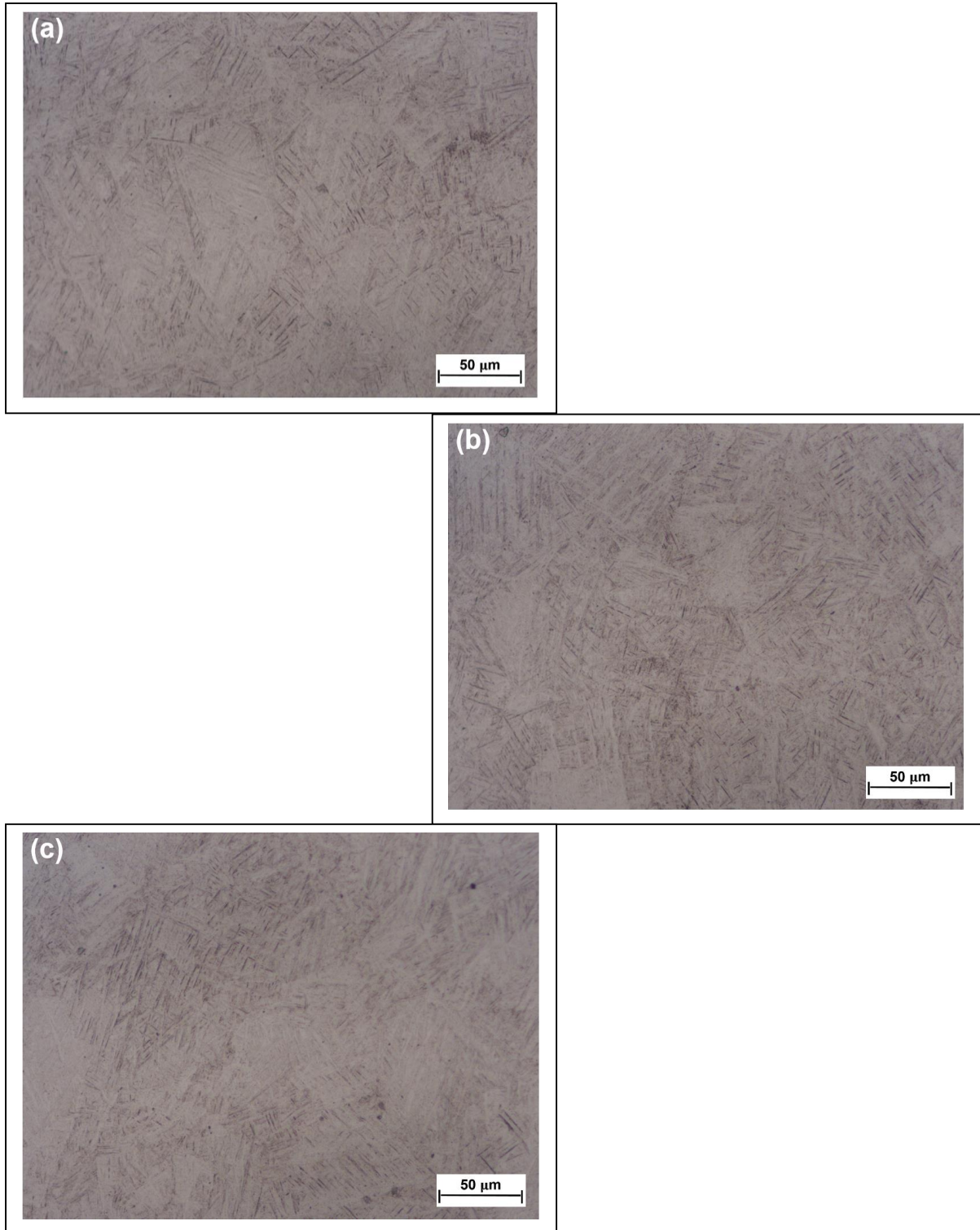


Figure 4.85: Optical micrographs at a distance of 6 mm from the edge of the projectile holes through the 10 mm thick plates

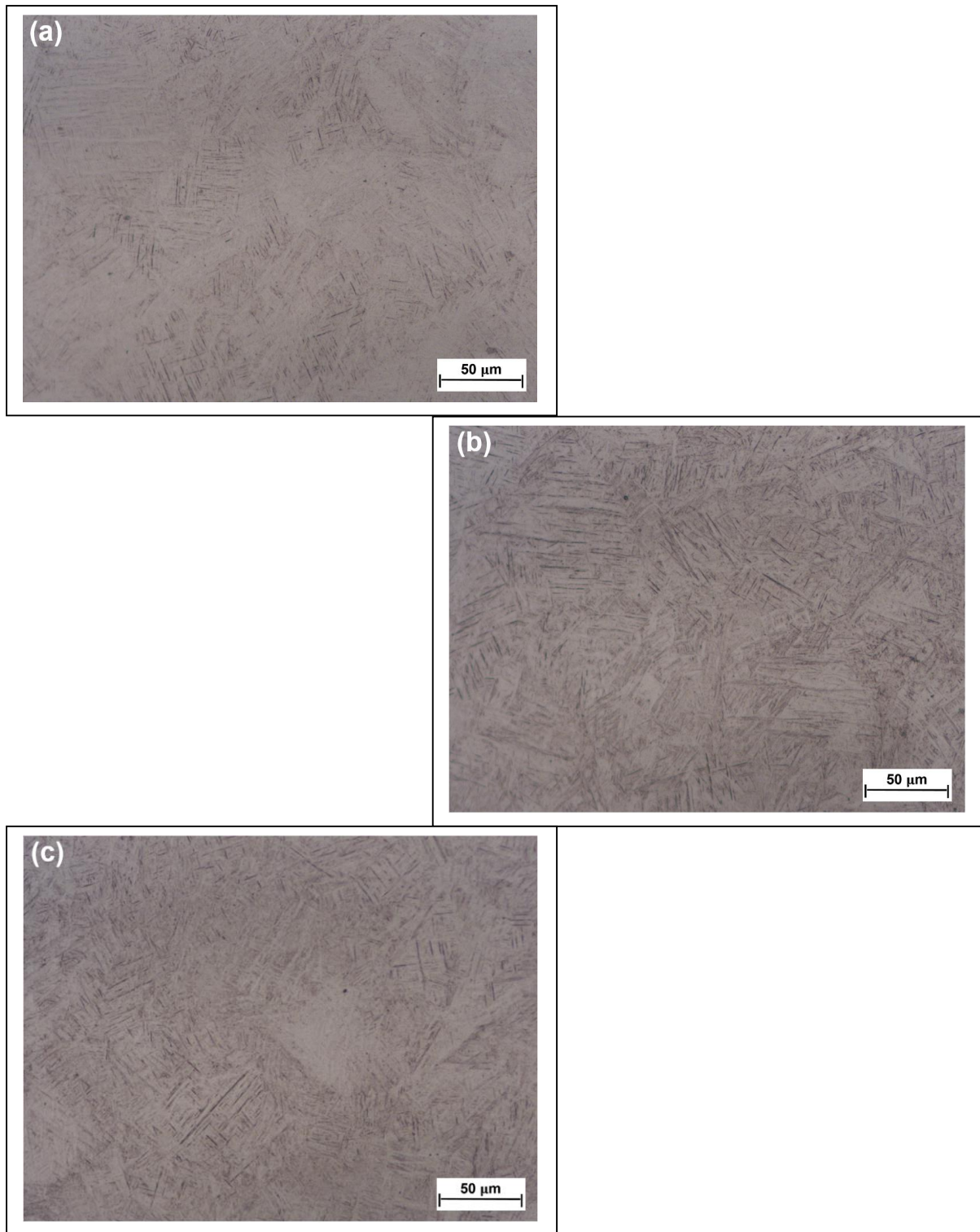


Figure 4.86: Optical micrographs at a distance of 6 mm from the edge of the projectile holes through the 12 mm thick plates

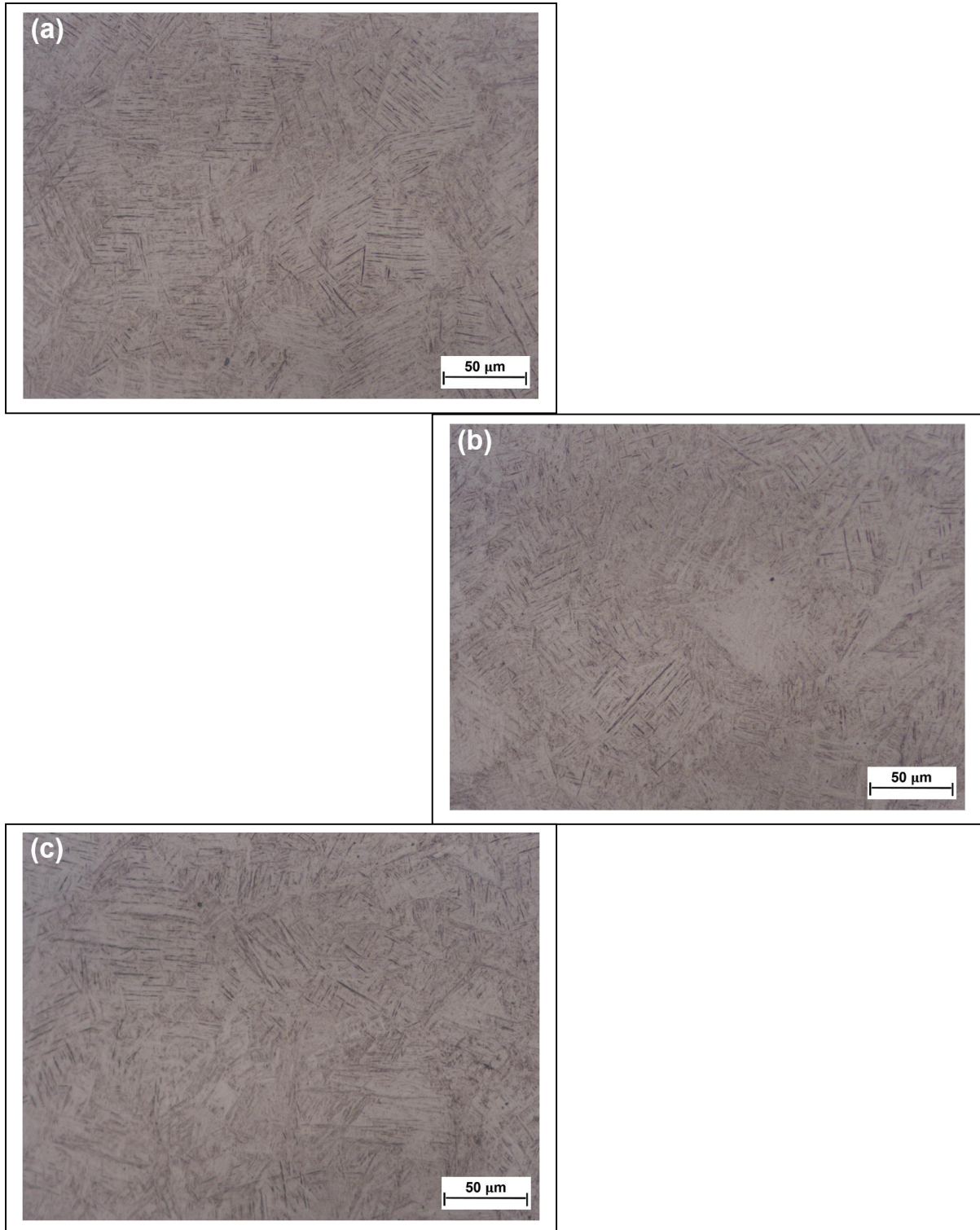


Figure 4.87: Optical micrographs at a distance of 6 mm from the edge of the projectile holes through the 14 mm thick plates

Based on similarities of the microstructure of all the plate thicknesses at a distance of 6 mm from the edge of the projectile hole seen in Figure 4.84 up to Figure 4.87, the key features here were be examined based on a plate of 10 mm thickness, selected randomly.

Figure 4.88(a) is an optical micrograph and (b) a magnified optical micrograph, both at distance of 6 mm from the edge of the projectile hole through a plate of 10 mm thickness.

