RESIDUAL STRESSES IN DIRECT METAL LASER SINTERED PARTS

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Abstract

Direct Metal Laser Sintering (DMLS) fabricates parts using a track-by-track, layer-by-layer method in which powder is formed by melting and solidification of single tracks and thin layers. A laser beam scans over the powder layer thus creating a cross-sectional area of the 3D object. High-concentration of laser energy input leads to high thermal gradients which induce residual stress within the as-built parts. Methods for measurement residual stresses and stresses in DMLS parts were analysed.

Keywords: Additive manufacturing, direct metal laser sintering, residual stress, titanium alloys

1. INTRODUCTION

Additive Manufacturing (AM) is a relatively new technology. From its development in the 1980's up to the present day AM has developed at a rapid rate. Products and services for AM grew at a compound annual growth rate of 35.2%, as stated by Wohlers Report (2014). Direct Metal Laser Sintering (DMLS) is a kind of AM which produces objects from metal powder deposited in a thin layer by selective laser scanning. The laser beam scans over the powder thus fusing the powder particles and also the previous layer. Sequentially, track-by-track, layer-by-layer, a 3D part is sintered. DMLS can produce fully dense parts with complex geometry and internal structures, lightweight lattice structures and multi-material objects. This technology opens up new avenues in the automotive, aerospace and medical fields where unique designs are required.

Modern DMLS systems use fibre lasers with high power densities. For a laser power of 200 W and spot size of 80 m, the power density reaches about 40 kW/mm2. The concentrated heat input leads to high thermal gradients which, in turn, induce residual stress within the DMLS part.

The Centre for Rapid Prototyping and Manufacturing at the Central University of Technology, Free State specializes in producing implants and functional parts from Ti6Al4V (ELI) using the EOSINT M280 system at prescribed parameters by Electro Optical Systems (EOS) for this alloy. Knowledge about values and directions of residual stress is of primary importance for manufacturing of reliable DMLS objects.

Residual stresses are those stresses locked in a solid material when it has obtained equilibrium, these stresses are in balance, with no external influences applied. The effects of residual stress may be either beneficial or detrimental. It depends upon the magnitude, sign and distribution of the stress with respect to the loading. Very commonly, residual stresses are detrimental and there are many documented cases in which these stresses were the predominant factor contributing to fatigue and other structural failures when the service stresses were superimposed on the already present residual stresses. The particularly insidious aspect of residual stress is that its presence generally goes unrecognized until after malfunction or failure occurs (Vishay Measurements Group, 1993). Leuders et al. (2013) studied fatigue resistance and crack growth performance in DMLS Ti6Al4V samples. It was found that the main influencing factor on crack growth behaviour is the residual stress. Vrancken et al. (2014) investigated residual stress in DMLS Ti6Al4V compact tension specimens produced at different building strategies (xz, zx and xy direction). With the contour method it was found that the residual stress is a major factor in the anisotropic behaviour of material produced by DMLS.

2 RESIDUAL STRESSES

2.1 Definition, types and sources

Residual stresses in a material or component are those stresses that exist in the object without (and usually prior to) the application of any service or other external loads. Virtually all manufacturing and fabricating processes – casting, welding, machining, moulding, heat treatment, etc. – introduce residual stresses into a produced object. In practice no component is entirely free of residual stress (Withers and Bhadeshia, 2001).

Another common cause of residual stress is in-service repair or modification. Also stress may be induced later in the life of the part by installation or assembly procedures, by occasional overloads, by ground settlement effects on underground structures, or by dead loads which may ultimately become an integral part of the structure (Vishay Measurements, 1993). Unlike stress caused by external loading, which can be calculated accurately using appropriate formulae, residual stresses are less predictable.

Residual stress is categorized differently depending on its length scale: Type I stress is a macro-stress which equilibrates over large distances or dimensions such as size of the part or structure. Type II are intergranular stresses equilibrate over an amount relating to the grain dimensions (usually 3-10 times that of the grain size). Type III stresses equilibrate over an area of a single grain size (Withers & Bhadeshia, 2001).

Type I macro-stresses in general may be introduced due to manufacturing or post-processing of the parts: non-uniform plastic deformations due to mechanical processing such as shot-peening, hammer-peening, etc.; different surface treatments (plating, coatings); heating or cooling; structural changing such as milling, lathe-work, bending; differing thermal expansion coefficients and mechanical mismatching of varying components of composites (multiphase materials, ceramic coatings) (Totten et al. 2002). Since different properties of elastic and thermal properties exist for differently orientated neighbouring grains and different phases, type II micro-stresses present in polycrystalline materials. Coherency at interfaces and dislocation stress fields cause type III stresses (Withers and Bhadeshia, 2001). Thus, origins of residual stress formation are, material, material processing and loading (Hauk, 1977).

