Selective Laser Melting of Inconel Super Alloy-a Review

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Abstract. Additive manufacturing is a relatively young technology that uses the principle of layer by layer addition of material   in solid, liquid or powder form to develop a component or product. The quality of additive manufactured part is one of the   challenges   to be addressed. Researchers are continuously working at various levels of additive manufacturing technologies. One of the significant powder bed processes for metals is Selective Laser Melting (SLM). Laser based processes are finding more attention of researchers and industrial world. The potential of this technique is yet to be fully explored. Due to very high strength and creep resistance   Inconel is extensively used nickel based super alloy for manufacturing components for aerospace, automobile and nuclear industries. Due to law content of Aluminum and Titanium, it exhibits good fabricability too. Therefore the alloy is ideally suitable   for selective laser melting to manufacture intricate components with high strength requirements. The selection of suitable process for manufacturing for a specific component depends on geometrical complexity, production quantity, and cost and required strength. There are numerous researchers working on various aspects like metallurgical and micro structural investigations and mechanical properties, geometrical accuracy, effects of process parameters and its optimization and mathematical modeling etc. The present paper represents a comprehensive overview of selective laser melting process for Inconel group of alloys.
Key words: SLM, Process, Parameter, Microstructure, Mechanical properties first, second, and third level headings (first level heading)

I INTRODUCTION

Additive manufacturing (AM) is an emerging technology that uses the principle of layer by layer addition of material   in solid, liquid or powder form to develop a component or product. Researchers and industry leaders across the globe have identified AM as a key emerging technology. The quality of additive manufactured parts is one of the major a challenge that is to be addressed. Researchers are continuously working on various levels of additive manufacturing technologies. Dimensional accuracy, material properties and surface finish measures are sometimes inferior to those achieved using conventional manufacturing methods. There may be multiple reasons for these inferior results and researchers are therefore developing comprehensive data about processing parameters and materials for Additive manufacturing.

II SLM PROCESS OVERVIEW

 Powder based additive manufacturing techniques that can fabricate structurally sound parts from directed laser are focus of the researchers. Selective Laser Melting (SLM), is one of   the   most promising powder bed processes for metals. In SLM the components are fabricated by selectively melting of subsequent powder bed with a focused beam. A 3 dimensional   CAD geometry is sliced in 2 dimensional stacks of layers. Each layer is then created by scanning a laser spot over a required cross sectional area,   and uses high power Yttrium fiber laser to melt, and fuse the particles together in thin layers(20-100μm) to build metallic functional components in inert gas environment(Argon or Nitrogen) shown in Figure-1(a). Finished additive manufactured parts are evaluated depending on a variety of factors such as material mechanical properties and surface quality[30]. Another main issue to be addressed with AM technology is cost and time parameters for processing that makes the technology applicable to only small lot size of customized designs and components of small size[6,9].
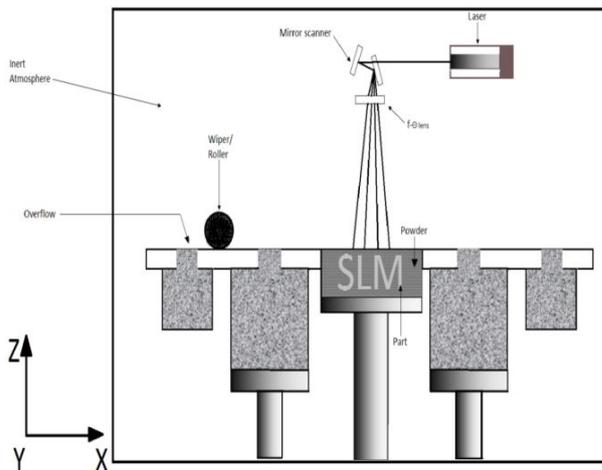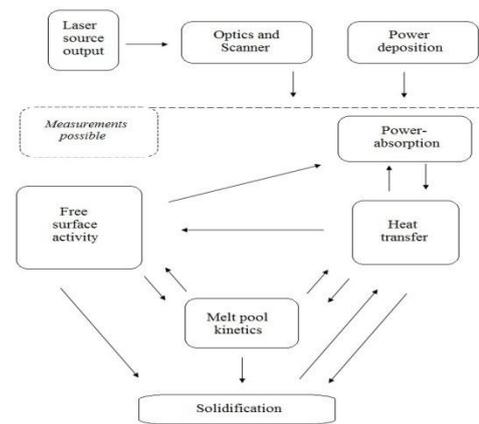
Figure 1. (a) Selective Laser Melting