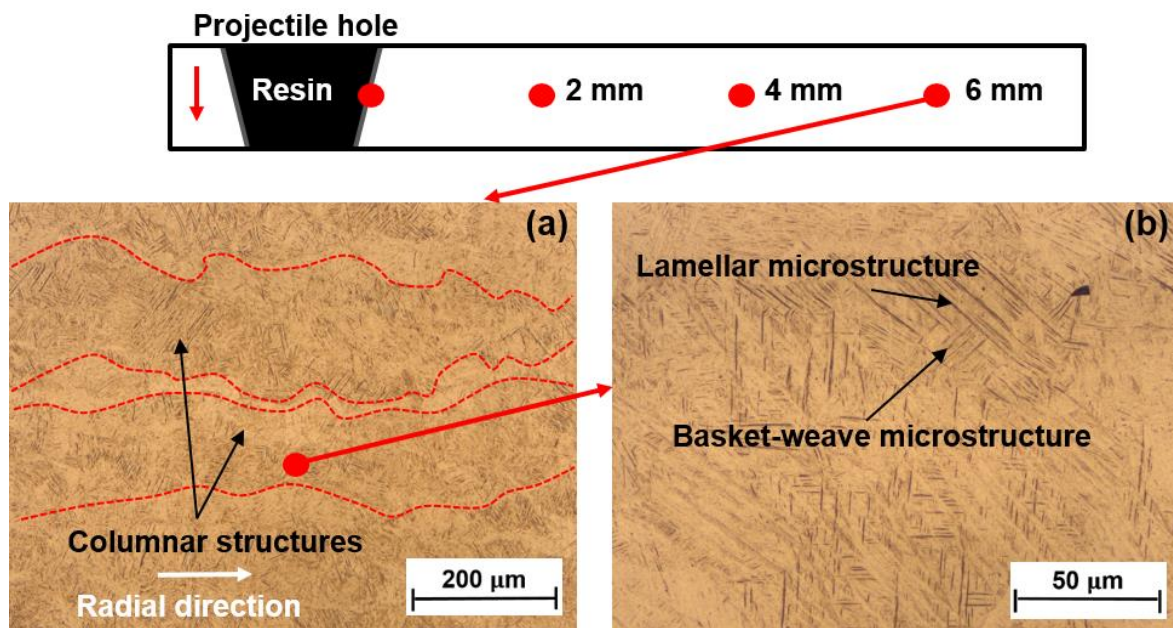


Figure 4.88: (a) Optical micrograph and (b) magnified optical micrograph, both at a distance of 6 mm from the edge of the projectile hole through a 10 mm thick plate

From Figure 4.88(a) and (b), it is seen that at this distance from the projectile hole, the microstructure comprises a combination of lamellae and basket-weave microstructure within columnar structures. Furthermore, there are fewer incidences of lamellae microstructure here compared to the cases at distances of 2 mm and 4 mm from the edge of the projectile hole [49, 50]. Furthermore, there is significantly more α phase in this case than at 2 mm and 4 mm [49, 50].

4.11.5. Microstructural analysis of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates at a distance of 25 mm from the edge of the projectile holes

The next set of micrographs were taken at mid span of specimens c and d, to investigate whether the impact of the high velocity projectile did also affect the microstructure of the alloy at a distance of 25 mm away from the edge of the projectile hole.

Figures 4.89(a), (b) and (c), 4.90(a), (b) and (c), 4.91(a), (b) and (c) and 4.92(a), (b) and (c) are optical micrographs at a distance of 25 mm from the edge of the projectile holes through each one of the three 8 mm, 10 mm, 12 mm and 14 mm thick plates, respectively.

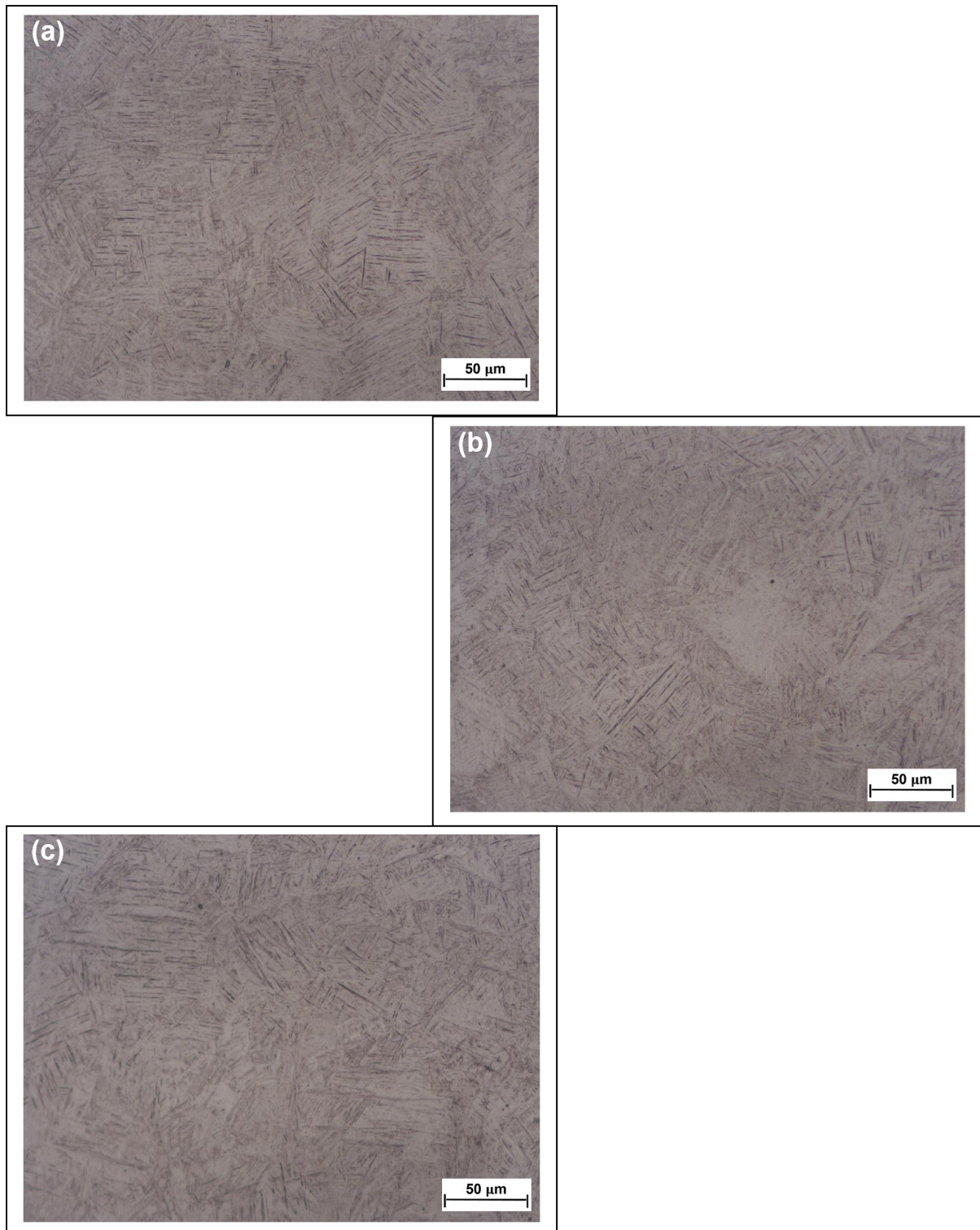


Figure 4.89: Optical micrographs at a distance of 25 mm from the edge of the projectile holes through the 8 mm thick plates

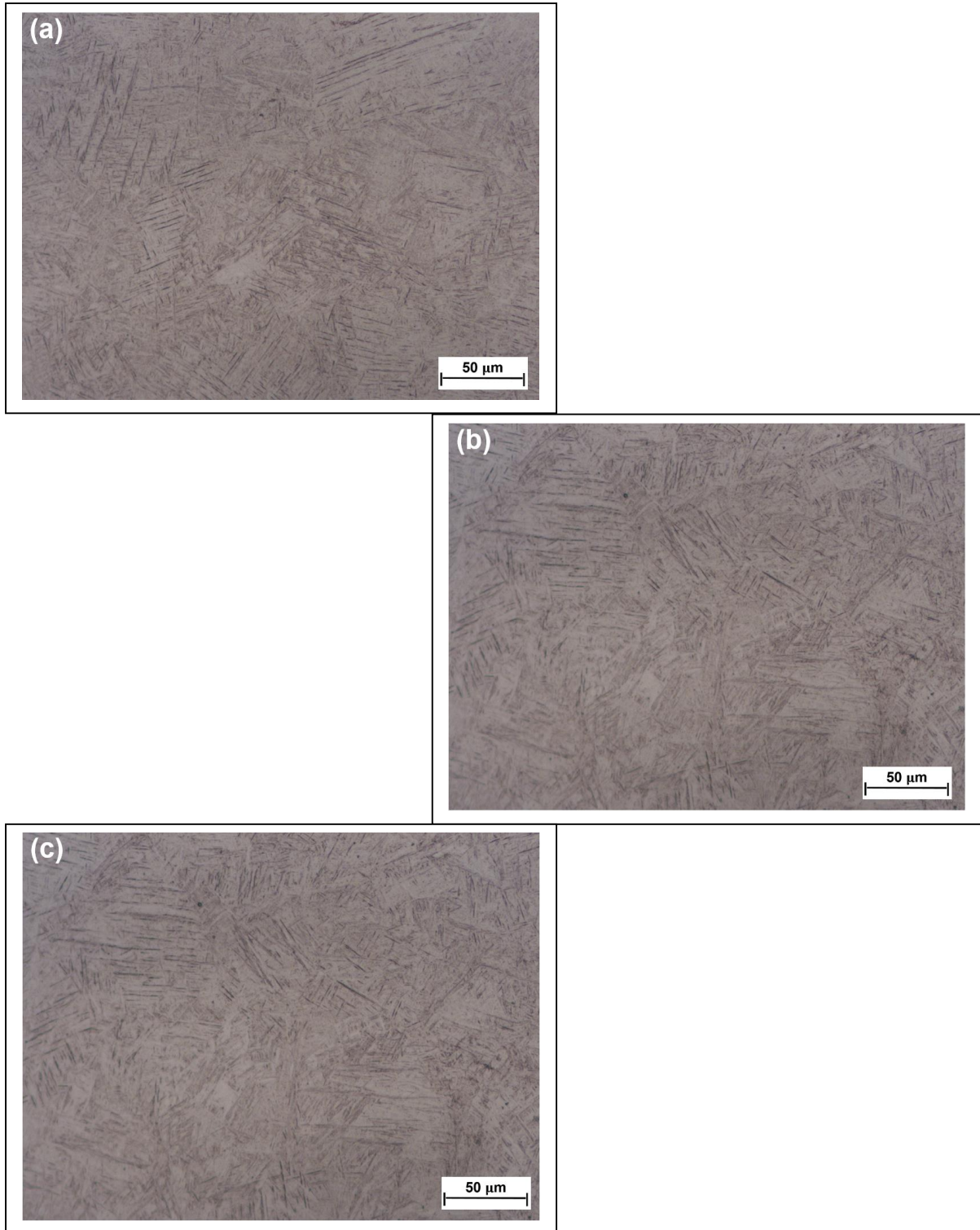


Figure 4.90: Optical micrographs at a distance of 25 mm from the edge of the projectile holes through the 10 mm thick plates

