CRITICAL REVIEW ON CHRACTERIZATION OF DMLS MATERIALS

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Abstract

Direct Metal Laser Sintering (DMLS) is an Additive Manufacturing (AM) technique in which the metal powder will be sintered in selected regions as per 3D CAD file in a layer by layer fashion in an inert atmosphere to produce part of any geometrical complexity with ease. Approximately 150 published works were examined. In this paper most widely used DMLS metal powders mechanical and tribological properties were analyzed and the effect of post processes on the material properties were discussed. The objective of the paper is to consolidate the works done so far and to identify apertures to extend scope of this technology. The emerging and out reaching application of this revolutionary technology in various sectors like biomedical, aerospace and automotive was also discussed based on material properties. This review would help researchers to find challenges in this booming technology. As per the materials point of view future research prospective was suggested in depth in light of present review.

Keywords, DMLS, Additive Manufacturing, Metal powders, Mechanical properties, Tribological properties.

1.0 Introduction

At present, additive manufacturing (AM) is an invigorated technology in sectors like bio medical, dentistry, aerospace, automobile and manufacturing [1]. In this technique, there is an addition of material in a stacking manner to build a prototype or a functional part despite of subtracting material from stock as in the case of conventional machining. Beside of having limited availability of feasible materials and machines, it is emerging technology capable of producing small and medium lot size parts in relatively less time with more accuracy. There is availability of more work space and flexibility of manufacturing due to no tooling. According to ASTM, the AM technologies are of two types namely Powder Bed Fusion (PBF) and Direct Energy Deposition (DED). The further classification was shown in Fig. 1[2].

In the present paper we emphasized only on Direct Metal Laser Sintering (DMLS) is one of the techniques of PBF. In DMLS metal powders are used to build a 3D object directly from a 3D CAD file. Basically, the final object can be obtained in the machine on a moveable platform by applying powder material as successive layers [3-7].
After a layer was spread by recoater blade, a high power laser beam is directed on to powder bed and it will sinter the powder particles at desired locations as per given 3D file. The platform moves down the pre programmed layer thickness, a fresh film of powder is spread and the next layer is melted with exposure to the laser source, so that it conforms to the previous layer. This process continues, layer by layer, until the object is fabricated. This process was depicted in Fig. 2.

Selective laser melting (SLM) machines are allude to with different names EOS, GmbH calls the process as DMLS [3] [8]. In this paper SLM also referred as DMLS. Various European countries produce machines with beds that are able to do laser sintering and laser melting [38]. It is a design driven wide spread process because of the availability of different metal powders with desired size, shape and weldability. In this technology it is desirable to have metal powders in the form of spherical and nearly spherical geometry and in tens of micron size to achieve good bonding, homogeneity and crack free products [9]. Among the 50 different atomized powders within reach, most widely used metal powders in AM technology are Ti-based alloys, Nickel based super alloys, Al based alloys, Co-Cr alloys, Stainless steels(316Land17-4PH), Precious metals (Au, Ag), Refractory metals(W, Ta), Cu based alloys, intermetallic and low alloy steels [10].

In DMLS process a porous internal structure can be used to lessen the weight and assuring the strength at the same time. This results in considerable redeeming in powder material and weight as well as energy consumption during processing [11]. This feature of...
DMLS will attract the automobile sector where there is a continuous research to reduce weight, improve strength and functionality [12].

The main intent of this paper is to analyze a group of studies conducted on DMLS process and to present the possibilities and difficulties of using different metal powders based on their properties.

2.0 Literature review

This chapter describes the studies conducted on most widely used DMLS metal powders like Ti-6Al-4V, AlSi10Mg, Stainless Steels, Ni based alloys and Co-Cr alloys. The conclusions drawn from those studies and various possible ways of improving their properties were also discussed along with future scope.

2.1 Characteristics of Ti-6Al-4V

The Ti-6Al-4V alloy is widely used in DMLS process because of its copious applications in biomedical, aerospace, marine and offshore applications. They have good fracture toughness, fatigue behaviour, corrosion resistance and biostability [13, 14]. DMLS technology helped automakers to produce parts of high quality, cost effective, robust and consistent parts [15], which could be a best alternate to traditional manufacturing processes. Since porous structured parts with desirable strength can be produced. Materials produced by DMLS comprehend few defects that have an effect on their mechanical properties. Various research works conducted to find the effect of input parameters on the defect engenderment in DMLS process. The DMLS product quality depends upon factors like laser power, laser scan speed, hatch distance, laser energy density and layer thickness.