Figure 1. (b) Process interaction in SLM

Energy transfer from laser beam to powder layer is very complex process involves different physical phenomenon like absorption, scattering radiation, conduction and convection heat transfer, fluid flow within molten pool. The molten pool dimension is directly affected by energy density(laser energy per unit volume),which is controlled by process parameters and scanning speed. Higher scanning speed causes unstable melt flow and splashing of molten material and affects the surface roughness[6,28].

SLM is characterized by high temperature gradients, causing non equilibrium conditions at the solid/liquid interface, thereby leading to rapid solidification as the melt pool undergoes transformation from liquid to solid. As a consequence, a wide range of effects are observed like formation of non-equilibrium phases, and changes in the general micro structural features, mostly in scale. Finer structures may be observed in the microstructure at sufficiently high cooling rates compared to the conventional manufacturing method. In addition, it should be pointed out that the grain structure is also controlled by the previously solidified layer grain structure and the SLM processing parameters [4,8]. SLM process is a complex process [31] and interaction between parameters is shown in Figure-1 (b)

The SLM process offers several advantages in comparison to conventional manufacturing techniques, like reduction in production lead time, high flexibility, high efficiency of material consumption and most important possibility to manufacture highly complex intricate components with dimensional accuracy[1,2,3]. However, very short interaction times with rapid heating with highly ionized heat source causes large thermal gradient and thermal stresses[5]. Rapid cooling and solidification of thin layers results in directional grain growth, micro segregation of constituents causes non equilibrium phases. Several renowned researchers have contributed in various area of SLM process like process overview, applications, effects of process parameters and optimization for better surface finish, micro structural and mechanical properties, mathematical modeling and process simulation[27], manufacture of complex net structures and deposition of new novel materials.

Since the material properties such as yield strength, elongation, ductility and hardness are highly affected by the micro structural features, the mechanical properties obtained with SLM might be different from the properties of bulk materials produced by conventional production techniques. In SLM process it is a challenge to avoid occurrence of process induced defects like pores due to non optimal process parameters, or powder contamination and local voids after deposition of a layer. Various authors have investigated the effects of certain parameters on the certain parameters on the micro structural characteristics and material properties of different materials with SLM process.Significant parameters effecting are shown in table -1:

Table 1 Significant Parameters for Selective Laser Melting [10]

Input	Process	Output	Environment
(Powder layer & material) Relative density, particle shape, particle size and shape distribution, thermal conductivity, absorptivity, reflectivity, emissivity, diffusivity Viscosity, surface tension, capillary force, conductivity, specific heat, melting temperature, evaporation temperature	Laser power, beam spot size, scan speed, hatch space, scan strategy, layer thickness, powder density.	Surface roughness, geometric dimensional accuracy, porosity, residual stress, mechanical and micro structural properties, residual stress,	Inert gas, chamber pressure, ambient temperature, gas flow rate and direction, surface free energy between the liquid metal and the gas.

III SLM PROCESS OF INCONEL SUPER ALLOYS

Inconel group of super alloys exhibit fantastic mechanical properties allowing their use in manufacturing of functional components in aerospace, automobile and nuclear engineering. Inconel 625 exhibits high strength due to added molybdenum, and niobium while in Inconel 718, the strength is mainly due to precipitation of gamma double prime (γ") elements. Inconel 718 is precipitation-hardened alloy, while Inconel 625 does not respond precipitation nucleating heat treatments.