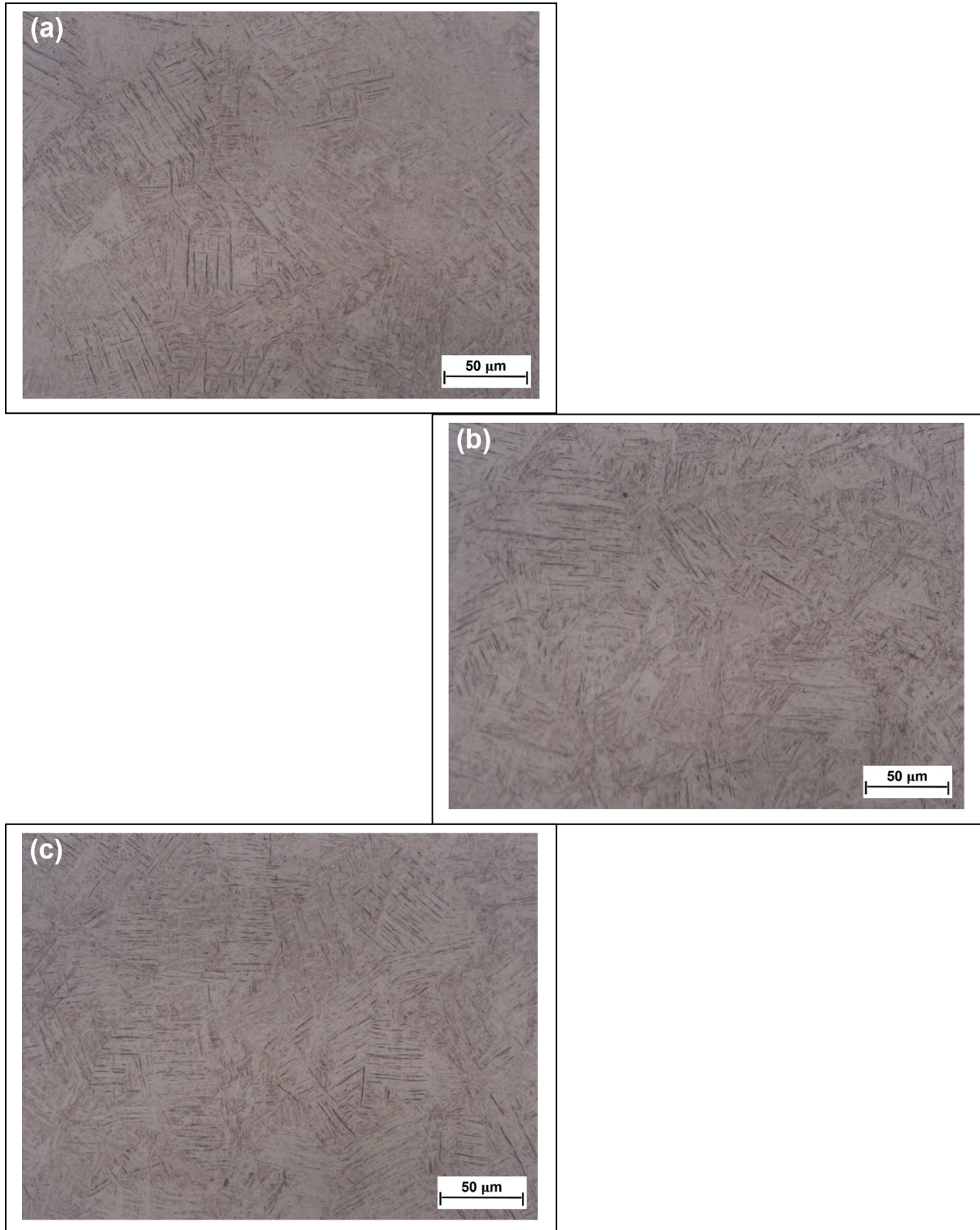


Figure 4.91: Optical micrographs at a distance of 25 mm from the edge of the projectile holes through the 12 mm thick plates

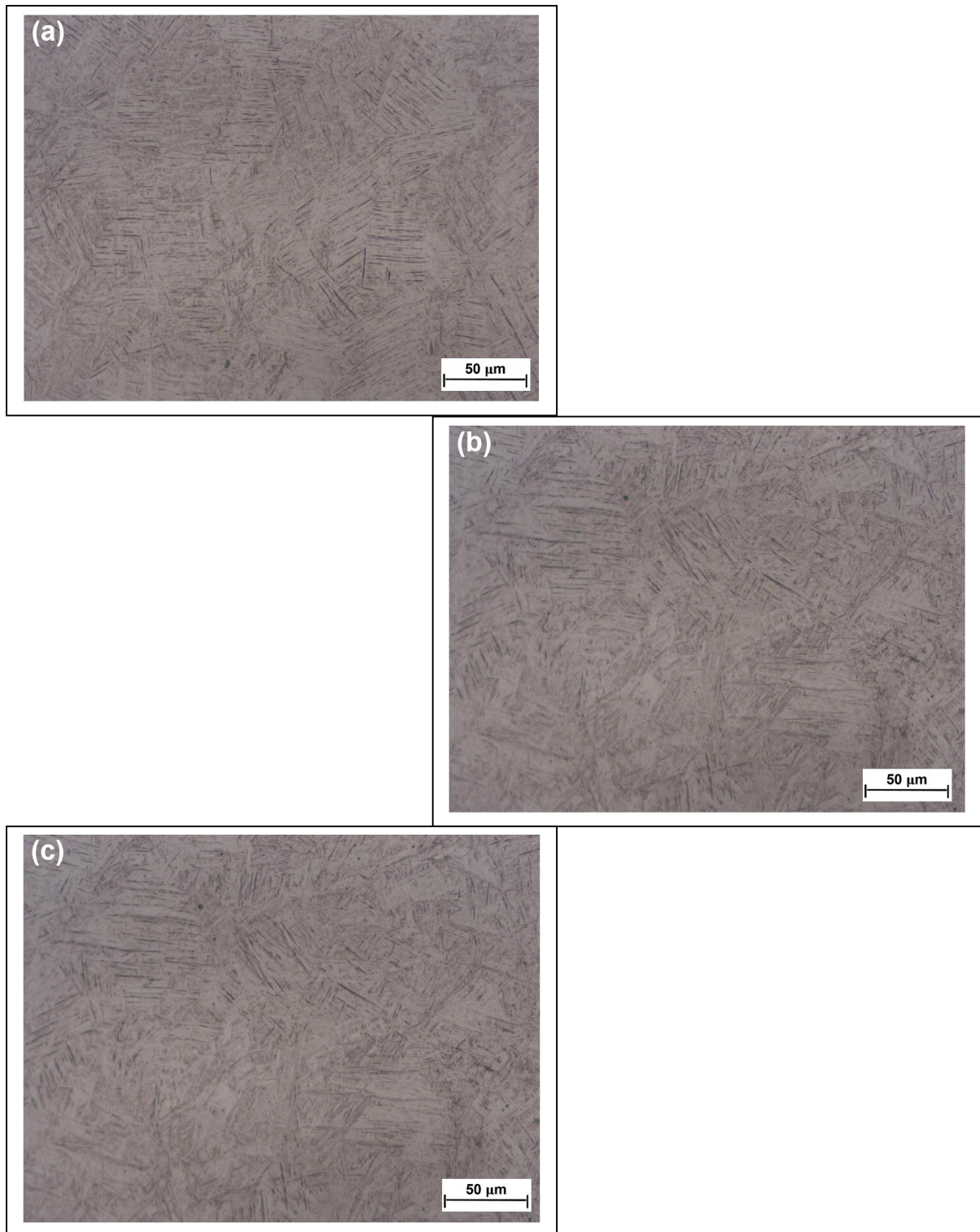


Figure 4.92: Optical micrographs at a distance of 25 mm from the edge of the projectile holes through the 14 mm thick plates

Based on similarities of the microstructure of all the plate thicknesses at a distance of 25 mm from the edge of the projectile hole seen in Figure 4.89 up to Figure 4.92, the key features here were be examined based on a plate of 10 mm thickness, selected at random.

Figure 4.93(a) is an optical micrograph and (b) a magnified optical micrograph, both at a distance of 25 mm from the edge of the projectile hole through a plate of 10 mm thickness.

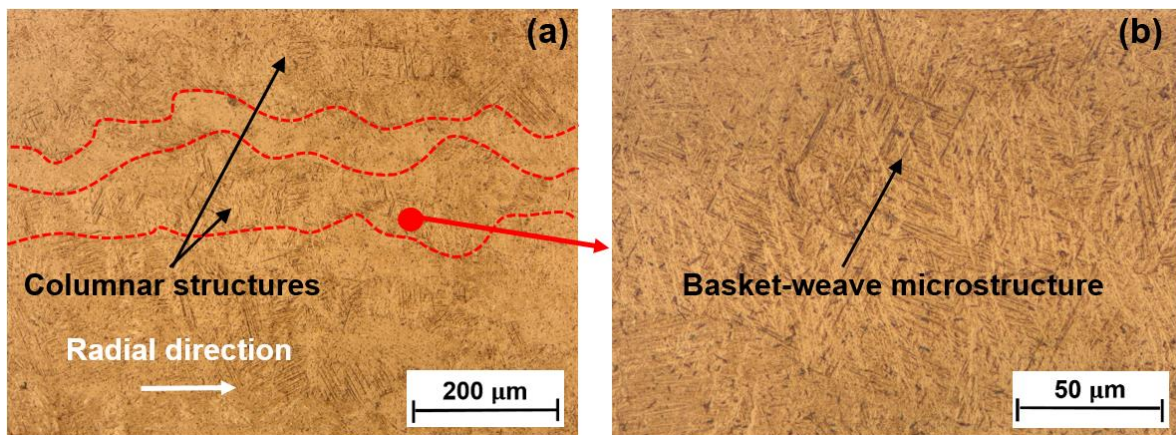


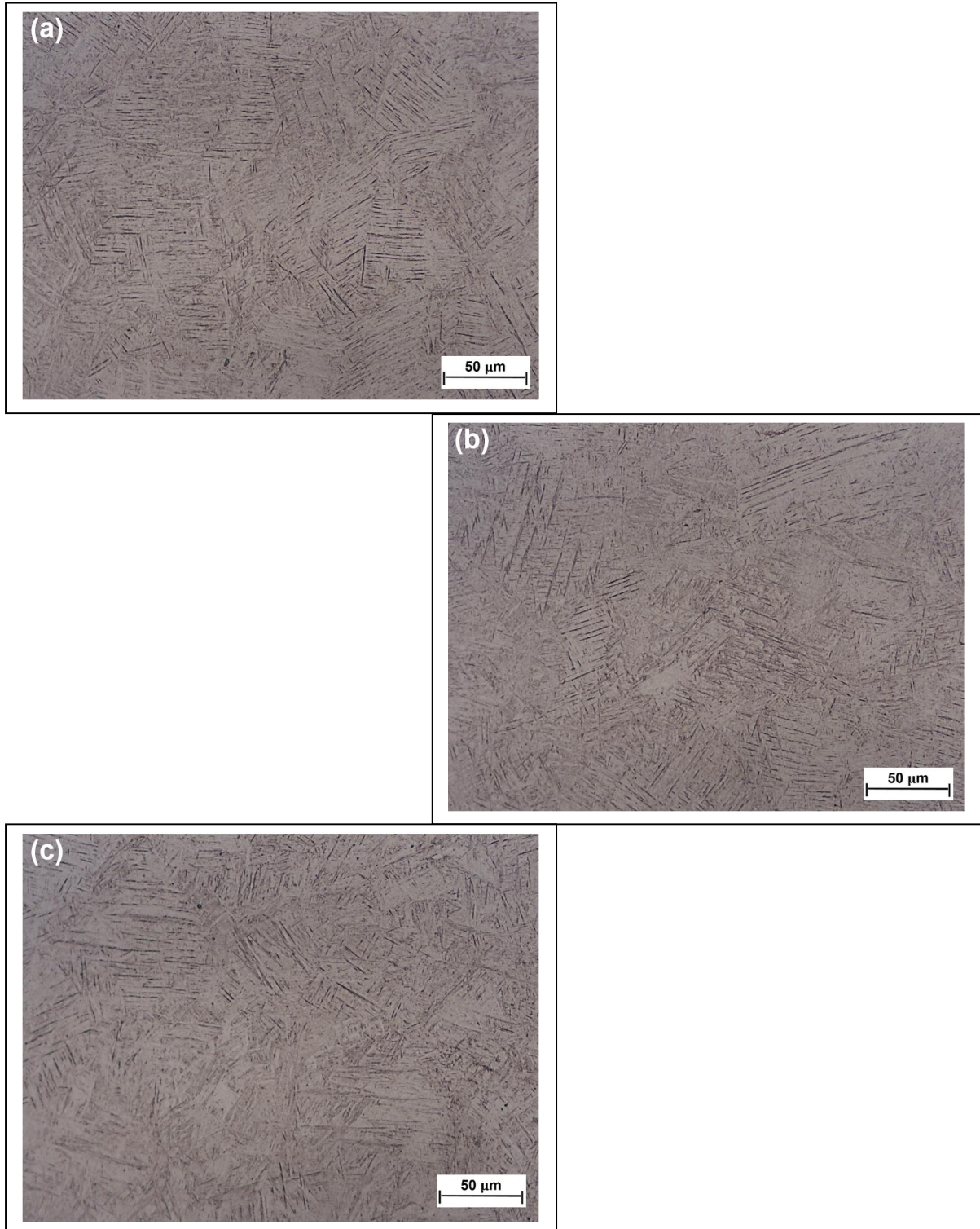
Figure 4.93: (a) Optical micrograph and (b) magnified optical micrograph, both at a distance of 25 mm from the edge of the projectile hole through a 10 mm thick plate

At 25 mm from the edge of the projectile hole, the microstructure is comprised of a basket-weave microstructure within columnar structures [49, 50]. Furthermore, the prevalence of the α phase has increased significantly here compared to the previous micrographs at distances of 4 mm and 6 mm from the edge of the projectile hole [49, 50].

4.11.6. Microstructural analysis of the initial microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI)

The last set of micrographs was taken at mid span of specimens e and f, for plates of 8 mm, 10 mm, 12 mm and 14 mm thickness to view what was expected to be the microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI) prior to testing.

