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Effect of Grain Structure on Machinability of LPBF Inconel 718: A Critical Review

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Abstract: Laser-powder bed fusion LPBF techniques can be used to manufacture complex-shaped, thin-walled, hollow, or slender parts. Although the dimensions of the generated components are close to the final measurements, additional machining processes are required to obtain the desired surface finish and dimensional tolerance. The melt pool dynamic during the LPBF operation results in directional gain structures in alloys. The resulting mechanical properties are strongly dependent on the component build orientation, which can affect the machinability of the produced part. This review paper provides knowledge on the role of microstructure in the machinability of LPBF-produced IN718. The effect of grain shape and distribution, grain boundary density on the surface integrity, and resulting cutting forces are investigated.

Keywords: LPBF, Inconel 718, Microstructure, Anisotropy, Machinability.

1. Introduction

Inconel 718 (IN718) is a nickel-primarily based totally alloy with advanced mechanical properties, which include outstanding corrosion resistance, thermal fatigue resistance, and creep at temperatures up to 650 Co [1]. In comparison to other nickel-based superalloys, IN718 offers improved weldability [2].

The use of LPBF techniques provides significant flexibility for manufacturing intricate geometries of strong alloys such as IN718 [2]. This processing technique comprises repeated rapid melting, solidification, and reheating, subjecting the material to unstable conditions that induce different grain morphologies [3], which cause anisotropic mechanical properties [4]. The mechanical properties of metals are also significantly influenced by the size of individual grains [2].

Machining is often required to obtain the final shapes with the desired geometry. LPBF components create additional machining issues due to material inhomogeneity and complicated geometries [4]. Machining causes phase transition and work hardening, which makes the IN718 alloy stronger and more abrasive, resulting in higher cutting force, irregular chips, and higher Ra [5]. However, research into the effect of grain

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morphology on the machinability of LPBF IN718 parts is still in its early stages. The aim of this review paper is to study the effect of microstructural variables such as grain shape, size, distribution, and grain boundary density on LPBF IN718 machinability, surface integrity, and cutting force.

2. Microstructure effects on mechanical properties of LPF IN718

The microstructure of LPBF components is determined by the melt pool dynamic, which is influenced by crucial and continuous temperature changes [3]. A significant cooling gradient results in non-equilibrium solidification that induces grain refinement on the build plane, while more uniform solidification produces columnar grains that elongate in the build direction [3], as illustrated in Figures 1(B and C). The elastic anisotropy of columnar-grained IN718 alloy is extensively documented, exhibiting varied elastic characteristics. In the LPBF-produced IN718, Ni et al. [4] found that parts tested along the build direction (Z) exhibit lower tensile strength (UTS = 1101 MPa, $\sigma_{0.2}$ = 710 MPa), but higher elongation (δ = 24.5%) than those tested along the build plane (XY) (UTS = 1167 MPa, $\sigma_{0.2}$ = 850 MPa, δ = 21.5%). Moriz et al. [1] and Deng et al. [2] obtained similar results with SLM-fabricated IN718. This anisotropy has a considerable influence on the stiffness of the components associated with vibrations and cutting forces during machining [6]. However, the anisotropy in the mechanical properties can be affected by heat-treatment post-processing [1].

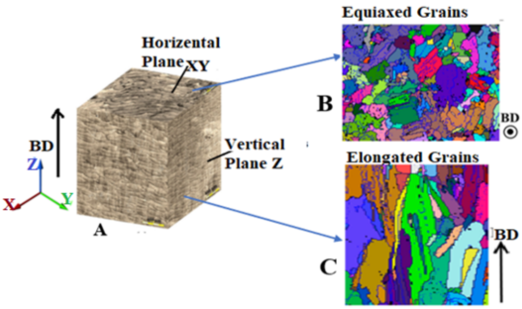

Figure 1: (A) Illustrates the build direction and the build plane, (B) SEM image depicting equiaxed grains on the build plane, and (C) elongated columnar grains on the build direction [3], [7].

3. The effect of microstructure on the machinability of LPBF IN718

A machinability index is determined by cutting forces, chip formation and evacuation, surface and subsurface integrity, and tool wear [8]. However, IN718 alloy exhibits poor machinability owing to its lower thermal conductivity, rapid hardening, and high resistance to plastic deformation at higher temperatures [9].

During the machining processes, the workpiece material is subjected to thermal and mechanical stresses, which can result in strain aging and recrystallization [10]. Many parameters are known to cause and/or support these shear deformations, including cutting parameters (cutting speed, feed, depth of cut), tool parameters (rake angle, edge radius, shape, coating, wear), workpiece parameters (material, grain size), and cutting fluid [8].

In terms of microstructure, Khanna et al. [9] stated that machining alloys with a large grain size reduce crack nucleation, whereas a small one limits crack propagation. Grain boundaries act as barriers to prevent crack development and dislocation displacement [1]. Since machining relies on crack propagation along the cutting edge to form a chip, the smaller the grain size, the more difficult the material will be to cut [10]. The grain size of LPBF IN718 is roughly thirty times larger than that of wrought material, as stated by Ducroux et al. [11]. Due to fewer grain boundaries, crack propagation is substantially more discernible while machining LPBF parts [12].

The presence of carbides is another issue in machining IN718 which are extremely difficult to cut [13]. There are three types of carbides: NbC, TiC, and (Nb, Ti)C, which are the sensitive determinants of IN718 machinability [11]. Three results are possible during the machining of these carbides, according to Dudzinski et al. [14]. First, the carbide is cut, causing significant cutting forces to be created locally on the cutting edge. Second, if the carbide is small enough, the tool tears it away from the material, leaving a hole in the machined surface. Otherwise, the carbide is not cut and destroys the tool by scratching the flank surface. Since wrought IN718 carbides are larger than LPB IN718 carbides, the cutting force generated when machining wrought IN718 is greater [11].