Table 2 Composition of nickel based super alloys found promising with SLM [32,33,34]

Element	Inconel 718		Inconel 625		Inconel 939
	Min (Weight Percent)	Max (Weight Percent)	Min (Weight Percent	Max (Weight Percent	Weight Percent
Nickel + Cobalt	50	55	58	N/A	Balance
Chromium	17	21	20	23	22.4
Iron	Balance		--	5	1.9
Nb	4.75	5.50	3.15	4.15	1
Molybdenum	2.80	3.30	8	10	--
Titanium	0.65	1.15	--	0.40	1.4
Aluminum	0.20	0.80	--	0.40	3.7

To build components with SLM with a nickel based super alloy requires in depth understanding of process parameters, its effects on microstructure, degree of porosity and mechanical properties. Only few research works are available based on this kind of investigations. Most of the studies have covered main aspects: microstructures, mechanical properties, textures, internal pores, effects of heat treatment, melt pool boundaries, residual stresses, reinforcement for composite manufacturing etc.

The micro structural characteristics (morphology and grain size) of SLM parts are highly sensitive to their thermal history during build with very high heating/cooling rate and non uniform temperature gradients. Many process variables impact the thermal history, predicting the micro structural features of SLM parts, and the degree of their dependence on process parameters, is still a major challenge. However, overcoming this challenge is vital for establishing the effective control mechanisms for fabricating SLM parts with Inconel super alloy with superior mechanical properties.

Yadroitsev et al [12] investigated the optimal hatch distance in relation to porosity and applied a scan method with dual heating for Inconel 625. They investigated the effects of contact angle, pulse width, percentage overlap, hatch strategy and scan strategy and bed geometry, and analyzed the bonding behaviour using metallographic micro sections and represented the process map with pulse width and specific energy. Ameto et al[13] found that better microhardness achieved at higher energy densities due to densification and refinement of dendrites and microstructure.Higher energy densities causes an aging treatment to previously deposited layer allows to precipitate γ' phase that causes lattice strain that resticts dislocation movements causes higher hardness Jia et al[18] presented a comprehensive study of densification behaviour, micro structural features, micro hardness, wear performance and high-temperature oxidation properties of Inconel 718 parts fabricated by selective laser melting (SLM), a typical additive manufacturing process. The relationship of processing conditions, microstructures and material properties was established. They suggested Linear Laser Energy Density by equation (1)

$$Linear\ Laser\ Energy\ Density\ \left(\frac{J}{m}\right) = \frac{Laser\ Power\ (Watts)}{Laser\ Speed\left(\frac{m}{s}\right)} \tag{1}$$

They found the densification response was controlled by laser energy density due to occurrence of open pores and balling effect. The microstructure of SLM processed component affected by laser energy density and gradually changes from course columnar dendrites, clustered dendrites and slender and uniformly distributed columnar dendrites with increase in laser energy density. Optimally prepared specimen had uniform micro hardness and better wear performance. A higher linear laser energy density correlates to a larger and hotter melt pool. The large temperature gradient allowed a suitable environment for the nucleation and growth of dendrites.

S. Li [15] investigated microstructure characteristics of Inconel 625 alloy manufactured with SLM. They compared microstructures of as fabricated specimen and after heat treatment with various techniques like SEM, EBSD and XRD .They observed that molten pool during the process was composed of elongated columnar crystals and microstructure was austenite with high solution distortions and absence of carbides. After heat treatment, the lattice constant decreases slightly due to Nb and Mo carbides precipitated. They also observed that grains with preferred orientation after heat treatment.
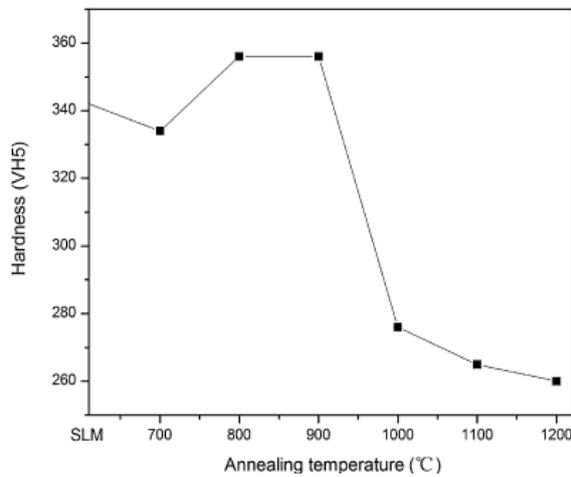