Residual stresses influence on mechanical properties (fatigue, yields and ultimate tensile strength), hardness, friction, corrosion and dimensional stability (Totten et al., 2002).

2.2 Measurement or residual stresses

Residual stresses measuring techniques can be divided in three classes: 1) non-destructive (such as X-ray diffraction method, neutron diffraction method, Barkhausen noise method, ultrasonic method); 2) semi-destructive (hole-drilling technique, deep-hole method, ring-core method) and 3) destructive (sectioning technique, contour method).

X-ray Diffraction (XRD) is the conventional and time proven technique for measuring residual stresses. Using the interatomic spacing d as the ultimate gauge length, the X-ray technique is ideal for and applicable to all crystalline materials, especially for metals, but also for ceramics (Stresstechgroup, 2012). The d-spacings are calculated using Bragg's Law: $\lambda = 2\ d\ sin\ \theta$. If a monochromatic X-ray beam impinges upon a sample with an ordered lattice spacing (d), constructive interference will occur at an angle θ. Changes in strain and thus the d-spacing translate into changes in the diffraction angle measured by the X-ray detectors. The diffraction pattern is in the shape of a cone for polycrystalline materials. The shape of the diffraction peaks can also be related to the dislocation density and coherent domain size. The most common sources of errors and misapplications in stress measurements by X-rays are related to stress constant selection, focusing geometry, diffracted peak location, cold-working crystallography, texture, grain size, microstructure, and surface roughness (Ruud et Farmer, 1978).

Neutron diffraction (ND) is capable of measuring the elastic strains induced by residual stresses throughout the volume of relatively thick steel components with a spatial resolution as small as 1 mm^3.

For residual stress measurements in most alloys, especially steels and cast irons, the unstressed spacing (d_o) between crystallographic planes at the exact point of strain measurement is not known and not easily measured. This means that d_o and θ (diffraction angle) cannot be precisely established, and this leads to various degrees of error in the accuracy and precision of ND residual-stress measurements (Totten et al., 2002).

Magnetic methods: Barkhausen noise analysis technique is concerned with measuring the number and magnitude of abrupt magnetic re-orientations made by expansion and contraction of the magnetic domains in a ferromagnetic metal. These reorientations are observed as pulses somewhat random in amplitude, duration, and temporal separation and therefore are roughly described as noise (Totten et al., 2002).

Ultrasonic methods are non-destructive methods based on variations in the velocity of ultrasonic waves, which can be related to the residual stress state. Transmitting transducer and two receiving transducers for generating and detecting the ultrasonic waves are used. These transducers are attached to the sample under investigation. It has not yet been proven that the conventional ultrasonic method can be used to accurately measure a non-uniform stress field (Sanderson and Shen, 2010, Uzun and Bilge, 2011). However, there are other characteristics of metals that affect the ultrasonic velocity to the same degree as stress. These include crystallographic texture, micro-stresses, multiple phases, coherent precipitates, composition gradients, and dislocation density and distribution (Totten et al., 2002). Laser-ultrasonic method is identical to that of the traditional ultrasonic method but it has the advantage of being noncontact.

Hole drilling and strain gauge technique. Among destructive methods of residual stress measurement, the hole drilling method is most widely utilised. The Hole Drilling Method (HDM) consists in drilling a very small hole into the specimen. Residual stresses relax in the hole, stresses in the surrounding area change causing strains also to change. Strain gauge rosettes are used for measuring these strains. Three methods are available for estimating non-uniform residual stress fields from relaxed strain data for the incremental HDM: 1) Power Series, 2) the Integral and 3) the ASTM E837-08 Methods (Schajer, 1988; ASTM E837; Casavola et al., 2010-2011). However, the utilization of the strain gauge method has some practical disadvantages. Firstly, it requires the hole to be drilled exactly in the center of the rosette in order to avoid sizeable errors. Secondly, it only measures the average strain in the range of the length of the strain gauge and thus is inaccurate in terms of the planar stress gradient (Cheng et al., 2008). As indicated by Rizwan (2008), the accuracy of the method depends on surface preparation, correct strain gauge rosette selection, installation of strain gauges, accurate alignment of the hole and correct selection of incremental hole depths. Since the stress gradient must be assumed to be constant across the hole or ring diameter, areas of high stress gradients should be avoided.

