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Advantages and Drawbacks of Additive Manufacturing

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Abstract - This paper presents some various imperfections that can occur during Direct Metal Laser Sintering (DMLS) and their effects on part quality. Direct Metal Laser Sintering is one of the Additive Manufacturing (AM) technologies that enables fast production of an accurate, functional, complex shape parts and tools, without additional tooling, directly from 3D CAD model. This process is based on layer by layer manufacturing, where the fusion of the metal powder is performed by selective melting with laser beam. The laser beam moves and scans area that correspond to section of the part for the specific layer. In the DMLS the part is built layer by layer, where the process of the melting and solidification occur in small volume in relatively short time. Thanks to this kind of approach, the DMLS has much less limitations than the subtractive methods of part production. However, the production in the layers has some drawbacks, which can have a significantly influence on the part geometry, structural errors and part imperfections. Some of the advantages as well and drawback of the DMLS of metal parts has been presented in this paper.

Keywords: Maraging steel, Stainless steel, Additive manufacturing, Direct Metal Laser Sintering, Porosities, Machining, Fatigue, Initial crack, Tooling, Defects.

0. INTRODUCTION

Unlike traditional methods of manufacturing, where products are made by removing or forming material using different sets of machines or tools, Additive Manufacturing (AM) technologies make product by joining successive layers of a material. Parts are being built using 3D CAD model and AM machine. CAD model is divided in layers of appropriate thickness that correspond to manufacturing process based on the type of machine and the material. Whole process of the melting of the material is performed in the one plane that corresponds to the one layer. There are various technologies for AM of the metal parts, which work on different principles and with different metal materials [1-3]. It is possible to distinguish two ways of material deposition and melting. One is where powder material is deposited on whole building surface where laser or electron beam selectively melts area that correspond to layer of the part. Second is where material is simultaneously deposited and melted on the needed area that correspond to section of the part that is being built. One of the AM technologies that enables manufacturing of functional metal parts is Direct Metal Laser Sintering (DMLS) to which accent is put in this paper. DMLS belongs to first group regarding to the material deposition and melting. This type of the methodology offers quick manufacturing of the complex and functional parts which are shown on Fig. 1. DMLS use the laser beam for melting of the powder, whose movements (scanning) are controlled with a set of mirrors. In this way, mirrors direct laser beam on the powder surface that need to be exposed and melted. In the process of the cooling, the melted powder has been bonded with previous layer, bonding in the vertical direction, as well and with previous laser trace in the current layer, horizontal bonding. In order to achieve a solid part, a good fusion and material bonding need to be performed in both directions. The parts in AM technologies are always built in the direction perpendicular to the layers, in the most cases in the vertical – z direction.

Fig. 1: Lightweight structures manufactured by DMLS

In DLMS, the parts are being manufactured on base plate, which has role to remove heat and prevent motion and deformation of objects that may occur due to the residual stresses caused by thermal gradient. Manufactured parts are thus connected to the platform by supports that are manufactured simultaneously with the object.

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1. APPLICATION OF THE AM

One of the interesting fields of the AM application is in light weight structures, where manufacturing via subtractive machining is impossible. The evaluation the manufacturability and performance of AlSi10Mg aluminium alloy based lattice structures, fabricated by DMLS has been published by Chunze Yan, et all [4]. There are possibilities to manufacture lattice structures using an investment casting or similar technologies, but this approach for single part or small series can be time and cost consuming. In this case AM has significant advantage. With DMLS, the structures were manufactured with volume fraction of 7.5% to 15%. In lower fraction, structures tend to damage due to small dimension of the strut, which are closed to dimension of the laser beam focus diameter. In this case, it is shown that there are the limitations in minimal thickness of the walls and struts of the lattice structures. Authors concluded that compressive modulus and strength of the DMLS manufactured lattice structures increase with increase of the volume fraction. The application of the light weight structures and their advantages are also performed and on finger exoskeleton part built from aluminium alloy AlSiMg using DMLS [5]. In the past, these types of the parts were bulky and heavy. Manufacturing these parts as light weight benefits to lower energy consumption in movement and speed of robotic arm, due to low mass and inertia.