Figure 4.94 presents optical micrographs of the initial microstructure from each one of the three (a) 8 mm thick plate, (b) 10 mm thick plate, (c) 12 mm thick plate and (d) 14 mm thick plate.



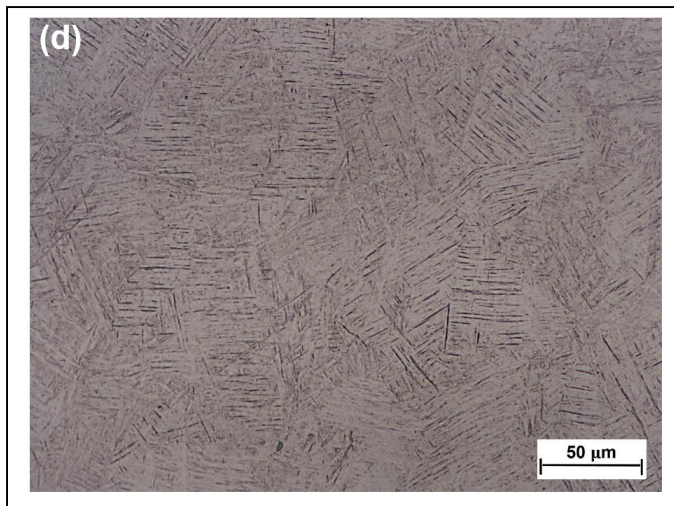


Figure 4.94: Optical micrographs of initial microstructure for the (a) 8 mm thick plate, (b) 10 mm thick plate, (c) 12 mm thick plate and (d) 14 mm thick plate.

Based on similarities of the initial microstructure of all the plate thicknesses seen in Figure 4.94, the key features here were to be examined based on a plate of 10 mm thickness, selected at random.

Figure 4.95(a) is an optical micrograph and (b) a magnified optical micrograph showing the initial microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI) plates used here. The micrographs were all taken at a distance 40 mm from the edge of the projectile hole.

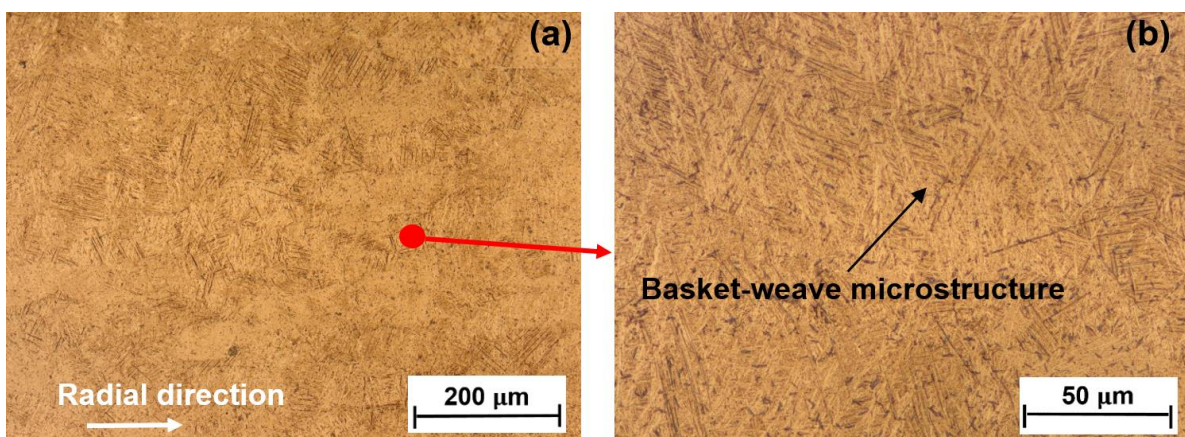


Figure 4.95: (a) Optical micrograph and (b) magnified optical micrograph, both showing the initial microstructure of a 10 mm thick plate

It is clear from Figure 4.95(b) that the as-built and stress relieved DMLS Ti6Al4V (ELI) used here had a basket-weave microstructure, before being exposed to high velocity impact [49, 50].

In the foregoing micrographs, from near the edge of the projectile hole moving radially outwards, it can be seen in the respective micrographs that there is a variation in the α phase and β phase fractions. Furthermore, it can be seen that the highest β phase fraction is on the ASBs.

In the foregoing micrographs, from near the edge of the projectile hole moving radially outwards, it is evident that there is an increase in the α phase over the β phase fraction. Microhardness tests were conducted at different distances from the edge of the projectile hole.

Using the FM 700 Digital Vickers Microhardness Tester at a constant load of 300 g for 15 seconds, multiple indentations were made at different distances from the projectile hole edge and also along the ASBs.

Figure 4.96(a) is an optical micrograph showing the indentations used for the Vickers Microhardness testing of a 10 mm thick plate.

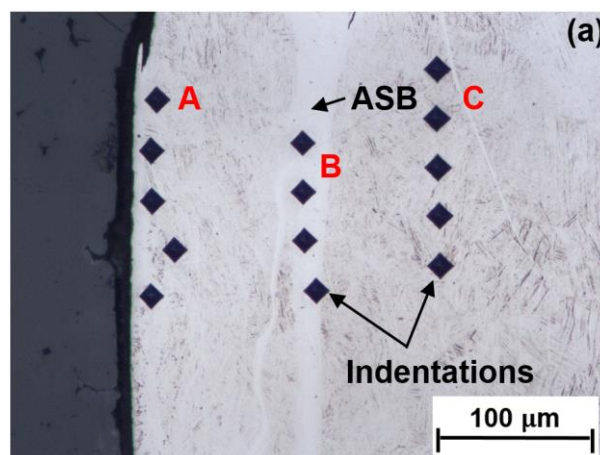


Figure 4.96: Optical micrograph showing the indentations for the Vickers Microhardness testing of a 10 mm thick plate

Table 4.11 shows the Vickers Hardness of an as-built and stress relieved DMLS Ti6Al4V (ELI) ballistic impacted 10 mm thick plate, from the edge of the projectile

hole, to a distance of 6 mm radially away from this edge. In the table and Figure 4.97, the symbol STD stand for standard deviation.

Table 4.11: Vickers Hardness of as-built and stress relieved DMLS Ti6Al4V(ELI), ballistic impacted 10 mm thick plate

	At the edge of the projectile hole (A)	Along an ASB (B)	To the right of the ASB (C)	2 mm radially away from the edge of the projectile hole	4 mm radially away from the edge of the projectile hole	6mm radially away from the edge of the projectile hole
	304.0 HV	307.9 HV	407.7 HV	344.1 HV	340.7 HV	334.9 HV
	323.2 HV	304.4 HV	326.8 HV	331.9 HV	349.8 HV	355.5 HV
	313.0 HV	292.2 HV	351.4 HV	350.7 HV	358.6 HV	351.4 HV
	331.8 HV	282.5 HV	320.2 HV	350.5 HV	346.1 HV	356.4 HV
	328.1 HV	299.8 HV	310.2 HV	349.6 HV	359.1 HV	357.5 HV
Mean	320.0 HV	297.4 HV	343.3 HV	345.4 HV	350.9 HV	351.1 HV
STD	11.4	10.1	30.5	7.9	7.9	9.4

Figure 4.97 is a graph showing the values of Vickers Hardness for an as-built and stress relieved DMLS Ti6Al4V (ELI), ballistic impacted 10 mm thick plate, from the edge of the projectile hole to a radial distance of 6 mm from this edge.

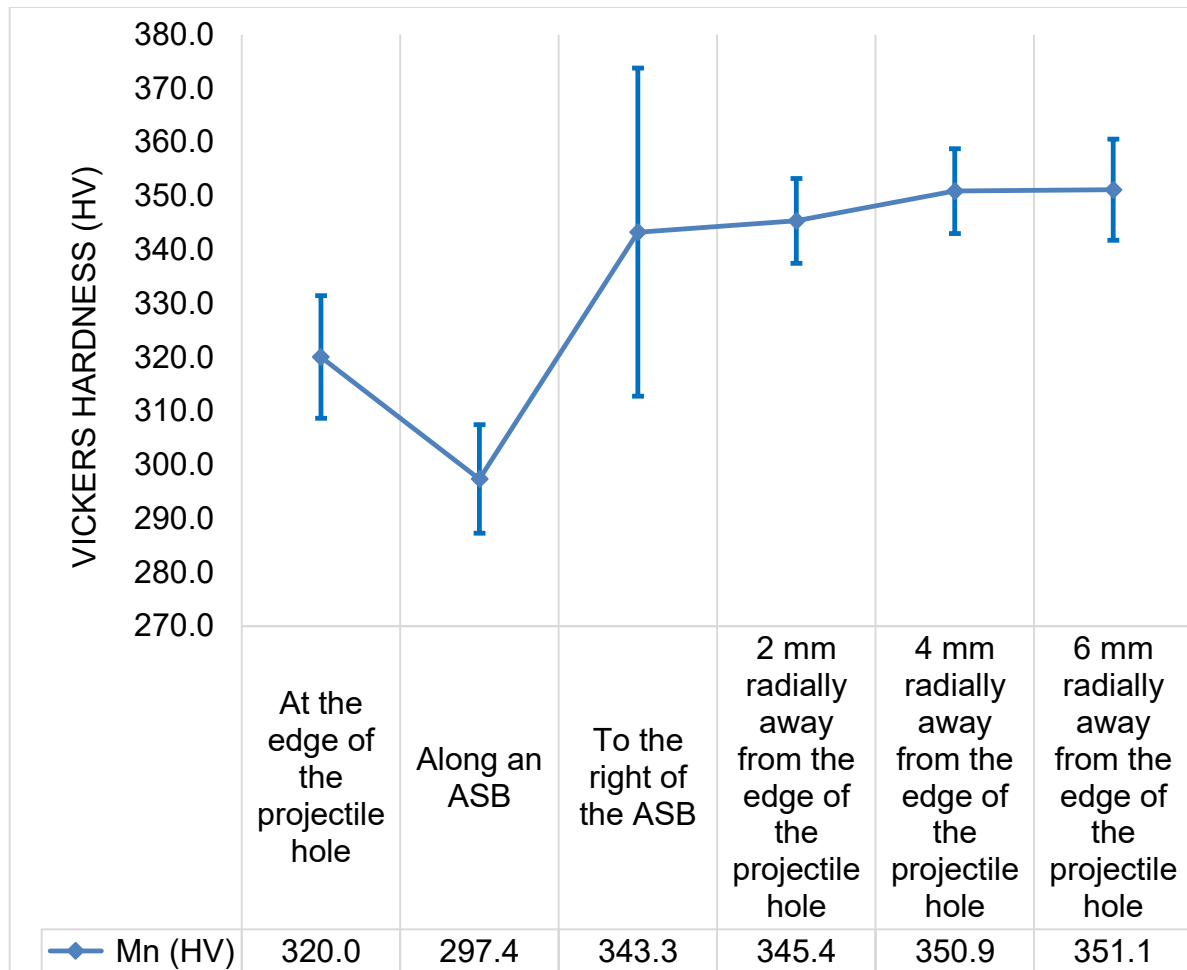


Figure 4.97: Vickers Hardness numbers for as-built and stress relieved DMLS Ti6Al4V (ELI), ballistic impacted 10 mm thick plate

From Figure 4.97 it can be seen that the microhardness of as-built and stress relieved DMLS Ti6Al4V (ELI) ballistic impacted plates, is lowest within the ASBs at a value of 297.4 HV. This is due to the fact that the most extreme deformation in the tested plates took place along the ASBs, which therefore, experienced the most thermal softening.

Furthermore, it can be seen that the microhardness of the alloy has an average value of 320.0 HV at the edge of the projectile hole and increases beyond the ASB with increasing distance radially away from the projectile hole to a maximum value of 351.1 HV at a distance of 6 mm from the edge of the projectile hole.

During the DMLS process, the alloy was cooled within an environment of argon gas, while during the ballistic testing it experienced cooling in the open air at an ambient temperature of 25°C. There are two significant factors in the two cases. Firstly, the

different starting temperatures of 3000 K and above 1000 K for the DMLS process and ballistic testing, respectively. Secondly, the cooling rate in the DMLS process is very rapid and varies between 10^5 - 10^6 K/s [50, 51, 52] and is much higher than the air-cooling prevailing in case of ballistic impact.

The consequence of increasing temperature above the beta transus temperature in the case of ballistic impact is the formation of ASBs and also the phase transformation from α phase to β phase within them and limited transformation away from them, near the edge of the penetration hole. The effect of the subsequent slower cooling rate in air would be transformation of the β phase to α phase away from the edge of the penetration hole. This is expected to give rise to a higher beta content and, therefore, lower values of hardness within the ASBs and towards the edge of the penetration hole, and explains the variations of hardness seen in Figure 4.97.