At stresses which are higher than one third of the yield strength of the material, local plastic yielding during metal removal occurs. Large errors in residual stress measurements can be caused by strain hardening of the steel in the vicinity of the hole which may occur during metal removal. As recommended by Totten (2002), the thickness of the part or specimen must be at least four times the hole or core diameter. Heating during drilling can affect results adversely. During the metal removal in different places of the part, the holes must be spaced apart at least eight times their diameter.

Electronic Speckle Pattern Interferometry (ESPI) is an optical technique which enables interferometric measurements of surface displacements on almost any surface and material. The non-contact and full-field measurement allows the calculation of the three dimensional distribution of the displacement and strain/stress of the object under test as a response to a mechanical or thermal loading (Stresstechgroup, 2012). Hole drilling and Electronic Speckle Pattern Interferometry measures changes in the part surface resulting from hole drilling and determines the previously existing residual stresses, and surface distortion measures by ESPI in real-time (Barile et al., 2011).

Contour Method is a solid mechanics superposition technique. This method helps predicting the residual stress in specimens via cutting a sample in two pieces. The deformation resulting from the cut, allows the relaxation of residual stresses, this deformation resulting from stress distribution (Fig. 1) can be modelled via appropriate numerical formulae and practical assumptions and be finitely analysed thus an accurate description of the two dimensional residual stresses normal to the cut plane can be determined. This method is typically performed on metallic parts utilizing the cutting of a wire Electric Discharge Machine (EDM). This method is not recommended for parts smaller than 5 x 5 mm² due to accuracy concerns, but this method is advantageous for complex, spatially varying residual stress fields and complex geometry parts (Olson et al., 2015).

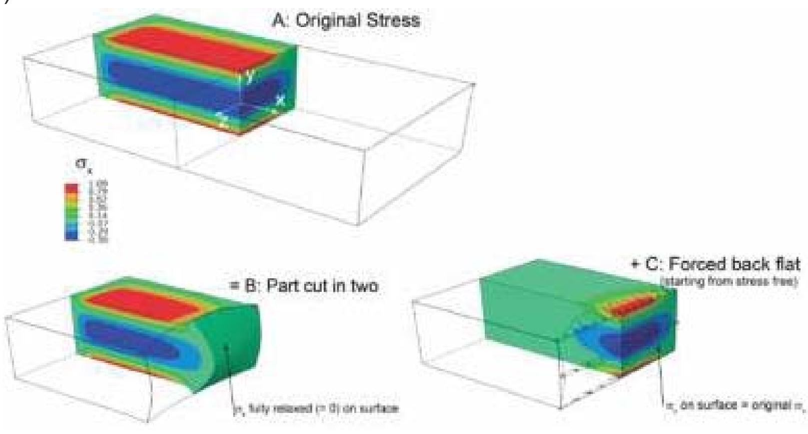

Fig. 1: The Contour Methods theoretical implementation (Olson, 2015)

Curvature methods as bridge curvature method (Fig. 2 and Fig. 3) and bending of cantilevers are used to assess and qualitatively compare the influence of different processing on residual stresses. Buchbinder et al. (2014) used cantilevers for investigation of Al alloy distortion during DMLS. After cutting right and left of the part, the bending angle of the detached arms can be measured. Different residual stress will led to changes in the bending angle.

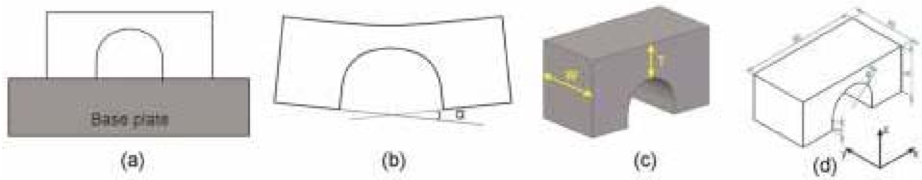

Fig. 2: Bridges for identifying the residual stresses in the test material. (a) Before, and (b) after removal from base plate. Geometry of the test parts: (c) variable width and thickness to optimize the bridge structure for repeatability. (d) Final dimensions of the optimized bridge geometry (mm) (Kruth et al., 2012).