The as built DMLS specimens are prone to cracks due to porosity defects. Porosity defect can form due to meagre energy input or due to the use of extravagant energy [16]. So even if the crack sprouted was observed to have incessantly started on the surface, the pores network can act as a barrier for the crack proliferation and cause the sample breakdown. Fig.3 shows the defect observed at fractured surface which is irregular in shape and these types of defects are occurred particularly due to fusion paucity and variable particle sizes of powder [17]. The possible sources for defect generation are unmelted or partially melted powders particles causing inadequate fusion, delamination between successive passes or earlier deposited layers and inducement of gases during manufacturing.

![Fig.3 Fatigue fracture origins of surface polished DMLS specimens [17].](image)

Excessive or much low energy input lead to emergence of different defect generation mechanisms [18]. The hatch distance and scan speed have an impact on surface hardness and final density [19]. Decrease in laser speed and hatch distance lead to increased hardness [20]. Janette brazinova et al. [21] studied the effect of laser power on the hardness of Ti-6Al-4V before and after annealing. It was revealed that the hardness and laser power are directly proportional for both perpendicular and parallel directions of the deposit layers before annealing and it was comparatively more in perpendicularly built specimen. After annealing
hardness shown negative impact for all laser powers for both build directions due dissolving of material structure pattern. Fig.4 shows the directions with respect to build platform.

![Diagram showing specimen orientations with respect to build direction]

**Fig.4 Specimen orientations with respect to build direction [21]**

Anna Guzanova et al. [22] stated that isotropy in mechanical properties of DMLS component resulted due to stress-relief annealing; it considerably reduced the difference in hardness between the two directions (Parallel and perpendicular to build direction). DMLS products have inherent surface roughness, which will limit their applications in automotive and biomedical applications. The as-built surface roughness can be reduced by some surface machining processes. The inherent surface roughness is mainly due to improper process parameters and partly melted powder particles. The surface roughness has a great effect on fatigue life of DMLS Ti-6Al-4V. The surface roughness depends on powder quality, AM system, Processing parameters and notch orientation. Surface machining improves considerably the fatigue strength of as-built Ti-6Al-4V product produced by DMLS [23]. Adrian Baca et al. [24] carried out a study on the effect of build orientation on fatigue strength of Ti-6Al-4V made of DMLS and found that the built direction had clear influence on fatigue performance and it was less in specimens built parallel to build direction.

Few authors tried to revamp the fatigue strength of DMLS Ti-6Al-4V by providing some post heat treatment processes. The Hot Isostatic Pressing (HIP) improves ductility of the DMLS Ti-6Al-4V samples due to the of α+β microstructure and it doesn’t have any effect on roughness since there is a limit in size and shape of internal pores [25]. The observed microscopic images were shown in Fig.5. D. Greitemeier et al. [26] suggested that in order to prevent influence of surface roughness on fatigue behaviour of DMLS component HIP was used since, it can minimize the internal defect size. The surface quality of DMLS Ti-6Al-4V can be improved by combining blasting and chemical etching. Blasting minimizes surface irregularities and etching makes surface clean [27].

![Microstructure images of a) As-built b) HIPed DMLS samples]

**(a)** (b)

**Fig.5 Microstructure of a) As-built b) HIPed DMLS samples [25]**
Due to rapid cooling in DMLS process there is a change of micro structure from columnar β grains to α martensite needle form through which the fatigue crack will grow [28]. As-built DMLS Ti-6Al-4V can be used for biomedical applications since after heat treatment at 680°C for 3hrs its tensile strength decreased from 1265 MPa to 1170 MPa, while ductility increased by 10.9% [29]. M.G. Moletsane et al. [30] concluded that the properties of DMLS specimens from Ti-6Al-4V (ELI) requires only stress-relieving and can meet required standards.

Based on the earlier works reported on DMLS Ti-6Al-4V, it is understood that DMLS component contains inherent surface roughness and defects. Proper selection of process parameters plays a major role in the quality of final product. Maximum of works done on mechanical characterization of DMLS product based on process parameters. Post processing is required in order to enhance strength of DMLS product. It is revealed that surface finishing treatments and HIP process improves ductility and fatigue strength. Stress-relief annealing is also required to relief stresses formed during rapid cooling of DMLS product.