4.12. Simulation of Bullet Impact on and Penetration into As-built and Stress Relieved DMLS Ti6Al4V (ELI) Plates

Table 4.12 shows the experimental and simulation results for as-built and stress relieved DMLS Ti6Al4V (ELI) plates, as provided by the Flamengro division of Armscor.

Table 4.12: Simulation results for as-built and stress relieved DMLS Ti6Al4V (ELI) plates

Configuration	Plate thickness	Projectile Yaw	Results Experimental	Results Simulation	Energy Dissipated [J]
7.62 x 39 API	8 mm	0°	Fail: Full Penetration	Fail: Full Penetration	7939.85
7.62 x 39 API	10 mm	0°	Fail: Full Penetration	Fail: Full Penetration	7937.93
7.62 x 39 API	12 mm	0°	Fail: Full Penetration	Fail: Full Penetration	7937.93

7.62 x 39 API

14 mm

0°

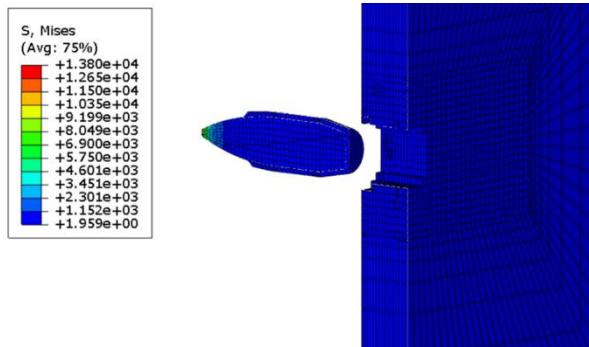
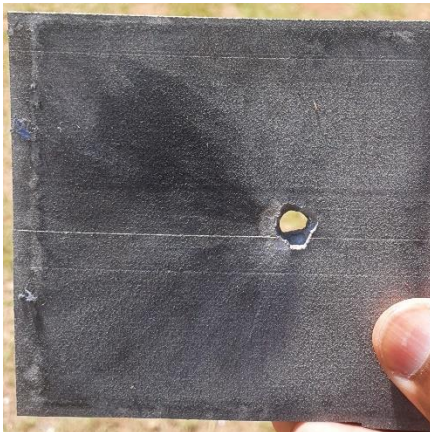
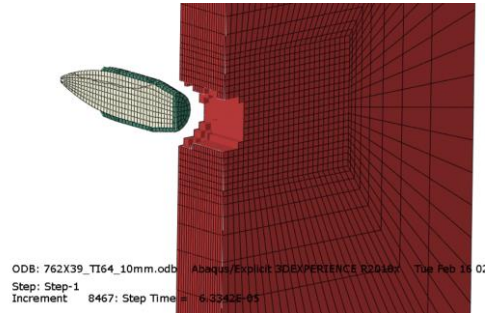
**Fail: Full
Penetration**

**Fail: Full
Penetration**

4727.68

Table 4.13 shows the comparison of pictures and diagrams of the experimental and simulation results for as-built and stress relieved DMLS Ti6Al4V (ELI) plates.

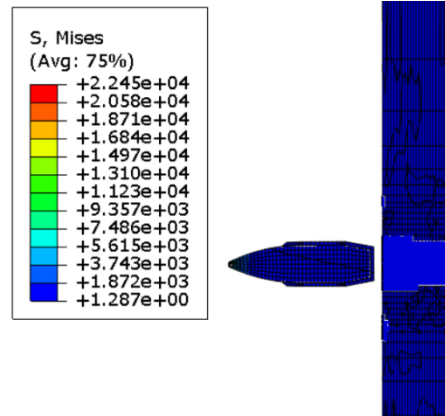
Table 4.13: Comparison of pictures and diagrams of the experimental and simulation results for as-built and stress relieved DMLS Ti6Al4V (ELI) plates.

Plate thickness	Experimental results	Simulation results
8 mm	 Fail: Full Penetration	 Fail: Full Penetration
10 mm	 Fail: Full Penetration	 Fail: Full Penetration

12 mm



Fail: Full Penetration

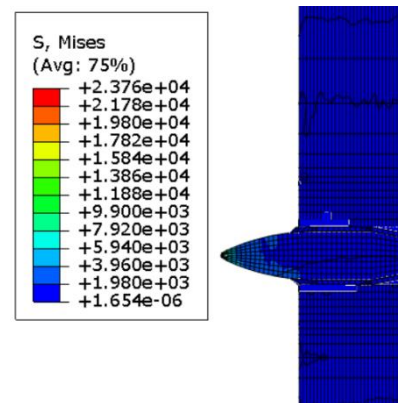


Fail: Full Penetration

14 mm



Fail: Full Penetration



Fail: Full Penetration

From the pictures and diagrams in Table 4.13 of the tests and simulation, it can be seen that in both cases there is full penetration of the 14 mm thick plate. The simulation results confirm made observation earlier from testing, that the minimum thickness to prevent through penetration for the alloy is above 14 mm.

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CHAPTER 5 - CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1. Introduction

This chapter gives insight on the conclusions reached upon analysing the results from the tensile testing, preliminary high velocity ballistic impact testing, fractographic analysis and microstructural analysis of wrought Ti6Al4V. The chapter further encompasses conclusions reached from the high velocity ballistic impact testing, visual inspection, fractographic analysis and microstructural analysis of as-built and stress relieved DMLS Ti6Al4V (ELI). Details of the conclusions reached from the simulations of bullet impact and penetration onto as-built and stress relieved DMLS Ti6Al4V (ELI) plates are also described briefly.

5.2. High Velocity Ballistic Impact Testing of Wrought Ti6Al4V

In the velocity range of about 700 m/s, the minimum thickness to prevent through penetration of the wrought Ti6Al4V used for the preliminary testing was established to be above 14 mm. This is less than RHA of 11.43 mm and is better than AA 5083 of 19.8 mm. Moreover, the wrought Ti6Al4V alloy gives a weight advantage of 1.4 over the RHA. The preceding, coupled with the alloy's high resistance to corrosion, makes it useful for applications in ballistic impact.

5.3. Fractographic Analysis of Wrought Ti6Al4V ballistically impacted Plates

Although wrought Ti6Al4V is classified as a ductile metal under normal loading conditions, the tests conducted here showed that under conditions of high velocity impact the alloy exhibits a brittle behaviour and ductile behaviour at the entry point and exit point of the penetration holes, respectively. At mid depth of the penetration holes, smearing was observed resulting from the frictional effect of the projectile as it penetrated through [1].

Furthermore, with an increase in plate thickness, it was discovered that there is a progressive slowing down of the projectile. The evidence for this was in the dimples

becoming more pronounced with an increase in plate thickness at the exit point of the penetration holes [3, 4, 5].

5.4. Microstructural Analysis of High Velocity Ballistic Impacted Wrought Ti6Al4V

During high velocity ballistic impact, the high strain rates imposed on the plates led to changes of microstructure in the alloy. At areas near the projectile hole, the microstructure became refined due to the increased cooling rate and hence the α -laths here were slightly thinner. The high strain rate and attendant high rise in temperature arising from high velocity impact was enough to cause the formation of ASBs, whose incidence dissipated with distance away from the edge of the projectile hole [6, 7].

The presence of α -grains that were elongated in the horizontal (radial) direction, which is also one of the directions of propagation of the induced tensile elastic stress waves is a sign of plastic flow of the plate-material and shows the extent of the effect of the transverse induced tensile elastic wave on the alloy. The observed microstructure at distances of 25 mm and 40 mm radially away from the edge of the projectile hole were similar and were characterised by lamellae and the presence of large globular α -grains. This similarity implies that the effect of the high velocity impact did not exceed a radial distance of 25 mm. This is thought to be the result of the low thermal conductivity of the alloy that led to the retention of most of the generated heat within a narrow radial region around the penetration hole.

5.5. High Velocity Ballistic Impact Testing of As-built and Stress Relieved DMLS Ti6Al4V (ELI)

The results here revealed a minimum thickness to prevent through penetration that is above 14 mm for as-built and stress relieved DMLS Ti6Al4V (ELI). This thickness fell short of the estimated 10.40 mm in the justification for testing the material. This can be attributed to the higher strength and hardness of the alloy coupled with the high velocity impact, which may have led to a significantly reduced ductile deformation that is the greatest absorber of strain energy in typical cases. Furthermore, there is also a possibility that at the initial impact, the degree of softening is such that the

material does not behave like it would under normal loading, which alters the values of yield and ultimate tensile stresses of the alloy.

The results here reveal that as-built and stress relieved DMLS Ti6Al4V (ELI) manufactured using the EOSINT M280 system with standard process parameters, can be used for high velocity impact applications. This is because the optimum thickness to resist through penetration of over 14 mm for the alloy does not fall too far short from that of RHA of 11.43 mm and is better than that of AA 5083 of 19.8 mm. This translates to a ballistic mass efficiency of 1.43 that is higher than those of RHA (1) and AA 5083 (1-1.2). The other advantage of this alloy is its method of manufacture that allows the manufacturing of complex geometries in one unit instead of many parts that would require assembly and/or welding.

5.6. Visual Inspection of As-built and Stress Relieved DMLS Ti6Al4V (ELI) Ballistically Impacted Plates

The as-built and stress relieved DMLS Ti6Al4V (ELI) ballistically impacted plates exhibited plastic deformation induced bulging and spalling on the entry side of the penetration holes for all the plate thicknesses. Furthermore, all the plates apart from the 8 mm thick plate, exhibited a ductile failure on the exit side of the penetration hole that was evidenced by the existence of dimples and petals on this side.

5.7. Fractographic Analysis of As-built and Stress Relieved DMLS Ti6Al4V (ELI) Ballistically Impacted Plates

The as-built and stress relieved DMLS Ti6Al4V (ELI) plates exhibited brittle behaviour at the entry point of the penetration holes and ductile behaviour at the exit point of the penetration holes for all plate thicknesses. Evidence of this was in the fracture surfaces with ridges at the entry points and dimples at exit points of the penetration holes in the plates.

The microstructure of the as-built and stress relieved DMLS Ti6Al4V (ELI), due to its higher hardness compared to wrought Ti6Al4V was expected to offer a better resistance to penetration by blunting the projectile. Furthermore, the higher strength and stiffness of the as-built and stress relieved DMLS Ti6Al4V (ELI), was expected

to offer more absorption of energy before failure of the target material [9, 10]. The tests here revealed this not to be the case.

5.8. Microstructural Analysis of High Velocity Ballistic Impacted As-built and Stress Relieved DMLS Ti6Al4V (ELI)

During high velocity ballistic impact, the high strain rate imposed on the plates led to microstructural changes in the alloy. The impact of a ballistic projectile on the plates brought about an increase of the β phase fraction towards the edge of the projectile hole. The increase in the β phase fraction arose from induced higher temperatures and larger cooling rates, which also led to a lower hardness. This was evidenced by the values of Vickers Hardness determined from the edge of the projectile holes of impacted specimens moving radially outwards.

5.9. Recommendations for Future Work

Future work should aim at investigating the performance of DMLS Ti6Al4V (ELI) thin plates combined to make up the required thicknesses for testing. Furthermore, future work should aim at investigating the performance of DMLS Ti6Al4V (ELI) thin plates of different properties in respect of hardness, strength and ductility to make up the required plate thicknesses. Surface hardening heat treatment of the top plate should be considered in order to enhance blunting of the projectiles. The possibility of using cellular structures in the plates below the front plate designed to increase the absorption of energy should also be investigated. It is also necessary to design experiments to quantify the rise in temperature due to impact and its spatial distribution.

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APPENDIX A

1.1. Justification for further Testing of As-built and Stress Relieved DMLS Ti6Al4V (ELI)

1.2. Summary

Upon completion of testing of wrought Ti6Al4V and analysis of the test results, the material was seen to be a good candidate for high ballistic applications. The advantages of additive manufacturing of the alloy then made it necessary to develop a justification for further high velocity ballistic impact testing of as-built and stress relieved DMLS Ti6Al4V (ELI). In doing so, the theories of the V_{50} ballistic limit and absorbed strain energy were used to estimate the optimum thickness for through penetration of the material.

1.3. Justification Based on V_{50} Ballistic limit

The V_{50} ballistic limit or limit velocity (v_{bl}) is the velocity required for a projectile or impactor to reliably penetrate a particular piece of material without any residual velocity [1]. Furthermore, the penetration has to occur reliably at least 50% of the time [1, 2].