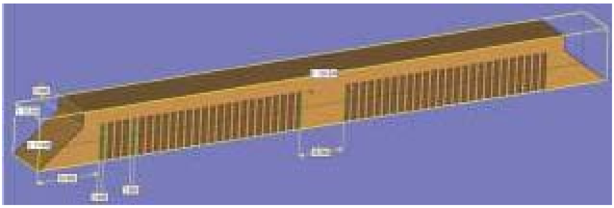

Fig. 3: Geometry of cantilever (Buchbinder et al., 2014)

Hardness testing is a method of determining specific material properties via a controlled testing method. The Vickers testing method is based on the basic principle of a materials ability to avoid plastic deformation. This involves a diamond indentation piece which is forced onto the material surface. The shape usually has a half angle of 60/63 degrees. The force is predetermined to suit the test piece. An indentation then appears upon the surface of the material. This indentation is then measured diagonally, the area of the indentation is thus determined, and so a force/area equation can be used to determine the hardness number. Because the area is not normal to the force it is not pressure that is calculated but a hardness number which can also be expressed in Pascal. When testing the hardness of a material which suffers from residual stress, the indentation may deform to a certain extent (or the RS may influence the hardness number). The magnitude of the deformity may be compared with that of a non-stressed material, the change in area of the indentation could be converted to strain and then a stress value (Hooke's Law), which could then be compared with the XRD results (Totten, 2002).

3. MANUFACTURING OBJECTS BY DMLS

3.1. Temperature gradients

DMLS is a kind of AM technology. The step-by-step sequence for the creation of 3D objects is schematically presented in Fig. 4. DMLS produces parts using a layer-by-layer method in which powder is pre-deposited on the building platform (substrate) in a thin layer. A high energy laser scans a 2D pattern on the deposited powder layer, fusing the powder as well as the previous layer. Then a new powder layer is delivered over the sintered material, the laser beam scans the sequenced layer thereby producing a 3D object.

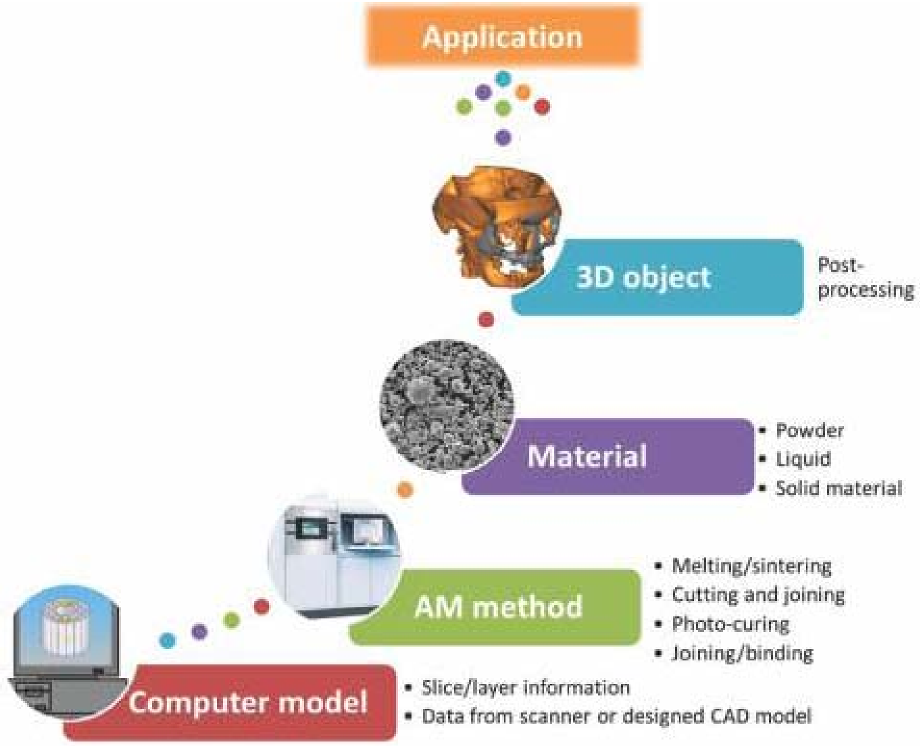

Fig. 4: Step-by-step additive manufacturing of 3D object.

Resulting temperature gradients play a key role in the genesis of the residual stresses in DMLS objects. Different process-parameters and temperature-dependent properties of materials led to the fact that residual stress distributions with AM are not the same from material to material and obviously process to process (Sochalski-Kolbus et al., 2015) (Fig. 5). Since SLM objects consist of multiple tracks and layers, each point of this object is exposed to multiple cycles of heating and cooling (Fig. 6).