Very few research works identified causes of defects and possible remedies. There is scope remained open to evaluate tribological characterization of DMLS Ti-6Al-4V product. Low cycle fatigue, fatigue crack growth, fracture toughness, impact, creep, creep fatigue, multi axial testing and environmental effects are needed to be explored more.

2.2 Characteristics of AlSi10Mg

Al-Si base alloys find wide applications due to its high strength to weight ratio, good corrosion and wear resistance. AlSi10Mg alloy can be used for high weight applications due to its high strength, hardness and good resistance to wear. AlSi10Mg is best suited for casting complex and thin walled parts. AlSi10Mg made parts are having the combined advantage of good thermal properties and low weight. Al alloy is mostly used in aerospace and automotive interior parts and few functional parts due to its high strength to weight ratio, good thermal conductivity and corrosion resistance [31]. Due to near eutectic composition of Al and Si they can be easily processed by laser application [32]. AlSi10Mg manufactured by DMLS and the effect of process parameters on its properties were studied. The brief review of works reported on DMLS AlSi10Mg was listed here.

Manickavasagam et al. [33] identified that hatching distance and scanning speed showed a much influence on mechanical properties of DMLS AlSi10Mg. The gas entrapment will be increased due to increase in hatch distance which consequently reduces melt pools overlapping. Reducing the scanning speed increases the energy density (LED). Among various process parameters, laser power and hatch distance have more influence on ultimate tensile strength [34]. Wang et al. [35] explored the impact of LED on the surface quality of As-built AlSi10Mg and concluded that the surface quality was improved by increasing LED. The effect of process parameters was studied by F. Calignano et al. [36] and identified that scan speed has a great influence on surface roughness and shot peening significantly reduced surface roughness as they observed through SEM analysis and were shown in Fig.6 Proper amalgamation of scanning speed and laser power can give better surface finish to DMLS products [37].

The powder characterization is also an important factor for DMLS AlSi10Mg. Very fine size powder particles shows negative impact on mechanical properties. Particles less than 10 micron size agglomerate and forms clusters which will avoid flowability and finally causes porosity. Diego Manfredi et al. [38] used AlSi10Mg powder particles of spherical shape size ranging from 21 to 27 microns and stated that the ultimate tensile strength, yield strength and elongation at break were improved as compared to cast Al360 alloy.
The parts made by DMLS AlSi10Mg have problem of porosity and surface roughness. The surface quality of DMLS AlSi10Mg had a great influence on its fatigue strength. The As-built DMLS component has inferior fatigue strength when compared to conventional part due to porosity and surface cracks [39]. The Al Metal matrix composites reinforced with silicon carbide particulates (SiCp) of different mesh sizes and volume fractions were prepared by Subrata Kumar Ghosh et al. [40] through DMLS route. They found that with increase in volume percentage of SiCp the Crack density increased and the specific wear rate increased with decrease in mesh size. The small size SiCp increased porosity. The porosity defect was depicted in Fig.7. The reason was coarser grain size lead to gap formation between grains.

Optimized combination of process parameters and surface finish can improve the fatigue strength [41]. The fatigue behavior enhancement was always difficult due to defects that remained even after surface polishing. The fatigue crack formation is a major problem in DMLS AlSi10Mg. The sudden cooling of DMLS component from high temperature will create temperature gradient which will induce residual stresses. Heat treatment will make the DMLS component isotropic. Raising the platform temperature will also reduce formation of residual stresses and there by crack propagation [42].

Massimo Lorusso et al. [43] studied the tribological behaviour of AlSi10Mg-TiB2 composite made by DMLS process. They found that DMLS AlSi10Mg-TiB2 Metal Matrix Composite (MMC) showed less wear than casted AlSi10Mg-TiB2 Composite. They further suggested that addition of nano sized reinforcements gives better wear properties. The wear rate comparison was shown in Fig.8. Arfan Majeed et al. [44] acknowledged that solution heat treatment process reduced the average surface roughness by 17% at 540°C for 2 hours. Sand blasting (post treatment) has a positive effect on DMLS component that reduced average surface roughness by uniform distribution of porosities in the cross section and created superficial compression state in material which improved fatigue resistance [45] [46].
The work done so far on DMLS AlSi10Mg given limited information regarding its mechanical properties. The selection of laser scan speed and power will show a considerable effect on porosity and surface roughness. Some authors came up with possible ways to reduce porosity and surface roughness. Shot peening and solution heat treatment showed a possible impact in decreasing surface roughness and thereby fatigue strength. Large number of studies was done on mechanical characterization of DMLS component based on input parameters.