An expression for the plastic work required to shear a plate and bring about failure by plugging can be developed from first principles. The expression is developed with an assumption that a plug pushed out of the plate has the same diameter as the projectile. By definition, work is done when a force that is applied to an object moves that object [3, 4]. Based on this definition, the work done to bring about plugging of a target can thus be represented by the following equation:

$$w_{Plug} = F \times x \quad (A.1)$$

In Equation (A.1), w_{Plug} is the work done to bring about plugging, F the applied shear force and x the displacement of the plug being pushed out of the target. In the case of a suddenly applied load such as in ballistic impact, the foregoing equation can thus be expressed as an integral as shown in Equation (A.2) [4].

$$W_{plug} = \int F \, dx \quad (A.2)$$

By definition a force is any interaction that when unopposed, will change the motion of an object [3, 4]. In this case the applied shear force (F), is the force acting on a material in a direction parallel to the extension or deformation of the material and thus causing shearing of the target material to form a plug as shown in Figure A.1. Figure A.1 is a diagram illustrating plugging of a target material under ballistic impact.

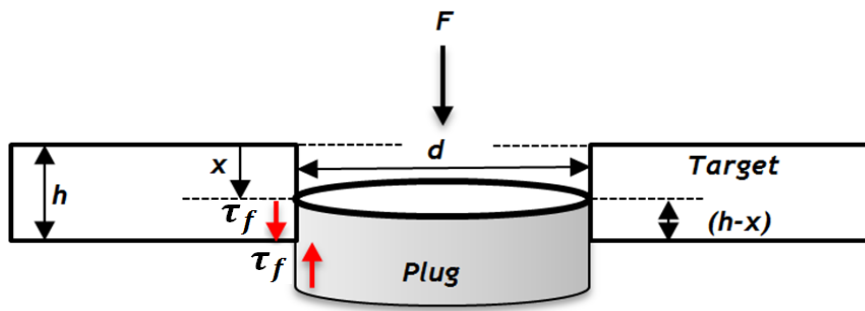


Figure A.1: Plugging under ballistic impact

From the failure shear stress (τ_f) and an elemental shearing area (dA), the elemental shear force (dF) can be calculated using Equation (A.3) as follows:

$$dF = \tau_f \times dA \quad (A.3)$$

In cases of high velocity impact, the rate of shear of the plug varies whilst the applied shear force (F) causing shear and the shear failure stress (τ_f) are both constant. The shear force (F) can thus be calculated using Equation (A.4) as follows:

$$F = \int dF = \int \tau_f \times dA \quad (A.4)$$

The elemental shearing area (dA) in Equation (A.3) and (A.4) is the area indicated in grey colour in Figure A.1. The area can thus be expressed using Equation (A.5) in which h is the target thickness and d is the diameter of the projectile, which is also assumed to be equal to the diameter of the plug.

$$dA = \pi d (h - x) \quad (A.5)$$

The expression for dA in Equation (A.5) is now substituted into Equation (A.3) to give:

$$dF = \tau_f \pi d (h - x) \quad (\text{A.6})$$

Integrating this equation leads to:

$$F = \int dF = \int \tau_f \pi d (h - x) \quad (\text{A.7})$$

Substituting this equation into Equation (A.2) yields:

$$W_{Plug} = \int \tau_f \pi d (h - x) dx \quad (\text{A.8})$$

Introducing the integration limits into the foregoing equation leads to:

$$W_{Plug} = \int_0^h \tau_f \pi d (h - x) dx \quad (\text{A.9})$$

Noting that the shear failure stress is constant and taking this and other constant terms from inside the integral sign leads to:

$$W_{Plug} = \tau_f \pi d \int_0^h (h - x) dx \quad (\text{A.10})$$

$$= \tau_f \pi d \left[x h - \frac{x^2}{2} \right]_0^h \quad (\text{A.11})$$

$$= \tau_f \pi d \left[\left[(h)(h) - \frac{(h)^2}{2} \right] - \left[(0)(h) - \frac{(0)^2}{2} \right] \right] \quad (\text{A.12})$$

$$= \tau_f \pi d \left[h^2 - \frac{h^2}{2} \right] \quad (\text{A.13})$$

$$W_{Plug} = \tau_f \pi d \left[\frac{h^2}{2} \right] = \frac{\tau_f \pi d h^2}{2} \quad (\text{A.14})$$

Equation (A.14) can now be equated to the change in kinetic energy of the system to develop an expression for the ballistic limit (v_{bl}) and from it the optimum thickness (h_{opt}) required to resist through penetration [4]. The kinetic energy of the projectile is not all converted to work done during ballistic impact. The efficiency (η) of conversion of the kinetic energy to work of deformation is usually assumed to be constant and equal to 0.9 [5, 6], thus:

$$\eta \Delta K_{kinetic} = W_{plug} \quad (A.15)$$

$$\eta \left[\frac{1}{2} m_{proj} (v_{iproj}^2 - v_{fproj}^2) - \frac{1}{2} m_{plug} (v_{iplug}^2 - v_{fplug}^2) \right] = \frac{\tau_f \pi d h^2}{2} \quad (A.16)$$

In the foregoing expression the initial velocity of the plug denoted ($v_{iplug} = 0$), because the target is stationary before impact. Assuming also that the plug (v_{fplug}) and the projectile (v_{fproj}) have the same final velocity of 0 m/s due to the fact that by definition of the ballistic limit the residual velocity should be so, Equation (A.16) then becomes:

$$0.9 \left[\frac{1}{2} m_{proj} (v_{iproj}^2) \right] = \frac{\tau_f \pi d h^2}{2} \quad (A.17)$$

Making the initial velocity of the projectile (v_{iproj}) the subject of Equation (A.17) then yields the following equation:

$$v_{iproj} = \sqrt{\frac{\tau_f \pi d h^2}{0.9 m_{proj}}} \quad (A.18)$$

In the ballistic impact tests done on wrought Ti6Al4V, an average initial velocity (v_{iproj}) of the projectile of 701.18 m/s was recorded for testing done for various thicknesses of wrought Ti6Al4V plates to investigate the optimum thickness [7].

At the optimum thickness of a target being impacted by a projectile travelling at a specific velocity, the initial velocity of the projectile and the ballistic limit are equal [2, 4]. The ballistic limit (v_{bl}) can thus be calculated using Equation (A.19), thus:

$$v_{bl} = \sqrt{\frac{\tau_f \pi d h_{opt}^2}{0.9 m_{proj}}} \quad (A.19)$$

Making the optimum thickness the subject of the foregoing equation gives rise to:

$$h_{opt} = \sqrt{\frac{0.9 m_{proj} v_{bl}^2}{\tau_f \pi d}} \quad (A.20)$$

There are no published standard values for ultimate shear strength (τ_{max}) like with the ultimate tensile stress (σ_{uts}) and yield strength (σ_y). The shear strength can be calculated using the Tresca or Von Mises criterion which both yield a value of 0.5 for uniaxial loading [8, 9]. This value ignores the effect of other principle stresses that develop during plastic shear failure under uniaxial loading and is therefore not adopted here [9].

The Taylor factor (M) and the ultimate tensile strength are used instead [10, 11]. The Taylor factor is defined as the ratio of the sum of the magnitude of the slip system shear rate to the effective deformation rate [12]. The ultimate or failure shear strength can thus be calculated from the ratio of the Taylor factor and the ultimate tensile strength using the following equation [12].

$$\tau_{max} = \tau_f = \frac{\sigma_{uts}}{M} \quad (A.21)$$

In the case of ballistic impact tests conducted on wrought Ti6Al4V and future tests on DMLS Ti6Al4V (ELI) using a 7.62 x 39 mm projectile traveling at an average velocity of 701.18 m/s, an assumption is made that the increase of temperature during impact is significant enough to bring about an α (HCP) to β (BCC) transformation [7, 13]. This assumption is based on findings that an adiabatic temperature rise exceeds 1000 K at an impact velocity of 550 m/s [13]. For BCC metals the appropriate Taylor factor (M) is 1.67 [14].

Table A.1 below shows the mechanical properties of wrought and additively manufactured Ti6Al4V.

Table A.1: Mechanical properties of wrought Ti6Al4V and DMLS Ti6Al4V (ELI)

Mechanical Property	Wrought Ti6Al4V (1)	DMLS Ti6Al4V (ELI) (2)
Elastic modulus (E) (Gpa)	105 [15]	112 [16]
Yield stress (σ_y) (MPa)	948 [15, 17]	1098 [16]
Ultimate tensile stress (σ_{uts}) (MPa)	994 [15, 17]	1265 [16]

From Table A.1, the ultimate tensile strength of DMLS Ti6Al4V (ELI) and wrought Ti6Al4V are seen to be 1265 MPa and 994 MPa, respectively. Taking these values of ultimate tensile strength and the Taylor factor of 1.67 and then substituting them into Equation (A.21), to calculate the ultimate shear strength gives rise to:

DMLS Ti6Al4V

$$\tau_{max} = \tau_f = \frac{1265 \times 10^6}{1.67} = 757.5 \times 10^6 Pa \quad (A.22)$$

Wrought Ti6Al4V

$$\tau_{max} = \tau_f = \frac{994 \times 10^6}{1.67} = 595.2 \times 10^6 Pa \quad (A.23)$$

The projectile that was used for the preliminary testing of wrought Ti6Al4V is a 7.62 x 39 mm bullet, with a mass of 7.9 grams and a diameter of 7.9 mm [7]. Taking the known values of the parameters of the projectile and the values of ultimate shear strength calculated in Equations (A.22) and (A.23) and then substituting them into Equation (A.20) gives rise to:

DMLS Ti6Al4V

$$h_{opt} = \sqrt{\frac{0.9 (7.9 \times 10^{-3}) (701.18)^2}{(757.5 \times 10^6) \pi (7.9 \times 10^{-3})}} = 13.64 mm \quad (A.24)$$

Wrought Ti6Al4V

$$h_{opt} = \sqrt{\frac{0.9 (7.9 \times 10^{-3}) (701.18)^2}{(595.2 \times 10^6) \pi (7.9 \times 10^{-3})}} = 15.38 \text{ mm} \quad (\text{A.25})$$

From the tests done on wrought Ti6Al4V it was established that the optimum ballistic thickness of the alloy is greater than or equal to 14 mm [7]. Taking this into account a correction factor (*CF*) is determined from the calculated and the experimental values as follows:

$$CF = \frac{\text{Calculated value} - \text{experimental value}}{\text{Calculated value}} \times 100 \quad (\text{A.26})$$

$$CF = \frac{15.38 - 14}{15.38} \times 100 \approx 9 \% \quad (\text{A.27})$$

Taking the correction factor for wrought Ti6Al4V calculated above and using it on DMLS Ti6Al4V to calculate the expected experimental value yields:

$$\text{experimental value} = \text{Calculated value} - \frac{CF \times \text{Calculated value}}{100} \quad (\text{A.28})$$

$$\text{experimental value} = 13.64 - \frac{9 \times 13.64}{100} = 12.41 \text{ mm} \quad (\text{A.29})$$

1.4. General Solution for the Absorbed Strain Energy in Cases of Gradually Applied Direct Loads

Based on absorbed strain energy, justification references the standard stress versus strain curve and considers the strain hardening phenomenon. Figure A.2 shows the stress-strain curves of as-built SLM Ti6Al4V, annealed SLM Ti6Al4V and wrought Ti6Al4V.

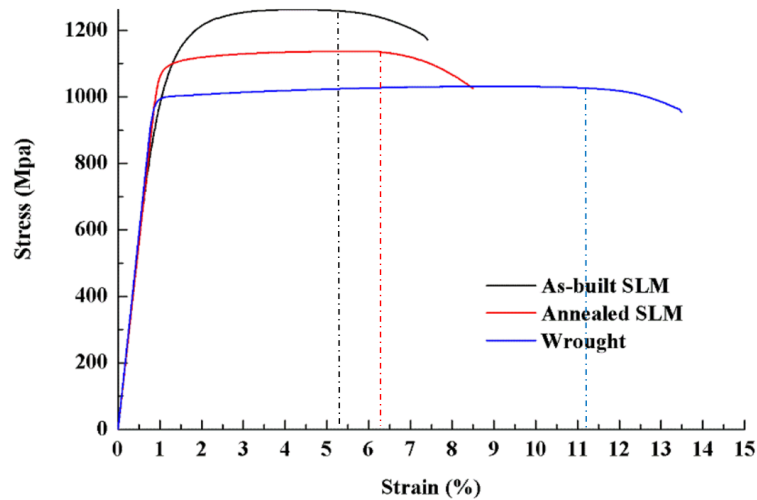


Figure A.2: Stress-strain curves of As-built SLM Ti6Al4V, Annealed SLM Ti6Al4V and wrought Ti6Al4V [18]

From Figure A.2 it can be seen that the non-uniform plastic deformation (from the advent of necking till fracture) part of the stress-strain curves makes up a very small percentage of the total deformation. Moreover, no equation was found in literature to describe this deformation. For this reason, the energy absorbed in this region is ignored in deriving the formula for estimation of the optimum ballistic thickness of DMLS Ti6Al4V (ELI).