EADS has shown an application of DMLS technology for manufacturing of brackets with optimised topology [6]. Their examinations have shown a better result in manufacturing off the brackets with DMLS than with investment casting. Savings are being made through carbon footprint and material waist. Renishaw used AM machine to manufacture bicycle frame for Empire Cycles with optimised topology [7]. Aim was to design parts with maximum strength and minimum part weight. The weight saving of the 33% was achieved through topology optimisation (shown on Fig.2).

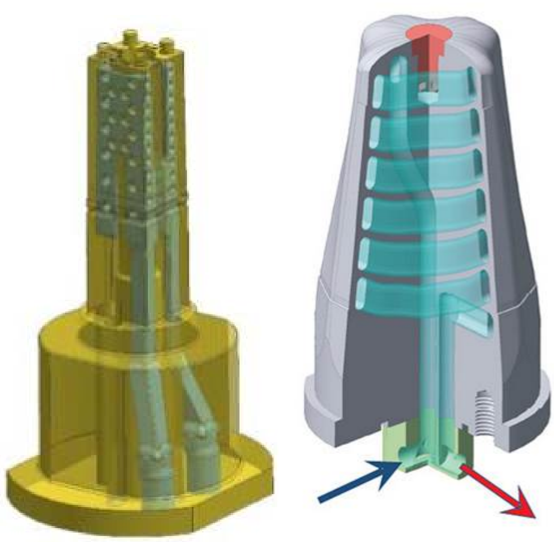
Fig. 2: Lightweight bycicle frame for Empire Cycles manufactured by Renishaw

Robot Bike Co. has also used Renishaw service and produced light weight montane bike frame, combining additively manufactured titanium lugs and carbon fibre tubing [8]. Parts had been produced on an AM250 laser melting machine with 200W laser (Fig. 3). This is good example of manufacturing light weight product using a different cutting edge technologies.

Fig. 3: Lightweight bycicle frame for Robot Bik Co.

European Powder Metallurgy Association had issued a brochure, with application of various AM technologies for manufacturing of metal parts and components with topology and mass optimization. Some examples, which they showed in brochure, are Ti6Al4V support for satellite antenna made by EBM with a lightweight design made by topology optimization, lightweight stainless screws, complex CoCr Fuel Injector made by DMLS, hollow Ni 718 turbine blades made by SLM, etc. [9]. This Brochure can be used as guideline for engineers to get a wider picture about AM possibilities. In topology optimisation, AM technologies provide great opportunity for engineers and designers to manufacture parts with best mass-load ratio. Engineers now can design parts which are optimised for loads in particular sections, with greater freedom in the part design and shape. Some restrictions that exist in classical manufacturing are not present in AM manufacturing. In the case where it is necessary achieve higher surface quality, the machining is mandatory and an attention in part design is needed. The AM has shown significant advantages in the manufacturing of the products with optimised mass.

Another application of AM has found in the tooling process for injection moulding. Since the AM technologies offers great design and manufacturing freedom, manufacturers of injection mould tools saw their opportunity to widely use this technology. Most important factor in injection moulding is quality of the part and cycle time. Quality of the part is depended up on surface quality of the mould, polishing capabilities and adhesion of the tool material. Cycle time is the second important factor even though it is a widespread opinion that it is first and most important factor. This is the true only if efficiency is not taken in consideration. Efficiency in injection moulding could be interpreted as production of the good parts for shortest cycle time. Two previously mentioned factors are interdependent. Using AM technology, it is possible to achieve lower cycle time with better part quality. This is achievable by using a cooling channels designed near by the surface of the tool. This kind of cooling channels are called “conformal cooling” channels. This type of cooling channels is hard to achieve using other manufacturing technologies than AM, and in this way, traditional straight cooling channels can be replaced with channels that follows geometry of the part. There are no limitations regarding channel tooling accessibility since they are being made during additive manufacturing process. Some research of optimisation, die conformal cooling channels had been performed by Suchana A, J. et all [10,11]. Authors used ANSYS workbench to analyse different channels cross section geometry, length and pitch number. The application of this type of the cooling have been results in cycle time reduction from 22% to 45% [12]. Authors underlined importance of temperature at the end of the channels, which depends upon channels length and cross section dimension. Research of AM conformal cooling for LEGO, gave lowest temperatures at the channels ends (inlet 20C°, outlet 51°C) Fig. 4 a). Cycle reduction of up to 42% was done for child goblet by Polymold Fig. 4 b) [13].



a) b)

Fig. 4: Example of conformal cooling chanels in tools

Tool insert with conformal cooling for LEGO

Conformal cooling for BKL, Polymold

More advantages and application of the additive manufacturing in the tooling production using DMLS are presented by EOS GmbH, manufacturer of DMLS machines [14, 15].