Limited research was addressed on the characterization of DMLS AlSi10Mg product using powder particles size, build orientation and post processing methods. These areas need to be work more. Addition of nano reinforcements in the fabrication of DMLS composites could be a new research area. For better quality of DMLS AlSi10Mg, concern remained open to explore more about process parameters and post or pre treatments to overcome problems listed above.

2.3 Characteristics of Stainless Steels

The stainless steel materials used in DMLS method were SS316L and PH1 steels. Stainless Steel PH1 is a pre-alloyed stainless steel in fine powder form. They have good corrosion resistance and high ductility which makes it a suitable material for biomedical and aerospace. These steels can be moulded into different shapes for different purposes by utilizing the maximum potential of this DMLS technology [47].

Porosity is still a problem which compromises its use though number of infiltration techniques were suggested [48]. So proper combination of processes parameters must be used to reduce defects normally present in DMLS steels. Kurain Antony et al.[49] carried out an experiment to understand laser power, scan speed and beam size influence on geometry characteristic and balling effect. They confirmed that laser power and scan speed have noticeable effect on distortion and irregularities. The mechanical properties can be improved by heat treating, changing energy density and combination of input parameters. The post heat treatment also increased the tensile strength in Stainless steel PH1 [50]. This was shown in Fig.9.

Mohamed Shehata et al. [51] found that horizontal specimens showed better density and mechanical properties than 45° oriented specimens in the case of 17-4PH Stainless Steel.
Dario Croccolo et al. [52] studied the effect of built orientation and thickness on the fatigue behaviour of DMLS SS 15-5PH and they concluded that the component built in slant position (45° to build orientation) showed reducing notch effect due to less scan errors. By removing the surface irregularities, residual stresses present at surface can be curtail and may lead to increase of the fatigue strength. Shot peening significantly stored high-magnitude compressive residual stresses on component surface which will improve the fatigue fracture resistance of DMLS component [53].

Ala’aldin Alafaghani et al. [54] conducted mechanical testing at elevated temperature up to 350°C heat treatment and concluded that 15-5PH can be used in different elevated temperature applications as there was no observable change in their micro structure but there is expected reduction in the tensile mechanical properties. The reduction of mechanical properties with temperature was shown in Fig.10.

Stainless Steel 316L is having high corrosion resistance and it can be used at temperature range below cryogenic temperature. It’s kind of austenitic stainless steel commonly used in food processing, medical and aerospace applications. According to P.P. Bandyopadhyay et al. [55] the DMLS SS 316L is harder than commercial stainless steel. The laser power is responsible for the quality of product in DMLS. So, the process parameters need to be controlled effectively. It was found that better densification can be achieved with high laser power and low scan rate and less layer thickness and line spacing. In addition to these process parameters the powder properties also showed significant effect on mechanical properties of DMLS Stainless steel.

Powder chemical composition, particle size and shape show a clear impact on the DMLS product quality. Fine powder particles will increase exposed surface area, which will absorb more laser power, thereby increasing sintering area. Higher laser power will vaporize the metal powder, which is uneconomical. Not only powder properties the laser sintering pattern and
laser sintering atmosphere will show a clear influence on densification of product. The delamination problem happens mainly due to thermal gradients present in the material. Fig. 11 shows that delamination in different steels at high laser power. The same was reported by A. Simchi [56].

M. Hussain et al. [57] fabricated a MMC through DMLS route using SS316L matrix and CBN reinforcement in nitrogen atmosphere. There was a good compatibility between SS316L and CBN. With increase in laser power the relative density of the sintered samples was increased as shown in Figure 12. Increase in CBN content the micro hardness and wear resistance increased but it showed negative impact on relative density as represented in Fig. 13.

![Fig.11 Example SEM images of different laser sintered steels [56]](image1)

![Fig.12 Effect of laser power on density [57]  Fig.13 Effect of CBN on the micro hardness [57]](image2)

Vijay mandal et al.[58] fabricated TiN reinforced SS316 metal matrix composite(MMC) and they observed that laser power showed a negative effect on part density and positive effect in reducing porosity up to certain level. With increase in TiN reinforcement the micro hardness of composite was improved. But, further increase in reinforcement after 20% volume increased wear rate due reduction in bonding between matrix and reinforcement. The mixing of TiN in SS316 Matrix was shown in Fig. 14.