3.1. Microstructure influences surface integrity of LPBF IN718

The surface quality of a machined surface is determined by three main factors: surface roughness Ra, residual stresses, and microhardness [15]. A Low Ra value indicates a reduction in stress concentration, micro-cracks, and fatigue cracks initiated at the grain boundaries [7], [16]. Pérez-Ruiz et al. 202 [6] stated that the initial Ra of LPBF as-built IN718 in the vertical (Z) plane can vary by up to 30 μm compared to the horizontal (XY) plane. Machining post-processing is still the most effective way to reduce roughness [15]. The surface roughness values of turned machined AM IN718 have been compared to their wrought manufactured counterparts and were comparable in several investigations [8], [17]. A comparison of Ra values for machined LPBF IN718, in the build plane and the build direction of the same part, was not available in the literature., but Brinksmeier [16] milled SLM 18 Maraging 300 short cylindrical components under similar machining conditions on the same part's build plane and build direction. The results revealed that the milled SLM part has less roughness on the build plane. The surface roughness is also determined by machining parameters [10]. According to research studies, machining IN718 with more productive parameters generates dislocation, phase transition, and micro-cracks due to the high heat generated at the cutting area [10].

The impact of thermo-mechanical stresses on the microstructures in the primary shear zone during machining induces material work-hardening on the machined workpiece surface [18]. The generated heat influences the phase transition, whereas strain and strain rate influence grain formation [3]. Kaynak et al. [7] investigated the surface hardening of SLM IN718 parts after turning in dry and cold air, which were compared to the as-built SLM IN718 non-machined sample. The hardness increased by around 16 % on average; however, the dry cut had a higher hardness, per the research. As a result, the microstructure behaviour has a direct impact on the machined surface outcome.

3.2. The effect of grain structure on cutting force

The machining cutting force is primarily derived from the plastic deformation in the primary shear zone, as well as the friction tension between the tool and the workpiece in the secondary deformation zone [10]. It is essential to consider the resistance provided by grains and grain binderies when evaluating shear resistance [19], as shown in Figure 2. At the macroscopic level, the cutting area is typically simplified as a plane [8]. However, the shear zone is made up of several slip directions that, when combined, generate the plane of the shear band [6]. The strength of metals and alloys improves with decreasing grain size, as per the Hall-Petch relationship [20]. The grain refinement of LPBF IN718 increases grain boundary density, leading to higher cutting forces during machining [6]. However, Malakizadi et al. [12] observed that, despite the wrought IN718 having lower grain sizes than the SLM IN718, the resulting cutting forces of facing were approximately the same. This is because SLM parts were faced against equiaxed gains on the surface perpendicular to the build direction.

The large anisotropic properties of LPBF-produced components relate to differences in grain shape and distribution in the build and transverse directions [12]. However, there is no comprehensive comparison of the resultant cutting forces in machining on different LPBF IN718 surfaces. Nonetheless, Shunmugavel et al. [21] investigated the influence of build direction on resultant cutting forces in three distinct relative directions between the cutting velocity vector and the columnar grain while machining SLM titanium alloy Ti64. The cutting forces were found to be the lowest when the cutting tool went along the cross-section of the columnar grains.

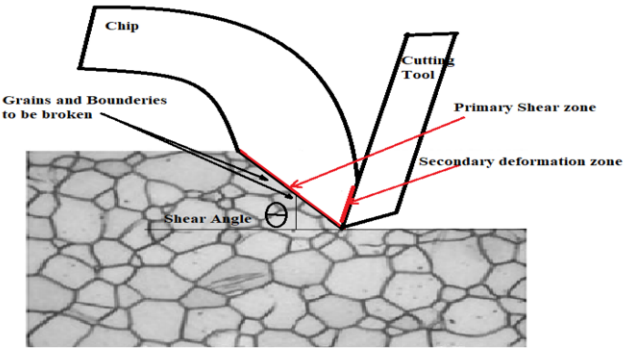

Figure (2): Illustrates the cutting tool breaks gains and grain boundaries.

3.3. Microstructure effects on chip formation

The type and nature of chips depend on the combination of different factors such as work material properties, cutting parameters, phase morphology, grain size, tool geometry, and cutting conditions [19]. The crack propagation in front of the cutting edge is core to the chip-separation process [22]. Since crack propagation is more apparent with fewer grain boundaries, chips will form earlier when cutting LPBF IN718 parts [12]. Chen et al., [8] turned wrought and SLM IN718 to differentiate between the produced chips. The study concluded that due to the high cutting temperature and large cutting deformation, all the chips had serrated edges. However, the SLM IN718 parts produced irregular, continuous serrated chips with uncontrollable outflow, whereas the wrought superalloy produced helical-form shapes that were easy to control. The different chip shapes and morphologies can be attributed to the various SLM IN718 microstructures.

The thermo-mechanical effect develops second-phase particles (γ' and γ'') at the cutting zone, making the IN718 alloy stronger and more abrasive, making it more difficult to remove [10]. Hence, the basic shearing process and chip generation in the cutting sequences will differ due to changes in the characteristics of the machined workpiece material [5]. The surface roughness increases as the number of serrations or segmentation of chips "saw teeth" increases [22].

4. Conclusion and future work

The mechanical properties of parts were shown to be affected by the developed grain structures. Further, the machinability of LPBF IN718 was shown to be effected by the second phase of the composition, specifically the inclusion of microstructure attributes. The AM-produced parts in IN718 can be subjected to heat treatment to reduce anisotropy and develop a more uniform microstructure that could improve machinability. This could be achieved by a homogenisation heat treatment.

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