Additive manufacturing also making its path in medical application. Nowadays, AM gives the possibility to produce custom medical implants with porous structure and tailored mechanical properties toward patients’ needs such as custom hip implants [16]. Cranioplasty surgery use AM technology to make implants shapes that perfectly fit a patient anatomical structure with good aesthetical results after recovery [17, 18].

Fig. 5: Example of custom made Foot orthoses [19]

Research about use of AM for manufacturing custom foot orthoses was also done [19]. Benefit of technology is fast and custom gained Foot orthoses and prosthetic sockets with good fit and adequate strength, which brings better comfort to a person. Only thing that could be drawback is based on financial aspect, dealing with the high manufacturing cost.

Maybe biggest potential of AM application is in Aerospace industry. This is one of most demanding industry area, constantly developing, where more and more demanding tasks are being posted to the engineers, regarding mass reduction and efficiency of machinery. A typical demand is a turbine development and manufacturing. The AM can meet demands in manufacturing complex and challenging structures. During turbine blade development and manufacturing, AM started to be irreplaceable due to reduction of the time and cost.

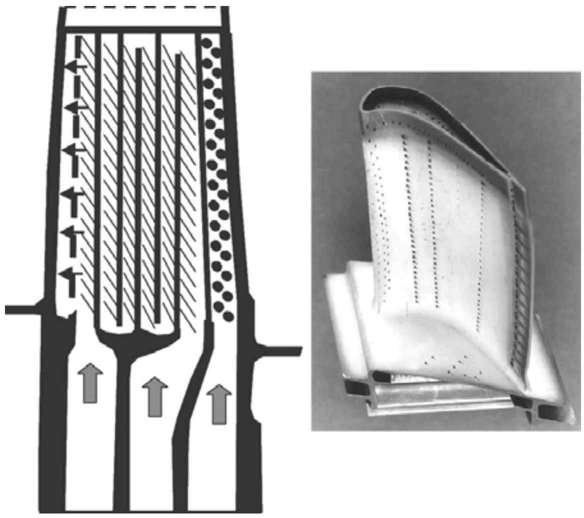


Fig. 6: Example of cooling circut inside blade [20]

Turbine blades are very complex machine parts, whose manufacturing is not so simple due to complex geometrical conditions. Outer surface shape complexity is one part of the problem, another problem is inner cooling channels, being built inside blade. Efficiency of turbine blade is depended from operational temperature. This temperature can sometimes exceed melting temperature of the blade material. Channels should cool the turbine blade and keep the temperature under melting point. Couple of the cooling methods can be used, such as: micro cooling passages that goes close to the blade surface, latticework (vortex) cooling, turbulated channel cooling etc. [20]. Due to small dimension and complex topography, inside blade, it is hard to imagine any other technology for manufacturing these types of cooling channels, other than AM.

Taking into account all advantages, the AM will be widely spread in the industry as well and on consumer market, in the near future. It has a great potential to be irreplaceable in development of new products, custom production and single product manufacturing, where small number of pieces is needed.

2. LIMITATIONS

Taking in consideration all presented by now it sounds like AM is almost "almighty" technology with almost no limitations. This is far from truth. This technology demand changes in approach of part manufacturing. In AM the material is not being taken off, but added where is needed. Production in the layers gives opportunity to take off restrains regarding shape complexity in large percent, but complete absence of machining process is questionable.

Some of AM technology limitations are:

- Minimal wall thickness is 0,4mm for DMLS; 0,3-0,5mm for SLM; 0,6-1mm for EBM;
- Building volume is limited according machine,
- Limited amount of material powder types is available,
- The price of the material is high due to powder manufacturing process cost,
- Supports are needed in manufacturing process,
- Surface quality,
- Residual stresses.