The previous work on stainless steel concentrated mainly on the influence of process parameters like laser power, scan speed and built orientation on its properties like tensile strength, micro hardness, surface roughness fatigue strength and wear rate. Some works stated that post heat treatment processes improved mechanical properties. There was a good compatibility of reinforcements in steels which improved its wear resistance.
DMLS steels are showing positive trend after some heat treatments so there is a need to study their effects on micro structure and correlating them with observed properties. Very few studies conducted on characterization of DMLS steels based on powders size, shape and densification effect. So the area remained open for future study. The possibility of mixing different nano reinforcements and their effects on DMLS steels need to be studied.

2.4 Characteristics of Ni-based super alloys

The Ni based alloys were developed rigorously in the 20th century, because of their use in jet propulsion, aerospace and more. The Nickel based alloys used in DMLS manufacturing process are Maraging steels, Inconel 625, Inconel 718 and Hastelloy X. These Ni based alloys find wide applications in aerospace and turbo machinery, where there is a need of having low thermal conductivity and good corrosion resistance. Moreover, they are not prone to age hardening and they have high creep life. They not only work well at high temperatures but they can work better even at low temperatures. This is the reason why these Ni based alloys used in cryogenic applications. The turbine engine components can be precisely obtained by DMLS process, because it can produce the quality component with ease [59].

Apparao.D et al. [60] fabricated DMLS maraging steel and tested mechanical properties and found that hardness and tensile strength were improved by heat treatment which resulted in precipitated-phase strengthening. Katarina Monkova et al. [61] declared that maraging steels mechanical properties were influenced by heat treatment and orientation. The heat treatment effect on conventional and 3D printed steels was shown in Fig. 15.

![Fig.14 FESEM image of DMLS MMC [58]](image)

![Fig.15 strain-strain diagram of maraging steel in different heat treatments [61.]](image)
A.Jagadish and Nadig Priyanka [62] tested the effect of cryogenic treatment and build orientation on DMLS Maraging steel grade 300 mechanical properties. They confirmed that precipitation hardening improved mechanical properties. The cryogenic and aging processes improved the tensile and hardness properties. There was no significant difference in properties of horizontally built specimens and vertically built specimen. The diagrammatic representation was given in Fig.16.

![Fig.16 Effect of thermal treatments on Tensile strength][62]

Hadadzadeh et al. [63] used new class of maraging steel known as corrax steel in DMLS process and it contains fine microstructure with an average particle size of 5.2 ± 1.5 µm. These grains were equiaxed and decorated with austenite. So, it can be expected to be best choice for high strength applications. Eva Schmidova et al. [64] found that DMLS maraging steel contains fine microstructure when compared to forging or casting and which is responsible for high dynamic and static strength. It was found that aging heat-treatment reduced Plastic anisotropy levels to a greater extent, however, transverse strain anisotropy was likely to remain due to the AM alloy’s fabrication history [65].

The mechanical properties were found to be relying on process parameters and build orientation. The AM parts have some structural and surface defects, which will affect their wear and fatigue behavior. So, there is a need to carry out some post treatments/processes to overcome these defects. Yen-Ling Kuo et al. [66] studied the creep properties of DMLS Ni-base superalloy with respect to build direction and heat treatment and concluded that the vertical (perpendicular to build direction) specimens showed higher values of creep life and ductility than horizontal built specimens, because of the interdendritic δ-phase precipitates. The materials creep life and ductility was found to be effected by a row of interdendritic δ-phase with incoherent interfaces. The Dendrite growth is as shown in Fig.17.

![Fig.17 Molten Pool Boundary with dendrite growth][66]
Paul F. Kelley et al. [67] studied the effect of parameters and build orientation on the properties of DMLS Inconel 718. There was an improvement of surface finish by post processing (micro machining). The fatigue strength in build orientation in Z is approximately 14% lesser than X/Y axes. The tensile and yield strengths were found to be 10% less in Z direction than X direction. The Z and X directions with respect to built platform were as shown in Fig.18. Onome Scott-Emuakpor et al. [68] concluded that Nickel alloy 718 was sensitive to DMLS process parameters and post processes like heat treatment and hot isostatic pressing. Components with fine grains were much harder than coarse grains. They found that vertically built specimens showed high tensile strength than horizontal built specimens. They used Ritz method to predict elastic modulus of DMLS Nickel alloy 718 plate and they suggested some alternative methods that might give good measurement of elastic modulus.