Figure A.3 is a stress-strain graph of two forms of DMLS Ti6Al4V (ELI) that exhibits no non-uniform plastic deformation. This further justifies ignoring the non-uniform plastic deformation shown in Figure A.2.

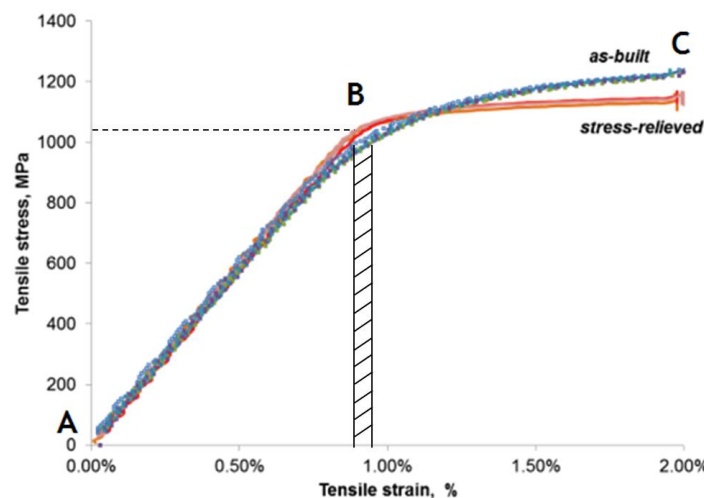


Figure A.3: Stress-strain diagram of DMLS Ti6Al4V (ELI) [16]

Strain energy is defined as the energy stored in a body due to deformation as a result of work done on it [19, 20]. During collision in ballistic impact, as the projectile makes contact with the target and deformation takes place the kinetic energy of the projectile is converted into strain energy in the target [19, 20]. This therefore means that the loss in kinetic energy of the projectile is equal to the work done on the target, which is equal to the strain energy stored in the target [19, 20]. There is an assumption in this that the projectile experiences minimal deformation and that negligible energy is absorbed through such deformation in it [21].

At failure and complete separation of a material, the total strain energy (U_T) stored in it is equal to the strain energy for elastic deformation (till the yield point indicated by point B in Figure A.3), plus the strain energy for uniform plastic deformation that is characterised by strain hardening till ultimate fracture indicated by point C in the same figure.

For elastic deformation of a uniform target under a direct load the strain energy per unit volume (U_E) can be calculated using Equation (A.30) [22]. In these equations the symbol σ stands for the direct stress induced in the target, V the volume of the target and E the modulus of elasticity of the target.

$$U_E = \frac{\sigma_y^2}{2E} \times V = W_E \quad (\text{A.30})$$

For the plastic region of deformation the strain energy per unit volume (U_P) can be calculated through an integration of the stress versus strain curve following two different approaches. Starting with the first approach where integration is carried out with reference to strain:

$$U_P = \int_{\sigma_y}^{\sigma_{uts}} \sigma V d\epsilon \quad (\text{A.31})$$

In Equation (A.31) the symbols, σ_{uts} and σ_y , stand for the ultimate tensile strength and yield stress for a material, respectively. The stress during strain hardening is related to the strain as follows [22]:

$$\sigma = K\epsilon^n \quad (\text{A.32})$$

In the above equation, K is the strength coefficient, ϵ the direct strain, σ the applied direct stress and n the strain hardening exponent. Making the strain the subject of the foregoing formula, yields the equation:

$$\epsilon = \left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \quad (\text{A.33})$$

Now taking Equation (A.32) and substituting it into the Equation (A.31), and noting that the volume and strength coefficient of the material are constant gives rise to:

$$U_P = \int_{\sigma_y}^{\sigma_{uts}} K \epsilon^n V d\epsilon = K V \int_{\sigma_y}^{\sigma_{uts}} \epsilon^n d\epsilon \quad (\text{A.34})$$

The foregoing equation is integrated to generate the equation.

$$U_P = K V \left[\frac{\epsilon^{n+1}}{n+1} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.35})$$

Now substituting Equation (A.33), into the foregoing equation leads to:

$$U_P = V K \left[\frac{\left[\left(\frac{\sigma}{K}\right)^{\frac{1}{n}} \right]^{n+1}}{n+1} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.36})$$

$$= V \frac{K}{n+1} \left[\frac{\sigma^{\frac{n+1}{n}}}{K^{\frac{n+1}{n}}} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.37})$$

$$= V \frac{K^{1-\frac{(n+1)}{n}}}{n+1} \left[\sigma^{\frac{n+1}{n}} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.38})$$

$$= V \frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma^{\frac{n+1}{n}} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.39})$$

$$U_P = V \left[\frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_{uts}^{\frac{n+1}{n}} \right] - \frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_y^{\frac{n+1}{n}} \right] \right] \quad (\text{A.40})$$

But as stated earlier, the total strain energy stored in a material is equal to the sum of the elastic and plastic strain energies stored in the material, therefore:

$$U_T = U_E + U_P \quad (\text{A.41})$$

$$U_T = \frac{\sigma_y^2}{2E} V + V \left[\frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_{uts}^{\frac{n+1}{n}} \right] - \frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_y^{\frac{n+1}{n}} \right] \right] \quad (\text{A.42})$$

The second approach is where integration is carried out with reference to stress is as follows, starting from Equation (A.31):

$$U_P = \int_{\sigma_y}^{\sigma_{uts}} \sigma V d\epsilon \quad (\text{A.31})$$

$$\sigma = K\epsilon^n \quad (\text{A.32})$$

$$d\sigma = Kn\epsilon^{n-1} d\epsilon \quad (\text{A.43})$$

$$d\epsilon = \frac{d\sigma}{Kn\epsilon^{n-1}} \quad (\text{A.44})$$

The expression for strain in Equation (A.33) is now substituted into Equation (A.44) to give:

$$d\epsilon = \frac{d\sigma}{Kn \left[\left(\frac{\sigma}{K} \right)^{\frac{1}{n}} \right]^{n-1}} \quad (\text{A.45})$$

$$= \frac{d\sigma}{\frac{K}{\frac{n-1}{n}} n \left[\sigma^{\frac{n-1}{n}} \right]} \quad (\text{A.46})$$

$$= \frac{d\sigma}{K^{1-\frac{(n-1)}{n}} n \left[\sigma^{\frac{n-1}{n}} \right]} \quad (\text{A.47})$$

$$d\epsilon = \frac{d\sigma}{K^{\frac{1}{n}} n \left[\sigma^{\frac{n-1}{n}} \right]} \quad (\text{A.48})$$

Substituting this equation into Equation (A.31) yields:

$$U_P = \int_{\sigma_y}^{\sigma_{uts}} V \sigma \frac{d\sigma}{K^{\frac{1}{n}} n \left[\sigma^{\frac{n-1}{n}} \right]} \quad (\text{A.49})$$

$$= \int_{\sigma_y}^{\sigma_{uts}} V \sigma \frac{1}{K^{\frac{1}{n}} n \left[\sigma^{\frac{n-1}{n}} \right]} d\sigma \quad (\text{A.50})$$

$$= \int_{\sigma_y}^{\sigma_{uts}} V \frac{K^{-\frac{1}{n}}}{n} \sigma \cdot \sigma^{\frac{1-n}{n}} d\sigma \quad (\text{A.51})$$

$$= \int_{\sigma_y}^{\sigma_{uts}} V \frac{K^{-\frac{1}{n}}}{n} \sigma^{1+\frac{1-n}{n}} d\sigma \quad (\text{A.52})$$

$$= \int_{\sigma_y}^{\sigma_{uts}} V \frac{K^{-\frac{1}{n}}}{n} \sigma^{\frac{1}{n}} d\sigma \quad (\text{A.53})$$

$$= V \frac{K^{-\frac{1}{n}}}{n} \left[\frac{\sigma^{\frac{1}{n}+1}}{\frac{1}{n}+1} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.54})$$

$$= V \frac{K^{-\frac{1}{n}}}{n} \left[\frac{\sigma^{\frac{n+1}{n}}}{\frac{n+1}{n}} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.55})$$

$$= V \frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma^{\frac{n+1}{n}} \right]_{\sigma_y}^{\sigma_{uts}} \quad (\text{A.56})$$

$$U_P = V \left[\frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_{uts}^{\frac{n+1}{n}} \right] - \frac{K^{-\frac{1}{n}}}{n+1} \left[\sigma_y^{\frac{n+1}{n}} \right] \right] \quad (\text{A.57})$$

The fact that the same expression for plastic strain energy is arrived at (Equation (A.40) and Equation (A.57)) following two different approaches validates it.

1.5. Justification Based on Absorbed Strain Energy

The two approaches adopted for the strain energy stored in a material (U_T) in the last section are ideal for the case of gradual axial loading till fracture. However, in a case of transverse loading such as in ballistic impact, there is no opportunity for direct deformation because of the high strain rates prevailing and the target fails solely by shearing. In this case, the expression for shear strain energy per unit volume ($U_{E(\tau)}$) during elastic deformation of a uniform target under shear is applied and is expressed as follows.

$$U_{E(\tau)} = \frac{\tau_y^2}{2E} \times V = W_{E(\tau)} \quad (\text{A.58})$$

In this equation the symbol τ_y stands for the shear yield stress of the material. The shear yield stress (τ_y) can be calculated from the direct stress using the Tresca or von Mises criterion, which both give the shear stress to be half the value of the direct stress elastic deformation [8, 9, 22].

The assumption is made here that there is no strain hardening during shear failure and that deformation beyond yield is purely plastic [23]. For the plastic region of deformation, the shear strain energy per unit volume ($U_{P(\tau)}$) is equal to the average work done to bring about plugging (W_{plug}) which entails shear failure of the material [4]. The plastic shear strain energy per unit volume ($U_{P(\tau)}$) can thus be calculated using Equation (A.59) as:

$$U_{P(\tau)} = W_{Plug} = \frac{\tau_f \pi d h^2}{2} = \frac{\tau_y \pi d h^2}{2} \quad (A.59)$$

As established in the earlier calculations, the total strain energy stored in a material is equal to the sum of the elastic and plastic strain energies stored in the material. This is also the case for the total shear strain energy ($U_{T(\tau)}$) thus:

$$U_{T(\tau)} = U_{E(\tau)} + U_{P(\tau)} \quad (A.60)$$

$$U_{T(\tau)} = \frac{(\tau_y)^2}{2E} \times V + \frac{\tau_y \pi d h^2}{2} \quad (A.61)$$

From the tests done on wrought Ti6Al4V it was established that the optimum ballistic thickness of the alloy is greater than or equal to 14 mm [7]. Assuming the same amount of energy exerted by the projectile on the wrought Ti6Al4V and the DMLS Ti6Al4V (ELI), the total shear strain energies of the two can be equated to one another and the optimum ballistic thickness of DMLS Ti6Al4V (ELI) calculated. Such calculation assumes the same front area (A) for the two metals. Wrought Ti6Al4V is denoted with subscript 1 and DMLS Ti6Al4V (ELI) with subscript 2, to generate the following expression.

$$U_{T_1} = U_{T_2} \quad (A.62)$$

$$\frac{(\tau_{y_1})^2}{2E_1} \times V_1 + \frac{\tau_{y_1} \pi d h_1^2}{2} = \frac{(\tau_{y_2})^2}{2E_2} \times V_2 + \frac{\tau_{y_2} \pi d h_2^2}{2} \quad (A.63)$$

The shear yield strength of wrought Ti6Al4V and SLM Ti6Al4V (ELI) are 523 MPa and 634 MPa, respectively [24, 25]. Furthermore, from Table A.1 the elastic modulus (E) of wrought Ti6Al4V and DMLS Ti6Al4V (ELI) are 105 GPa and 112 GPa, in that order. The projectile that was used for the preliminary testing of wrought Ti6Al4V is a 7.62 x 39 mm bullet, with a mass of 7.9 grams and a diameter of 7.9 mm [7].

