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Finish Machining of Additively Manufactured Inconel 718 – A Review

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Abstract. Additive manufacturing (AM) of Inconel 718, IN718, is increasingly being used for the manufacture of complex geometry parts for high temperature applications. However, the low surface integrity and build resolution of as-built AM IN718 parts demands post processing such as machining. This paper reviews the machining of AM IN718 to understand the effect of anisotropic behaviour of the AM part and the hardening post AM treatment on the machinability of the latter. A better understanding on the cutting parameters and machining performance measures such as cutting forces, tool wear, chip morphology and surface integrity of workpiece led to the development of a workplan for future investigation.

Keywords: Additive Manufacturing, Finish Machining, Inconel 718, Anisotropy

1. Introduction

Inconel 718 (IN718) is a nickel superalloy used extensively in high temperature applications such as aerospace industries due to its high mechanical strength, good oxidation resistance, good creep properties and corrosion resistance at high temperatures. Metal additive manufacturing (AM) processes, such as electron beam melting (EBM) and laser-based powder bed fusion (LPBF), are increasingly being used in manufacturing IN718 components with complex geometries more efficiently, than the traditional manufacturing methods [1]. Nonetheless, the inferior build resolution and surface finish of metal AM parts requires them to be post-processed [2]. Machining is one such post processing method that is commonly used for metals and their alloys [3]. The main indicators for the machinability of any part including hard AM alloys are the cutting force (CF), tool wear and surface integrity [3]. The interaction between the cutting tool and the hard alloy and the plastic deformation of the chip formation affects the CF which then influences the surface integrity and tool wear. Nickel alloys such as IN718 and other alloys such as titanium alloys and steel are considered as hard-to-machine alloys due to their high hardness, yield strength and ultimate tensile strength. These mechanical properties are dependent on the microstructure of the alloys [4]. IN718 fabricated by AM are known to have anisotropic and heterogeneous microstructures and mechanical properties. Hence machining AM IN718 are expected to result in anisotropic cutting

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forces, tool wear, chips and surface integrity [5]. This review will aim to elucidate the machinability of AM IN718 with respect to the anisotropic properties.

2. Anisotropic Behaviour of AM IN718

The microstructure and resulting mechanical strength of AM IN718 is largely dependent on the AM process itself followed by post-processing treatment, if any [6]. As-built IN718 using EBM has higher strength than those manufactured by LPBF owing to the higher processing temperature [6]. The microstructure of as built LPBF IN718 is displayed in Figure 1 which shows equiaxed grains on the XY plane and elongated grains on the ZX plane.

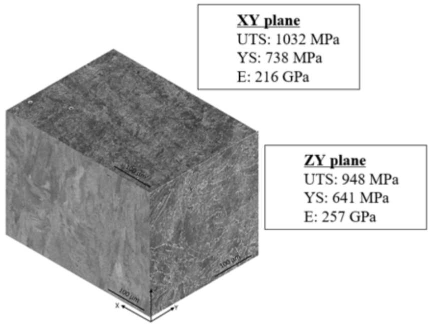

Figure 1. Scanning Electron Microscopic image of LPBF IN718 built in XY, YX and ZX direction with the UTS, YS and young modulus, E of the XY and ZX samples

The equiaxed grains and higher residual stress on the XY plane causes a higher resistance to deformation under loading [7] which results in the higher ultimate tensile strength, UTS and Yield strength, YS of XY samples as compared to ZX [Figure 1]. It has also been shown that the hardness of ZX samples are lower than the XY samples and this is related to the residual stress as well [8]. Post AM heat treatments have been shown to tailor the mechanical behaviour of the AM Part by manipulating the phase precipitation, limiting the number of dislocated cells and modifying the grain shape and size as reviewed by Kouraytem and colleagues (2021) [9]. The author also successfully showed the increase in yield strength and decrease in anisotropic behaviour of AM IN718 as compared to as-built AM IN718 by applying a post AM heat treatment.

3. Finish Machining of AM IN718

Finish machining of AM IN718 has been done through mainly 2 types of machining processes known as turning and milling [10]. During turning workpiece is rotating and the cutting tool remains stationary while milling removes material from a stationary workpiece using a rotating cutting tool [11]. Cutting parameters can be defined as the cutting speed, feed rate, spindle speed and the depth of cut whereby the cutting speed is dependent on the tool material, work material, depth of cut and tool geometry. Hence, the difference in microstructure and mechanical properties of AM IN718 will affect the cutting speed which will in turn affect the cutting force and surface integrity of machined workpiece. Understanding the relationship between the cutting force, surface integrity and tool wear and the different build orientation of AM IN718 will help develop empirical models that allow the AM and machining chain coupling. Various researchers have machined AM IN718 using different machining parameters and made varying conclusions as shown in Table 1.