The DMLS components made of Nickel based powders found wide range of applications in automobile and aerospace sector. So there is a necessity of concentration over its wear and surface roughness. Due to unavoidable surface roughness, the wear rate in DMLS components was relatively higher, the post treatments and optimized input parameters can improve the performance of these additive manufactured parts.

C. D. Naiju et al. [69] did research work on wear behaviour of Automobile self-starter center bush and front bush made up of bronze-nickel powder and they found that the wear rate of DMLS component is relatively higher than conventional manufactured bush, but they fall within the acceptable limits. From this, one can improve process performance by developing appropriate processing strategies in order to reduce defects normally arise in AM process.

According to Ezgi Uur Solakolu et al. [70] the surface texture of DMLS component can be improved by reducing scanning speed and hatch distance. Despite of many attractive features of DMLS process in the production of functional parts but there is factor which influences its use is surface quality, which shows a predominant effect on its properties. Various post processes and heat treatments were tried to improve the surface quality as well as mechanical properties of DMLS Ni alloy based components. K.L. Tan, S.H.Yeo [71] were studied surface quality of DMLS Inconel 625 after ultrasonic cavitation abrasive finishing (UCAF). They concluded that UCAF process improved surface quality of as built Inconel 625 significantly and it is shown in Fig.19. This process had removed surface irregularities efficiently without much altering of the DMLS part surface.
The ascendancy of different process parameters like scan speed, laser scan rate, laser power and hatch distance on micro hardness, final part density, dimensional accuracy and roughness was studied. With increase in laser speed there was increase in micro hardness and decrease in part density (Shown graphically in Fig.20) of DMLS Inconel 625. They also mentioned that decrease in hatch spacing (0.3mm and 0.4mm) will decrease micro hardness because of the formation of coarse grains due to low cooling rate [72].

Sankarnarayanan seetharaman and manickavasagam Krishnan [73] reviewed additive manufactured (DMLS process) Ni based alloys and concluded that the properties of DMLS Ni alloy was greatly influenced by input process parameters and post processes. Powder characterization, thermal conductivity and chemical composition were also important factors while manufacturing through DMLS route. The properties of additive manufactured parts showed better or equal mechanical properties compared to conventional manufactured parts. The influence of powder properties on product quality is shown in Fig.21. There is a need to use DMLS route to manufacture Inconel 718 than conventional manufacturing processes to save material being it is costlier. DMLS process also offers quick and easy method. Ni based alloys can be used in situations where the there is a need of high thermal resistivity and corrosion resistance.
O. scott-emuakpor et al. [74] tested the possibility of using DMLS Ni alloy 718 to manufacture hot section components like turbine blade and heat exchangers and compared tensile and fatigue properties of DMLS component with cold rolled Ni. Tensile properties were observed to be comparatively high for DMLS Ni alloy 718 mainly in transverse build direction.

For high temperature and corrosion resistance applications like gas turbine blades, aircraft engines and for process in which usage of chemicals there is a need of such alloy known as Hastelloy X. It is a Ni-Cr-Fe-Mo alloy. Wrought Hastelloy X exhibits a high tensile strength of 800 MPa and a percent elongation of approximately 50% at room temperature [75]. Hastelloy X can be used for the flame tube and casing of the combustion chamber due to its high creep strength and corrosion and oxidation resistance [76]. The alloy has nickel-based austenitic structure, called gamma (γ) that can be strengthened by the addition of alloying elements [77]. While the addition of molybdenum and iron increases the strength, Hastelloy X is primarily used for its high corrosion resistance, because of its chromium content [78]. Chromium improves the oxidation resistance because it forms a protective Cr2O3 oxide layer on the surface. This oxide layer is specifically known for its high corrosion resistance.

There is a problem in using Hastelloy X through DMLS route because of the formation of micro cracks resulted from porosity and residual stresses. So there is a compromise in its mechanical properties. The methods like Solid solution strengthening, addition of carbides, heat treatments, hot isostatic pressing were improved its mechanical properties. Abbaschian et al.[79] altered the composition of Hastelloy X by adding Molybdenum to increase its solid solution strength thereby decreasing the crack density and marked an improvement of mechanical properties.