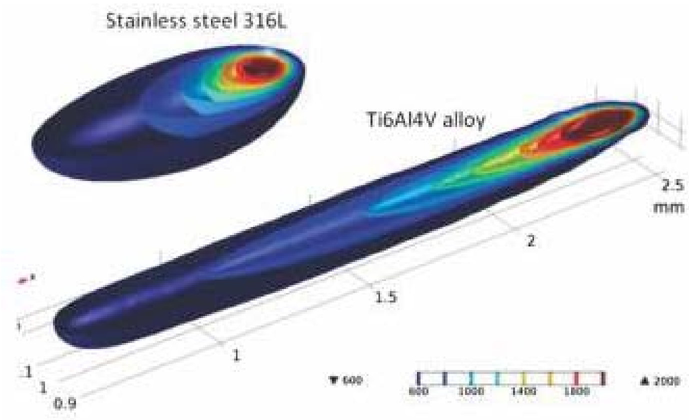

Fig. 5: Isothermal contours for 316L and Ti6Al4V; Process-parameters for Ti6Al4V are laser power density of 19.1 kW/mm^2, scanning speed of 1.2 m/s; for 316L steel 13 kW/mm^2 and 0.1 m/s accordingly (Yadroitsev and Yadroitsava, 2015).

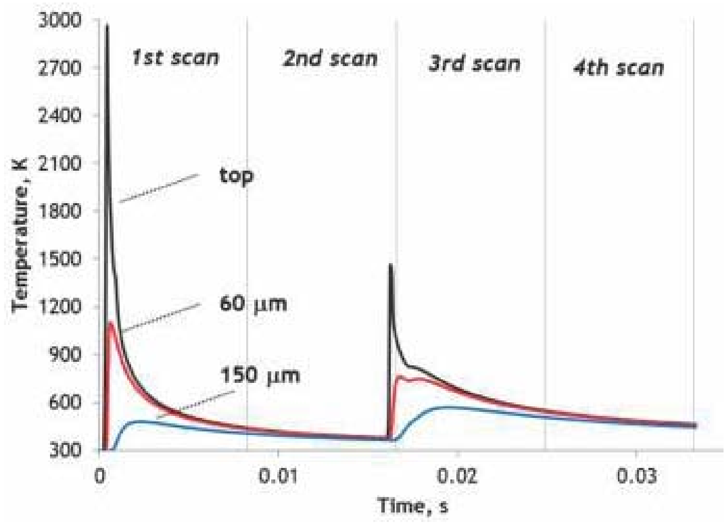

Fig. 6: Temperature profiles (point x=0.5 mm, depth z= 0, 60 and 150 m) during back-and-forth laser scanning of the Ti6Al4V sample with length of 1 cm. Process-parameters for Ti6Al4V are laser power density of 19.1 kW/mm^2, scanning speed of 1.2 m/s.

The temperature of surrounding solid material near the molten pool (heat affected zone) increases during DMLS. High compressive and tensile stresses are present under the front of the molten pool (Yadroitsev and Yadroitsava, 2015).

When the laser beam leaves the irradiated zone, the track begins to solidify and cool down. Since temperature-dependent thermal conductivity defines the heat dissipation and temperature equalization in solids, various layers of material cool at different rates. The Contraction therefore occurs at different speeds. Deformation in the surrounding material and solidifying track are the result of lowered yield strength at elevated temperature of the material. Non-uniform deformation of the surrounding solid material results in residual stress being present in the DMLS objects.

3.2. Residual stress

Residual stresses are the consequences of the interaction with time, temperature, deformation, and microstructure (Fig. 7). Material or material-related characteristics that influence the development of residual stress include thermal conductivity, heat capacity, thermal expansion, elastic modulus and Poisson's ratio, plasticity, thermodynamics and kinetics of transformations, mechanisms of transformations, and transformation plasticity (Totten et al., 2002). The main tensions occurring immediately after DMLS are: tensile and compressive stresses: metals expand when heated and shrink when cooled. Stress due to phase transformation, causes a change in volume and it develops during phase transformation of austenite (face centered cube, fcc) to ferrite (body centered cube, bcc), or α-phase (hexagonal close-packed crystalline structure) of titanium alloys to ß-phase (body-centered cubic) (Donachie, 2000). If the part consists of multi-material, different materials will shrink at different rates, causing strains in or between the materials.