Figure 2. (a) Hardness with different annealing temperatures different annealing temperatures of Inconel 625 [15]
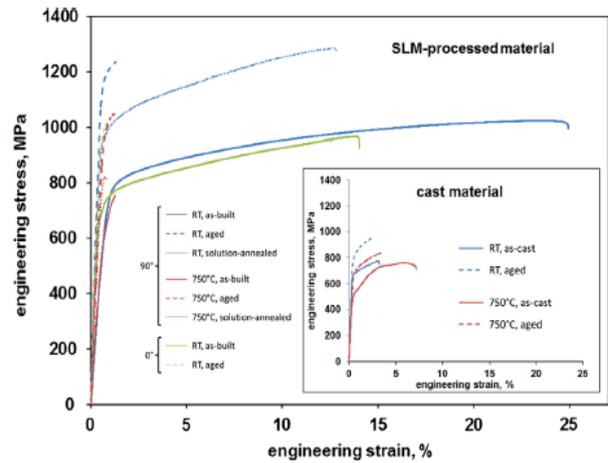
Figure 2. (b) Comparison of stress strain curve for Inconel 939 for casting and SLM processed [17]

Q.Jial[16,18] further studied the high temperature oxidation mechanisms for selective laser melted Inconel 718 with isothermal oxidation testing, X-ray diffraction, scanning electron microscopy and energy dispersive X-ray spectroscopy. They found that the kinetic behaviour of oxidized Inconel 718 with lower energy density was irregular. Higher energy density improves high temperature oxidation performance and improved relative density. The high-temperature oxidation resistance was enhanced as the applied laser energy density increased and the elevated high-temperature oxidation property was primarily attributed to the formation of refined micro structural architectures of SLM-processed parts.
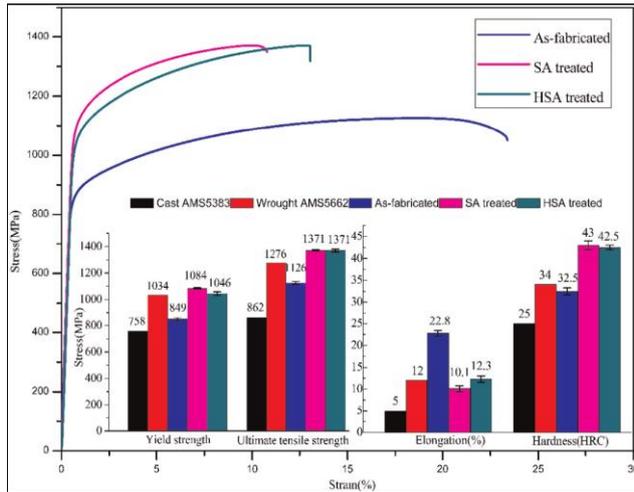
Figure 3. (a) Stress strain curves with effects of standard heat treatments on cast, wrought and SLM processed Inconel 718 [19]
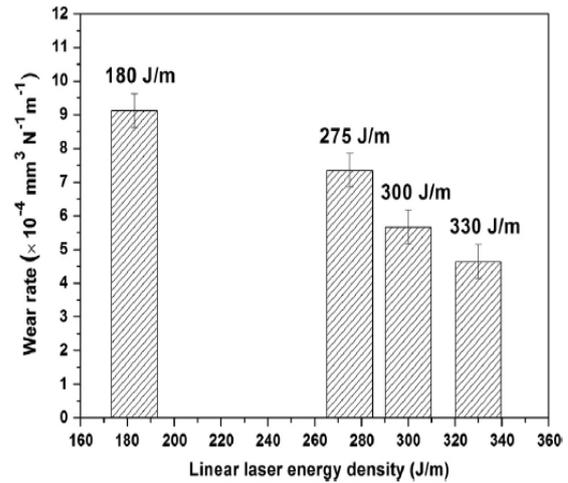

Figure 3. (b) Wear rates of SLM processed Inconel 718 with different processing parameters [18]