In addition to the above, there are more limitations, and they can all cause the difficulties during the production process or in exploitation.

Minimal wall thickness is in correlation with integrity of previously sintered layers. Integrity of previously sintered material must not be endangered and must enable sintering and good bond of successive layers. In this way, separation of the sintered material from the built part and crash of work is prevented. This all depends from laser, electro beam or wire diameter. The bigger diameter demands the grater wall thickness of the part. For example, it is not possible to manufacture wall of 0.3mm thickness with laser or wire diameter of 0.5mm. This is technological restrain.

Part dimensions are conditioned by building volume dimension and amount of material at disposal for manufacturing. Manufacturing is usually performed in vacuum or inert atmosphere, in order to prevent oxidation during the process of sintering. Building volume dimension is sometimes better to be small, in production of small scale parts due to lower cost and higher speed of production. The example is production of jewellery from gold. Gold as a material is very expensive and pieces of jewellery are rather small parts. In this case machines with large building volume are not suitable for production from two reasons. The first reason is the amount of material required for the production of the part which has a small volume. Second reason is the time for application of material is bit higher and raises production time in certain percent. Compromise could be powder and wire feed technology, where material is applied only where needed and material stock is depended just from the part volume.

The materials which can be used for AM will play a significant role where the process will be used. Materials are mostly based on Titanium alloys, Aluminium alloys, Nickel alloys, Chrome alloys. Metal alloys, available for classical manufacturing technologies are not suitable for Additive manufacturing. Most interesting metal alloys for AM technologies are being selected and prepared on the specific way. In the AM machines, the metal alloys are mainly used as powder or wire. Powder materials are usually made by gas or water atomisation. This type of the process production of powder is expensive and gives a limited amount of material which can be used.

Regarding AM process of metal parts, the beginning of manufacturing process must start from base plate. The base plate is a metal plate from material that corresponds to material of the part that needs to be built. For instance, base plate for building parts from aluminium alloys, need to be made from aluminium alloy, etc. The reason for this is compatibility of two materials in the contact, which will lead to the better bonding between parts and building plate. The base plate has double role. One is, to position part on it, keep the part in fixed position and enable precise building one layer over the other. Second role is to transfer heat from the built part away.

As a part of process, melting and solidification of material is done in small volume in short period of time. Result of this are residual stresses in built parts [22,23]. If residual stresses overcome limit of tensile stress, micro cracks can occur [24,25]. To keep part not to curl or deviate, a good connection between part and base plate is mandatory. In the case of the part deformation or curling, the job crash or more serious, damage of the machine due to collision of the moving elements with built part, can happened. The residual stress can be lowered down or even eliminated, using heat treatment or hot isotactic pressuring [23,26]. It is noticed that residual stresses are lower in parts where base plate is heated on higher temperatures [27]. This is the characteristic for EBM process [28]. To prevent curling and detaching parts from base plate, support connection between part and plate must be strong enough. Strong residual stresses can induce cracks on the support structure, as it is shown on Fig. 7.

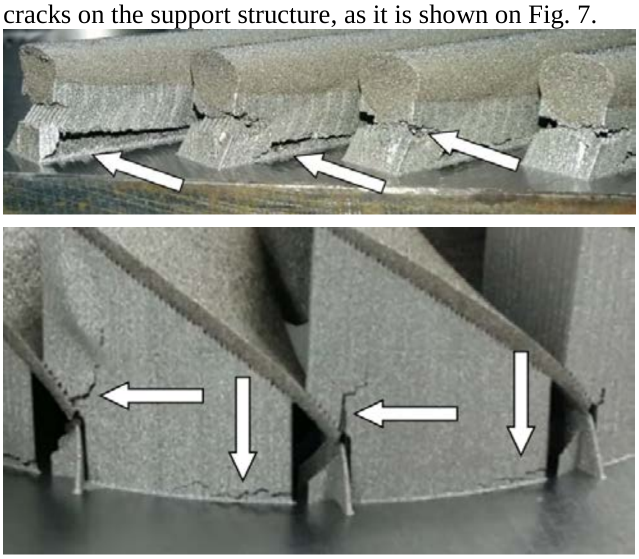


Fig. 7: Example support structure cracks, caused by residual stress on DMLS build part

On the picture (Fig. 7.) cracks are marked on the support structure, between building plate and the part.