Equation (A.63) can be rewritten as:

$$\frac{(\tau_{y_1})^2}{2E_1} \times A_1 h_1 + \frac{\tau_{y_1} \pi d h_1^2}{2} = \frac{(\tau_{y_2})^2}{2E_2} \times A_2 h_2 + \frac{\tau_{y_2} \pi d h_2^2}{2} \quad (A.64)$$

Noting that areas (A_1) and (A_2) are equal reduces Equation (A.64) to:

$$\frac{(\tau_{y1})^2}{2E_1} \times h_1 + \frac{\tau_{y1} \pi d h_1^2}{2} = \frac{(\tau_{y2})^2}{2E_2} \times h_2 + \frac{\tau_{y2} \pi d h_2^2}{2} \quad (\text{A.65})$$

Substituting in the known values of the parameters in Equation (A.65) gives rise to:

$$\begin{aligned} & \frac{(523 \times 10^6)^2}{2(105 \times 10^9)} \times 0.014 + \frac{(523 \times 10^6) \pi (7.9 \times 10^{-3}) 0.014^2}{2} \\ &= \frac{(634 \times 10^6)^2}{2(112 \times 10^9)} \times h_2 + \frac{(634 \times 10^6) \pi (7.9 \times 10^{-3}) h_2^2}{2} \end{aligned} \quad (\text{A.66})$$

$$18.235 \times 10^3 + 1.272 \times 10^3 = 1.794 \times 10^6 \times h_2 + 7.867 \times 10^6 \times h_2^2 \quad (\text{A.67})$$

$$19.507 \times 10^3 = 1.794 \times 10^6 h_2 + 7.867 \times 10^6 h_2^2 \quad (\text{A.68})$$

$$7.867 \times 10^6 h_2^2 + 1.794 \times 10^6 h_2 - 19.507 \times 10^3 = 0 \quad (\text{A.69})$$

Equation (A.69) is a quadratic equation in terms of the parameter h , whose general solution is equal to;

$$h = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (\text{A.70})$$

Substituting the know values of the parameters in this equation gives rise to:

$$h = \frac{-(1.794 \times 10^6) \pm \sqrt{(1.794 \times 10^6)^2 - 4(7.867 \times 10^6)(-19.507 \times 10^3)}}{2(7.867 \times 10^6)} \quad (\text{A.71})$$

$$h = 10.399 \times 10^{-3} \quad \text{and} \quad h = -238.44 \times 10^{-3} \quad (\text{A.72})$$

In Equation (A.71) the discriminant ($b^2 - 4ac$) > 0 , therefore the quadratic equation has two real roots as seen in Equation (A.72). Based on the fact that the solution in this case is for an actual dimension of a plate, the positive root is the logical choice between the two roots.

$$\therefore h = 10.399 \text{ mm} \approx 10.4 \text{ mm} \quad (\text{A.73})$$

1.6. Justification Based on Microstructure

Comparison of the microstructures of as-built and stress relieved DMLS Ti6Al4V (ELI) and wrought Ti6Al4V provides further insight into the former as a better candidate than the latter for high velocity impact applications. At room temperature the microstructure at equilibrium of Ti6Al4V alloy consists mainly of the hexagonal close packed α phase with some retained body centered cubic β phase [26, 27]. As the temperature is raised the alloy undergoes a α to β transformation [26, 27]. The lowest temperature at which a 100% β phase can exist is called the beta transus and it is about 995°C [26]. Figure A.4 and Figure A.5 show the microstructure of wrought Ti6Al4V and DMLS Ti6Al4V, respectively.

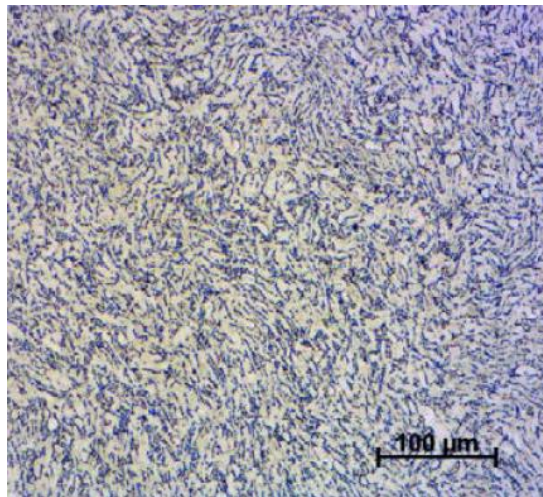


Figure A.4: Microstructure of wrought Ti6Al4V [28]

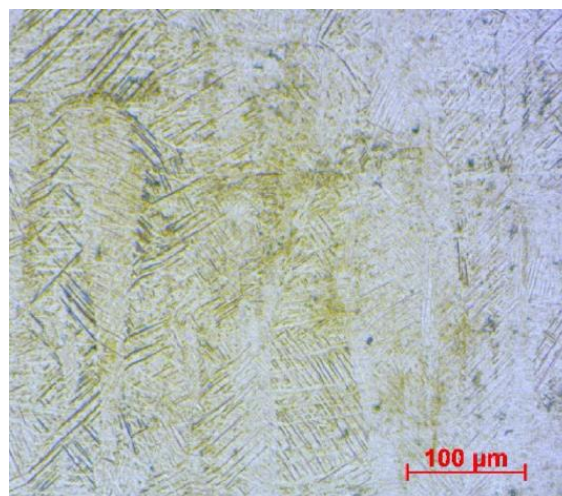


Figure A.5: Microstructure of SLM Ti6Al4V [28]

Wrought Ti6Al4V has an equiaxed microstructure, while as-built and stress relieved SLM Ti6Al4V has a martensitic α' microstructure [9, 16, 29]. This fine microstructure avails more grain boundaries which in turn provide better resistance to crack propagation in the alloy over the wrought Ti6Al4V [16, 29]. Additionally, the fine microstructure of the as-built and stress relieved SLM Ti6Al4V has higher hardness, strength, and stiffness values over wrought Ti6Al4V [28]. The higher hardness comes with an advantage of having a better blunting effect of the projectile during impact, while the higher strength and stiffness offer more absorption of energy before failure of the target material [19, 21].

1.7. Discussions

Table A.2 shows the calculated optimum thicknesses from each approach adopted here.

Table A.2: Calculated values of optimum ballistic plate thicknesses

Material	Density (g/cm ³)	Description	Optimum thickness (mm)
Wrought Ti6Al4V	4.2	Calculated V_{50} ballistic limit	15.38
		Experimental ballistic limit	≥ 14 [4]
As-built and stress relieved DMLS Ti6Al4V (ELI)	4.2	Calculated V_{50} ballistic limit	13.64
		Corrected calculated V_{50} ballistic limit	12.41
		Calculated ballistic limit based on the absorbed shear strain energy	10.40
RHA	7.8	Military standard MIL-A- 12560H (MR): Military specification for armour plate, steel, wrought, homogeneous (for use in combat-vehicles and for ammunition testing)	11.43

AA 5083	2.7	Military standard MIL-DTL-46027K (MR) Military specification for armour plate, aluminium alloy, weldable 5083, 5456 and 5059.	19.80
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From Table A.2 it can be seen that the calculated values of optimum thickness of as-built and stress relieved DMLS Ti6Al4V (ELI) of 13.41 mm and 10.40 mm respectively, based on the V_{50} ballistic limit and shear strain energy are lower than those of wrought Ti6Al4V of 15.38 mm and 14 mm, based on theoretical calculations of V_{50} ballistic limit and experimental results, respectively. The difference between the experimental and V_{50} ballistic limits for wrought Ti6Al4V can be attributed to the fact that the non-uniform plastic and elastic deformation of the material was not considered in the calculations.

Taking this into consideration, the difference between the two was expressed as a correction factor of 9 % in Equation (A.27) and then applied to the calculated V_{50} ballistic limit obtained for as-built and stress relieved DMLS Ti6Al4V (ELI) to give a final value of expected experimental optimum thickness of 12.41 mm. In the calculations based on shear strain energy, the comparatively much lower value of 10.41 mm obtained can be attributed to the disregard of the non-uniform plastic deformation of the material; wrought and as built and stress relieved DMLS Ti6Al4V (ELI).

While theory normally assumes pure plastic deformation after yield, the work of Somnath Chattopadhyay and Byoungchul Hwang shows this not to be entirely so, and small amounts of shear strain hardening do occur in practice [35, 36]. The much lower value implies a more significant shear strain hardening effect for the wrought alloy than the DMLS alloy, and therefore a more significant error of calculation for the former than the latter, when ignoring this effect.

The optimum plate thickness of 10.40 mm calculated for as-built and stress relieved DMLS Ti6Al4V (ELI) using the strain energy approach is significantly lower than those of RHA and AA 5083 at 11.43 mm and 19.8 mm, respectively. The calculated

V_{50} optimum plate thickness of 12.41 mm is marginally higher than the value for RHA and significantly lower than the value for AA 5083.

Considering the effects of the densities of RHA, AA 5083 and Ti6Al4V of 7.8 g/cm^3 , 2.7 g/cm^3 and 4.2 g/cm^3 , in that order, the as-built and stress relieved DMLS Ti6Al4V (ELI) with a density of 4.2 g/cm^3 gives a weight saving of about 46% over RHA for plates of the same in-plane sizes.

The foregoing analysis shows that as-built and stress relieved DMLS Ti6Al4V (ELI) is expected to perform better under ballistic impact than the wrought Ti6Al4V. Therefore, ballistic testing with the DMLS Ti6Al4V (ELI) is recommended to validate the theoretically determined values and with anticipation that the material would yield better ballistic impact properties than wrought Ti6Al4V.

1.8. Conclusions

The deviation of the theoretical calculations from the experimental results of optimal thickness is 9 %. This deviation can be attributed to not considering the non-uniform plastic deformation of the material before failure, which is not the case in reality. In estimating the minimum plate thickness using the V_{50} ballistic limit, a correction factor of 9 % should be used to adjust the calculated value of thickness down.

It is safer to use the higher value of calculated minimum thickness of penetration for as-built and stress relieved DMLS Ti6Al4V of 12.41 mm obtained from the method of V_{50} ballistic limit, over the lower value of 10.40 mm obtained from the method of shear strain energy, as the former is the more conservative estimate.

The lower calculated values of minimum thickness for DMLS Ti6Al4V (ELI) imply expected better performance of the material in comparison to thicknesses of RHA steel of 11.43 mm, AA 5083 of 19.8 mm and wrought Ti6Al4V of 14 mm. This justifies further investigation into the high velocity impact performance of the additively manufactured alloy.

As the calculations done here are based solely on the strength and deformation of the impacted plate, considerations of hardness are expected to further decrease the optimum thickness of DMLS Ti6Al4V as-built and stress relieved plates.

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APPENDIX B

Figure B.1 is the wrought Ti6Al4V supplier material certificate

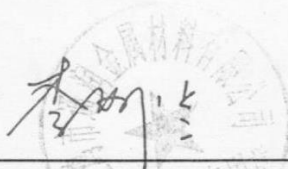
BAOJI TONGRUN METAL MATERIAL LIMITED COMPANY											
MILL TEST CERTIFICATE						No: 20181221					
EN10204 3.1						DATE:11.Dec.2018					
Commodity: GR5 TITANIUM PLATE						Finish:ANNEALED					
Specification:ASTM B265											
Size [mm]		Heat NO.		Quantity [pc]		Net Weight [kg]		/			
6×100×100mm		534-3928		6		1.6		/			
Chemical Composition(WT%)											
Requirement		Ti	Al	V	Fe	C	N	O	H	Residual element	
		Remainder	≤	≤	≤	≤	≤	≤	≤	≤	≤
			5.5-6.75	3.5-4.5	0.30	0.08	0.05	0.20	0.0125	≤ 0.10	≤ 0.40
Result	Top	Remainder	6.53	4.36	0.168	0.005	0.006	0.13	0.003	≤	≤
	Bottom	Remainder	6.45	4.21	0.170	0.005	0.007	0.12	0.002	0.10	0.40
Tensile Test											
Requirement Min		Tensile Strength		Yield Strength 0.2%		Elongation		/			
		[Mpa]		[Mpa]		[%]		/			
		895Min		828Min		10Min		/			
		1034		988		16		/			
Other Test											
Visual Inspection			Dimensional Inspection			/					
Acceptable			Acceptable			/					
/			/			/					
/			/			/					
I hereby certify product conforms to all specifically listed technical requirements, and other requirements for these specifications. Furthermore, I certify the above quantitative were derived from testing and analysis and are in accordance with the reference specification(s) requirements.											
 VICE-MANAGER OF QUALITY DEPARTEMENT BAOJI TONGRUN METAL MATERIAL LIMITED COMPANY											

Figure B.1: Wrought Ti6Al4V supplier material certificate