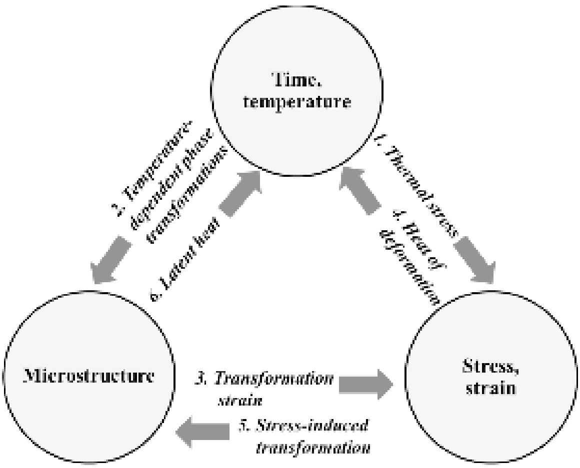

Fig. 7: The coupling of temperature, stress, and microstructure (Inoue and Wang, 1985)

Residual stresses are mostly dependent upon the manufacturing process and cannot be completely avoided. Ritchie et al. (1999) found that DMLS components that remained attached to the base plate contained stress levels near to that of the material yield strength, whereas components removed from the base plate had lower stress levels – yet deformation was present. One way to minimise the degree of temperature gradients (which seem to cause the high residual stresses) is to equip the DMLS machine with a heater that reduces the severity of the temperature gradient around the laser spot (Zhang et al., 2010; Knowles et al. 2012). Geometry of parts should be optimized in order to keep residual stresses and distortions low (Casavola et al., 2011). To reduce the thermal stresses Concept Laser GmbH patented the island scanning strategy, it divides the area to be scanned into small square islands, the sequence in which the islands are scanned is chosen randomly. Kruth et al. (2012) used bridge curvature method showing that a short scan DMLS strategy or preheating of the base plate reduce the thermal stresses.

In order to improve the mechanical properties and the dimensional accuracy of the DMLS samples, Shiomi et al. analysed heat treatment at 600 and 700°C for one hour. It was found that it reduces the residual stress effectively by about 70%. Re-scanning with the laser and heating of the powder bed decrease the tensile stress by 55% and 40%, respectively. Sanz et al. (2008) subjected DMLS CrCo parts to different thermal and mechanical stabilization treatments with the objective of determining the optimum treatment according to material state and residual stress. The stabilization treatments studied consist of different thermal treatments carried out at several temperatures and under three different atmospheres, followed by the application or non-application of shot peening. Among the treatments studied, the combination of shot peening plus a heat treatment of 2 hours at 850 ºC in N2 atmosphere leads to the highest compressive residual stresses at the surface and to the highest hardness in the core. Using other heat treatment atmospheres (air or vacuum) and/or other temperatures (650ºC, 1000 ºC) or applying only shot peening (without heat treatment) do not result in such compressive surface stresses. The final polishing has also a beneficial effect in the piece as it induces higher compressive residual stresses at the surface. Wang (2012) applied Hot Isostatic Pressing (HIP) treatment after DMLS to consolidate the microstructure and eliminate the defects. Good mechanical properties and acceptable surface finishes were produced via SLM Hastelloy® X. The varying properties of different alloys mean that not all materials are suitable for this process. It was indicated that further research is needed to build a database of processing conditions for different materials. Due to the nature of manufacturing, DMLS parts have anisotropy of mechanical and structural properties (Yadroitsev, 2009).

4. CONCLUSION AND FURTHER RESEARCH

XRD is effective in measuring residual stresses within materials. This method is widely applied in industry because a large variety of samples large or small with complex geometry can be measured, also as a non-destructive method it is preferred for various reasons (in the case of layer removal it can be seen as semi destructive). XRD is to the authors' knowledge the most commonly used non-destructive method to accurately measure residual stress in multiphase materials. Since the main source of residual stress during DMLS is the thermal gradients, residual stress will depend not only on material properties, process parameters, powder layer thickness, scanning strategy, preheating, etc., but also the geometry of the samples and support structures. During manufacturing, heat treatment is seen as the optimal method to reduce residual stresses in DMLS parts. Before removal from the substrate, all DMLS samples, especially those with fine structured features, must be heat treated to avoid significant deformation. Determination of optimal conditions for different materials to relieve the residual stresses during manufacturing and to obtain acceptable performance properties of DMLS parts are the subject for further in-depth studies in DMLS.

5. ACKNOWLEDGEMENT

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