From past reported studies it is clear that Ni alloys plays a vital role in aerospace and aviation sector, where there is a need to have good thermal resistivity, corrosion resistance, better mechanical, fatigue and wear properties. Majority of researchers reported the effect of input parameters on mechanical as well as on surface quality of DMLS products. Some of the findings of earlier researchers revealed that post processing improved surface quality, fatigue and creep life. The effect of build orientation was also studied by few researchers and they found that specimens build in transverse direction (vertical specimens) showed better properties.

There is need to study the impact of different orientations on fatigue as well as mechanical properties. More focus needed to be done on Powder characterization and its effect on properties like part density and surface defects. More literature was present on Inconel 625 and Inconel 718 and maraging steel. Very few works reported on Hastelloy X. Being Ni alloys are relatively costlier and significant engineering materials, DMLS is best AM technique which considerably saves time and material despite of its ability to develop complex parts.
2.5 Characteristics of Co-Cr based alloys

In order to produce biomedical parts from Co-based alloys, AM techniques were used in the recent past. Co alloys are high tensile strength and biocompatible material mostly used for medical and turbine engine applications. Cast cobalt-base alloys were originally proposed for surgical implants over 60 years ago. Metallurgical uses of cobalt exploit its properties such as high temperature strength, biocompatibility, high wear and corrosion resistance, magnetic properties, low expansion coefficient etc. It is widely used in gas turbine nozzles, jet engine blades and vanes and hard facing wear resistant applications [80].

Compared to casting AM is more suitable for fabrication of dental prosthesis. In casting material expands and contracts during formation of wax patterns and there is a problem of defects like blowholes which will affect the strength of product. But in this laser sintering process dimensional accuracy is more and dense parts without blow holes can be easily obtained in relatively less time. Additive manufacturing (AM) can be more productive if the resources used efficiently [81], providing high density and homogeneity in work piece. [82][83].

Co-Cr alloy was used in manufacturing of artificial implants such as hips, knees and bone plates. There are no allergic problems by using Co-Cr alloys, since they are nickel free alloys [84]. These can be used for high load bearing applications due to their high strength and toughness. DMLS could be better choice to make surgical implants from Co-Cr-Mo alloys due to manifestation of increased hardness and uniform microstructure.[85].Cobalt-based alloys finds wide application in other areas like nuclear power plants, rocket fuel nozzles and turbine engine vanes where there is high temperature, oxidation, and hot corrosion [86]. In the field of dental restorations, DMLS is more productive, economic and time saver because it offers good repeatability and faster delivery in the production of metal-ceramic fixed partial dentures (FPDs) [87].

Theodoros Koutsoukis et al. [88] concluded that DMLS is more time and cost effective process to manufacture dental restorations where it is possible to achieve more or similar properties that we generally obtain by casting or milling. The SEM images of Laser sintered, milling and casted Co-Cr samples were shown in Fig.22.

![Fig.22 SEM images from the polished cross-section of Co-Cr dental alloys fabricated by A) SLM B) Milling and (C) Casting [88]](image)

TatjanaPuskar et al. [89] used artificial saliva to do comparative corrosion study of DMLS and Cast (CM) Co-Cr-Mo Dental Alloy. They concluded that highest elution observed in high acidic environment and ion release is more in Co. Less elution observed for DMLS alloy in all acidic environments than cast metal. The density variations are shown in Fig.23.
Diana-Irinel Baila et al. [90] studied the effect of hydroxyapatite (HA) $\text{Ca}_5\text{HO}_3\text{P}_3$ coating on DMLS Co-Cr samples, they found that the hydroxyl apatite formed after immersion in simulated biological fluid (SBF) is uniform (Shown in Fig.24) and the implants have a better adherence to the bone. The faster healing of the patient was observed.

Diana-Irinel Baila [91] used Co-Cr alloy for dental restorations and stated that DMLS was a best process to make dental restorations because part being produced was having limited mechanical stress due to good sinter and mechanical properties of Co-Cr powder. The products made by laser sintering were shown in Fig.25.