Table 1. Machining of AM IN718

AM process	Machi-ning	Machining Parameters				Main Conclusion	Ref
		Speed (m/min)	*Feed*	*DoC (mm)*	*Coolant*		
EBM LPBF	Face Turning	40	0.12 mm/rev	0.4	5.5-6.5 % Emulsion at 6-8 bar pressure inlet	- Cutting force dependent on texture and extent of work hardening before crack formation - EBPBF → larger cutting forces than LPBF and wrought	[12]
LPBF	Side Milling		40 mm/min	4	6% Emulsion	- Cutting forces lower on AM IN718 than wrought - Tool wear → abrasion on flank face, notching at DoC and BUE - Tool life in wrought half that in AM IN718 - Tool wear affects cutting forces.	[13]
LPBF	Micro-milling		5, 10 mm/min	0.2 (axial)		- Increase in spindle speed (25 000 – 30 000) and feed → Decrease in residual stress and increase in toolwear - Increase in spindle speed and decrease in feed→ Increased surface roughness - LPBF parts had lower roughness than wrought	[14]
LPBF	Turning	60	0.1mm/rev	0.4	Dry	- Cutting force, temperature and vibration lower on AM part than wrought - Tool has longer life on AM than wrought - AM and wrought IN718 had same roughness	[15]
LPBF	Turning	60	0.12 mm/rev	0.5	Dry	- Turning reduced roughness by 96% -Turning affected microstructure and micro-hardness. - Turning → reduction in wear rate by 12%	[16]
LPBF	Face Milling	20-40	0.05-0.15 mm/min	0.3	Dry, Wet (IGOL USINOV; 30 bar; 7%) and MQL (Vascomill; 2 bar)	- Specific cutting energy same for dry and MQL - Zone of functionality for MQL 2 times larger than dry - Wet → less energy consumption and surface modification than dry and MQL	[17]

						- Lower tool wear on LPBF samples than wrought	
LPBF	Milling	30	0.1mm /tooth	0.5	Dry and Wet	- Cutting force higher during dry cutting than wet (higher thermal load) → Higher fatigue resistance → Better surface finish - Wet Cut→ Random crack initiation and propagation	[18]
LPBF	Turning	60,90,120	0.1 mm/rev	2	Dry	- High porosity in AM IN718 → lower cutting forces at high speed; higher coefficient of friction [higher rate of BUE formation]	[19]

Most researchers used a cutting speed of less than 60 m/min for the finish machining of LPBF IN718. Although wet machining of AM and wrought IN718 has been long known to result in the best surface finish, dry cutting has been investigated more. For hard alloys parts that have interrupted cuts, such as gears, dry machining at high speeds is preferred [20]. The resulting high tool tip temperature in dry machining would anneal the pre-cut material which would in turn reduce the hardness of the latter facilitating the cutting process [20]. Furthermore, dry cutting and minimum quantity lubrication (MQL) have been shown to be more sustainable as compared to other cooling strategies [21]. Hence further investigation on the machining of AM IN718 would provide a better understanding on the effect of dry machining on anisotropic microstructures. The most adopted tool for IN718 in general were cubic boron nitride (CBN), ceramics and coated carbides. Among the different tools that was used for the different cutting coated carbide tool was found to be suitable for the turning of LPBF IN718 due to its longer tool life [22].

3.1 Machining Performance Measures

The main measures for machining performance for AM IN718 as identified by table 1 were cutting force, tool wear, chip morphology and surface integrity (roughness and hardness). The cutting forces were lower when machining AM IN718 as compared to wrought under both dry and wet conditions [13, 15]. The cutting forces is dependent on the rake angle whereby a zero rake angle would result in the cutting forces being independent of the hardness [23]. The cutting force has 2 components known as the radial force and tangential force component. When machining hard alloys such as IN718, the radial force is expected to be higher than the tangential force component [23]. When investigating the machinability of AM IN718, all the components of cutting forces have to be analysed while considering the effect of rake angle. Tool wear deteriorates the surface finish of machined hard alloys which then limits the tool life [20]. Hence monitoring the latter would ensure that cutting force changes during finish machining are not being affected by tool wear. During the machining, higher wear rate were observed for heat treated AM IN718 as compared to as-built ones [12]. This was associated with the higher hardness of heat-treated AM IN718 which resulted in more mechanically and thermally induced tool wear. Segmental and serrated chips are mostly obtained during the machining of hard alloys due to the adiabatic shear whereby the shear angle increases with the hardness of the material [23]. Similar observations have been made for AM IN718 whereby heat treatment resulted in deeper cracks [12]. The shape of chip and type of tool wear affect the surface roughness and microhardness as stated in Table 1. Increasing cutting speed and feed also has shown to increase the surface roughness and decrease in microhardness of AM IN718 with a speed of 60m/min (DoC – 0.6mm and Feed – 0.15m/rev) resulting in a surface with the best surface roughness during dry cut [24].

4. Conclusion and Future works

Post AM heat treatments has been shown to reduce the anisotropic behaviour of IN718. Further investigation is needed to relate grain size and shape of AM IN718 to AM and machining parameters using empirical modeling. Then the efficiency of developing an adaptive machining process with respect to the model should be evaluated with respect to machining AM IN718 after heat treatments. The efficiency study could also involve the study of AM IN718 machining using bio-based coolants targeting to reduce the greenhouse gas emissions associated with coolant use.

5. References

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