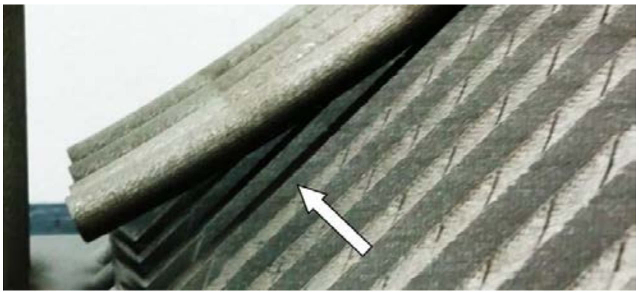


Fig. 8: Example of support structure deatach, caused by residual stress on DMLS build part

For easier detach of parts from support structure, a teeth are generated as bond of support and parts. Teeth need to be strong enough to hold part fixed and enable easy detach of the parts from the supports. If teeth structure is not strong enough, residual stress can cause detachment of the part from support (example of detachment Fig.8). In this case, the collision of mobile elements and parts is certain and job crash is imminent.

Fig. 9: Curling of overhang

The metal powder is not self-supporting so it is not possible to produce the parts without support structure due to weight, forces during powder application and heat generated in melted area. This can be problem if overhangs are neglected in process of support generation. Small overhangs can cause curling, over burn and jam of the machine. This happened during DMLS process where recoater jammed with curled material of small overhanging structure without support (Fig.9). In this case, it was not possible to continue with the production process because the overhanging surface was damaged. The influence of the supports on the overhanging surfaces on the AlSi10Mg parts has been presented in the research of Atzeni. E et all [29].

As a part of the process, porosities in parts are present in certain amount. This phenomenon is present as a consequence of process the laser sintering. For example, in DMLS or SLM process, laser power, laser diameter, speed, offset, layer thickness and scanning speed, has influence in presence of porosities and voids in material [30,31]. It is possible that for different machines and same material, porosities and inclusions presence are completely different.

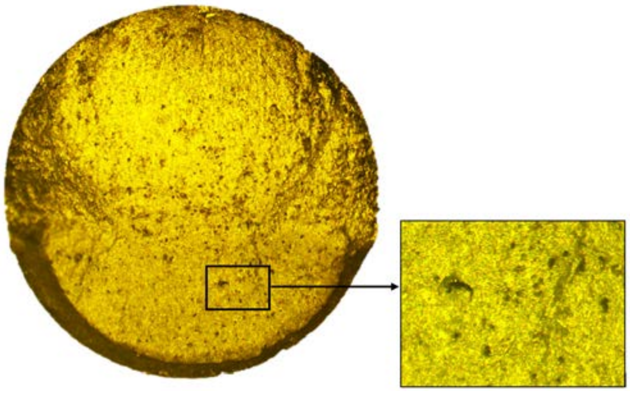


Fig. 10: Break surface of MS1 (EOS Gmbh) DMLS built sample

3. CONCLUSION

Advantages of technology offers great freedom in manufacturing complex shape, light weight parts with topology optimisation, tools for mould industry, prosthetics, and medical implants. AM enables fast production of metal parts without additional tools just with use of 3D CAD model. Considerably saves in the time of development a new product, in production of prototypes or small series can be achieved by using AM. This technology is almost irreplaceable for manufacturing of complex internal structures like conformal cooling channels and lattice structures.

Cost efficiency of AM is disputable. Machines themselves have comparable prices with modern CNC machines, but the material price is still high compared to stock material.

AM offers wide possibilities in custom product manufacturing but it will not completely replace classical production technologies in the near future.

Designers and engineers must be introduced with AM and properly educated, in order to understand all advantages and limitations of the new technology. AM offers great freedom in part shape, but residual stress, porosities, surface roughness, part dimensions, available materials and additional post processing, are just some of the main restrains which needs to be considered.

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