DMLS Co-Cr-Mo alloy can be used in dental applications because of its excellent mechanical properties like high ultimate tensile strength, the elongation at break and the hardness [92]. The durability of DMLS made dental clasps was superior to that of cast clasps. Additive manufacturing was best technology than dental casting [93]. Josef Schweiger et al. [94] claimed that DMLS made Co-Cr-Mo dental clasps contain relatively less porosity compared to casted specimens. They can sustain for long time due to higher consistency of retentive forces.
The quality of clasps mainly depends on input laser power, speed and layer thickness which will decide porosity levels and micro structure in the laser sintered part [96] did not affect the mechanical properties of the layered manufactured alloy was not influenced by powder characteristics and the layer thickness [97]. Since DMLS involves utilization of high laser power more heat is generated during manufacturing and rapid cooling also takes place due to this some thermal stresses will remain in the products, which will lead to thermal strain which is not desirable. So, better strength can be obtained with some post heat treatments.

Swee Leong Sing et al. [98] fabricated laser sintered Co-Cr-Mo samples and were solution heat treated. After heat treatment the both ultimate tensile strength (UTS) and yield strength (YS) decreased due to carbides formation, but the as built specimens showed twice the values in UTS and YS of casted Co-Cr-MO alloys. Solution heat treatment process showed a great effect on mechanical properties of DMLS Co–28Cr–6Mo alloy, since solution heat treatment increased ductility and reduces yield strength [99]. Solution treated material will offer good mechanical properties. Because it leads to $\gamma \rightarrow \epsilon$ martensitic transformation of microstructure, which will result in significant improvement in mechanical properties [100].

The Co-Cr metal is best suitable for biomedical applications mainly in dentistry which resulted in porous surface with desired strength. The porous surface is desirable for better adherence with body tissues. The sintered micro structure resulted in better mechanical properties than conventional methods. So DMLS is the best method for fabrication of artificial prosthesis using Co-Cr metals.

The works reported so far on DMLS Co-Cr-Mo mainly focused on the compatibility to use in dentistry. It’s a better material for the manufacturing of prosthesis due to its high strength and hardness. Since it is nickel free alloy, it is safe to use in prosthesis preparation in human body. It is known for its good thermal and corrosion resistance which makes it ideal material for the fabrication of aircraft fuel nozzles and vanes. The load carrying capacity and various methods to improve it should be studied further.

3.0 Conclusions

The following conclusions are drawn based on works reported by various researchers on DMLS process.

- The DMLS made parts were showing better mechanical properties than wrought, cast or forged parts.
- Regarding Ti-6Al-4V, from the review it is clear that, it is a light alloy with excellent mechanical properties, low specific weight with good biocompatibility. So it’s a suitable material for aerospace and medical fields. Post processing like HIP is required to improve its fatigue strength.
- For good strength and thermal characteristics AlSi10Mg is the best suitable material in DMLS process. The studies on DMLS AlSi10Mg reported that there is a need to improve surface quality, in order to enhance the fatigue life. The pre heat treatment of build platform showed a considerable improvement of fatigue life and shot peening diminishes surface roughness.
- DMLS Stainless steel exhibits good mechanical properties with better fatigue strength. The laser power and scan speed clearly have impact on their mechanical properties.
Post heat treatments showed improvement in their mechanical properties

- Because of their excellent thermal and corrosion resistivity properties DMLS Ni alloys are playing vital role in aviation and aerospace industries. They retain high strength at elevated temperatures due to precipitation hardening.

- Due to superior mechanical properties and bio compatibility of DMLS Co-Cr alloys they mainly used in dentistry to make dental restorations. DMLS is appropriate method for fabrication of implants and dental restorations because there is little or no problem like porosity and uneven contraction or expansion.

4.0 Future scope

- For DMLS Ti-6Al-4V, there is a need to do explore more about its compressive strength, creep resistance and to find suitable post processing methods to improve its fatigue strength by reducing crack propagation tendency. In order to use it as a successful material in biomedical filed proper methods should be adopted to decrease its elastic modulus despite of losing its strength.

- For DMLS AlSi10Mg, the surface quality is not up to the desired level. So, researchers should try to find better ways to reduce As-built surface roughness, which is adverse effect on its fatigue strength.

- For DMLS Steels concern remains open for better control of input parameters and post heat treatments to extend its applications. Few works reported on its tribological behaviour.

- For DMLS Ni based alloys there is need to reduce anisotropy and residual stresses which mainly occurs due to directional solidification and rapid cooling. So, proper build orientation and process parameters optimization could be stimulated.

- For DMLS Co-Cr alloy the ductility is less, so it’s a challenging area for the researchers to work on. Very limited works reported on its dilution nature and corrosion behaviour.

REFERENCES