Y. Wang[22] have presented research on Metal Metrix composite with Graphene Nano Particles with Inconel super alloy with selective laser melting. Graphene Nano ,Platelets (GNPs) have attracted many researches with noticeable features with high mechanical strengths, light weight, and high electric conductivity. These unique properties make it suitable for reinforcement with metal matrix composite (MMCs). In the past few years, many studies have been performed to incorporate GNPs into metal matrix and investigate the properties of obtained metal matrix composites. Fabrication of GNPs reinforced MMC using SLM is feasible[22]. They studied strengthening effect with three main reinforcing mechanisms, thermal expansion coefficient mismatch, and dislocation hindering. The obtained composite possesses dense microstructure and significantly enhanced tensile strength. Kanagrajah and Wang [17, 14,26, 29] focused on the fatigue performance of SLM fabricated components with Inconel 939 and Hastelloy. During SLM process, the interaction between moving laser beam and the powder leads complex physical phenomena. [26] Observed that fatigue strength was lowest for direction parallel to build direction for Inconel 718.

Kanagrajah [17] presented investigations on growth of long fatigue cracks is investigated in Inconel 718 super alloy produced by selective laser melting. The fatigue crack growth curve and the threshold value of the stress intensity factor are experimentally determined on compact tension specimens fabricated using a system recommended processing parameters. The crack propagation curve and the crack propagation threshold of this SLM material are compared with literature data describing the behaviour of conventionally manufactured Inconel 718. The fatigue crack growth is discussed in terms of the specific microstructure and residual stresses produced by selective laser melting.

D. Zheng [19] studied the effect of standard heat treatment on the microstructure and mechanical properties of selective laser melting manufactured Inconel 718 super alloy. Micro structural and mechanical properties were investigated under solution aging standard heat treatment, homogenization solution aging with SEM, TEM and X-ray analysis methods. After heat treatment, mechanical strengths and ductility were improved (by 22%) and comparable to that of wrought Inconel 718.

Y.Lu [23] investigated the effects of different island scanning patterns on microstructure and residual stresses. For manufacturing high accuracy mould inserts with conformal cooling with Inconel 718 and suggested optimal island scanning strategy of 55 for highest tensile strength. Hakan Brodin et al [23] studied the effect on high temperature mechanical fatigue and creep tests on SLM manufactured part for super alloy. It was found that the creep properties are inferior to hot rolled material in all directions $0° \leq \alpha \leq 90°$ and that the material cannot compare to a standard hot-rolled material regarding creep.

B. Zhang [24] fabricated composite with reinforced micron-size TiB_2 particles into Inconel 625 produced by selective laser melting. Exceptional micro hardness of composite was obtained. In further investigation, the microstructure and mechanical properties of Inconel 625/TiB_2 composite significantly influenced by addition of TiB_2 particles during SLM. It was found that the long directional columnar grains

observed from SLM processed Inconel 625 were totally changed to fine dendrites matrix due to the addition of TiB$_2$ particles. Re formation of particle surface can increase the micro hardness and Young's modulus.

Trosch [25] compared the micro structural and mechanical properties of Inconel 718 with forging and casting with tensile tests at different temperatures. They found that at room temperatures, the properties were better than forged and cast material. At elevated temperatures SLM processed parts exhibited equal properties with forged material due to high proportion of intra granular delta phase.

IV CONCLUSION AND FUTURE SCOPE

Based on this overview, there are significant gaps in literature for fully understanding the relationship between the process parameters, thermal history, solidification, microstructure and mechanical properties of SLM processed parts especially with super alloys. Some potential areas that can be focussed in future are listed below:

i. Material characterization, understanding the effects of process parameters on SLM parts, powder characteristics, thermal processing, surface textures of SLM Part.
ii. Establishing standard design practices, development of guide lines for mechanical designs, testing of specifications, management of uncertainties with mechanical properties and operational environments for SLM process.
iii. Process modelling with thermal history, monitoring and control and prediction of material properties based on material characteristics and build parameters and thermal effects.
iv. Developing a micro structural sensitive fatigue and creep behaviour models with understanding of effects of heat treatments on residual stresses and mechanical properties correlating the effects of porosity, pores, and inclusions, shape and their distance, grain size and orientation etc. to optimize SLM process parameters.
v. Development of composite materials for customised applications with SLM process.

Micro structural features, the mechanical properties obtained with SLM might be different from the properties of bulk materials produced by conventional production techniques. In SLM process it is a challenge to avoid occurrence of process induced defects like pores due to non optimal process parameters, or powder contamination and local voids after deposition of a layer.

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