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*The Effect of the Heat Treatments on the Tool Wear of Hybrid Additive
Manufacturing of IN718*

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Abstract

The application of the Direct Energy Deposition (DED) in the aerospace field offers the potential to manufacture and repair critical components. Nevertheless, the parts produced by DED require finishing operations such as machining. Consequently, the tool wear analysis is usually required to better understand the quality of the manufacturing process, especially when difficult-to-machine materials are involved. In this study, the tool wear analysis was carried out after performing machining operations on DED IN718, considering the material as “as-deposited” and “heat-treated” conditions. The microstructural investigation by electron microscopy analysis was performed to study tool wear depending on the variation of the process parameters. The study highlights the presence of different tool wear mechanisms during the machining of the DED IN718. The results demonstrate a correlation between cutting speed, feed rate, material conditions and tool wear. Indeed, although high values of the process parameters (high cutting speed, high feed rate) caused high wear rate, the material

conditions affected the tool wear mechanisms involved. It was also found that the main wear mechanisms during the processing of IN718 were adhesive and abrasive. The tools used to machine the heat-treated materials were characterized by extreme wear as suggested by the crater formation, due to the superior mechanical properties exhibited by the material.

Keywords: Additive manufacturing; Machining; Superalloys; Tool wear; Electron microscopy.

1. Introduction

The introduction of the Additive Manufacturing (AM) technology, in the production of near-net-shape components in the aerospace and biomedical sectors, reduces waste material, and manufacturing steps. However, the surface quality of the products manufactured by AM process can meet the required specifications and geometrical tolerances by using post-process machining operations [1]. The aero-engine materials, such as Ni-based superalloys, are characterised by their superior mechanical properties, corrosion, and oxidation resistance at high temperature. Recently, the aerospace sector has invested in laser-based AM technologies (e.g. Direct Energy Deposition, or Selective Laser Melting), to produce or repair critical components. Tremendous interest has been shown in this technology as highlighted by numerous scientific contributions related to the development and the optimization of the different AM techniques. Benn and Salva [2] analysed and compared the microstructure, the mechanical properties, and the surface quality of the main AM methodologies in the industrial field. The AM processes studied were Electron Beam Wire Deposition (EBWD), Direct Metal Laser Sintering (DMLS), Laser Powder Deposition (LPD), and Gas Metal Arc Welding (GMAW). Once the process parameters for the production of IN718 cubes were

optimized, the same manufacturing procedure was applied to produce the other specimens. The authors found that the DMLS process was superior to produce samples with higher density and lower porosity. The mechanical properties of the DMLS specimen, the ultimate and yield stress, and elongation were comparable to those of the wrought material. Also, the DMLS technique allowed to produce parts with higher surface quality than the components produced by the other tested technologies. The application of the laser deposition technology used in this work is nowadays quite extensively employed in the industrial environment. Due to its advantages to manufacture and repair components, different studies on the optimization of deposition parameters are available in the literature. Tabernero *et al.* [3] and Calleja *et al.* [4] have provided initial information for future researches and development of this AM technique. These works show some improved production strategies that enhance the quality of the components produced through DED. Tabernero *et al.* [3] analysed the main variables involved in the manufacturing process such as: laser power and deposition head stand-off. They also developed a criterion to objectively select the optimum process parameters considering most of the aspects related to the quality of the product that needs to be produced. While Calleja *et al.* [4] focused on finding the optimal values of the laser power and the deposition feed rate. The analyses were carried out by an algorithm implemented for the optimization of the parameters, highlighting how the deposition feed rate continuity avoids the manufacturing of nonhomogeneous parts with uneven shapes and geometrical issues. In both studies, however, a machining operation was performed as post-process finishing operation.

Consequently, the machining operation as a post-process strategy afterward the laser deposition is mandatory during the final steps of the component production. The investigation of the machining parameters and the influence on the materials properties are of fundamental importance to have a better knowledge of the process and to develop optimised

manufacturing strategies. It is well known that the Ni-based superalloys, such as IN718, are also classified as difficult-to-cut materials [5]. Furthermore, the rapidly solidified microstructure usually results in higher residual stresses within the produced parts affecting the machining operations and the final geometrical tolerances achieved [6]. Consequently, different studies have recently been conducted to investigate the machining of the wrought IN718. The correlation between the machining process and the tool life was analysed. Moreover, the effects of different process parameters and the tool wear mechanisms on important characteristics of the final product, have been studied [7,8]. In the last decade some studies have been conducted on the surface integrity and the tool wear when materials produced by DED were machined. Gong *et al.* [9] studied the correlation between the machining parameters of AM-processed stainless steel AISI 316L and the tool life. They also found a correlation between the heat dissipation, the roughness and the tool wear rate (low, medium and severe). Sartori *et al.* [10], instead, described the influence of the cooling conditions on tool wear during the turning of AM-processed Ti6Al4V. They quantified the adhesive and abrasive wear, describing the main tool wear mechanisms involved during the dry and cryogenic machining. They also achieved a significant tool life enhancement when adopting Liquid Nitrogen during the turning process. Park *et al.* [11] investigated the tool life during dry machining of the AM-processed IN718 and they compared the machinability with the wrought material. The outcomes suggested that different wear mechanisms were present, and the abrasive wear was significantly evident on the tools used to machine AM-processed material. The authors also observed that, during the machining of the wrought material, the adhesive wear and the fracture were also evident. Although recent works suggest that the use of lubricants (e.g. Liquid Nitrogen) can help improve the machining operations of difficult-to-cut materials, dry machining remains one of the most environmentally friendly manufacturing processes [12]. Furthermore, the use of cooling strategies, such as Minimum

Quantity of Lubricant (MQL) and cryogenic coolant, does not always guarantee better results in terms of tool wear. As reported by Musfirah *et al.* [13], although the use of cryogenic lubrication reduced the friction at the interface between the tool and workpiece, dry machining assurances enhanced tool life (longer cutting time and less tool wear). Indeed, the authors observed an embrittlement of the tool at cryogenic temperature. Furthermore, the use of the MQL did not seriously increase the tool life compared to the dry machining [14]. As a result, in this study the analysis of the tool wear was carried out considering the machining operations in dry conditions.

Due to the nature of the DED, post-process heat treatments are usually applied to increase the mechanical properties of the IN718 by homogenisation, solution and, ageing treatment. During these heat treatments the microstructure changes and the precipitation of different phases, including the strengthening γ'' -phase, occurs [15,16]. The heat-treated material generally shows isotropic mechanical behaviour. This is the result of the transformation of the columnar dendritic microstructure, formed during the DED process into an equiaxed microstructure thanks to the recrystallisation phenomenon [17]. Additionally, the combined effects of the precipitation hardening and the stress relief improve the material properties. [18,19].

Despite the studies carried out on the machining AM-processed IN718, the authors mainly investigate the machinability and surface integrity rather than on tool wear. Since the tool wear can significantly impact the costs of the process chain, this study aims to investigate the tool wear mechanisms during the machining of the DED IN718 in dry conditions, including the influence of heat treatments. The tool wear was experimentally assessed using advanced characterisation techniques (e.g. Scanning Electron Microscopy, Energy Dispersive X-Ray Spectroscopy). The influence of the different turning process parameters on the tool wear was also evaluated.

2. Material and Methods

2.1. Material

The investigated material was the Ni-based superalloy IN718 supplied as powder. The particle size was in the size range 45 to 106 μm and the chemical composition in %weight is listed in Table 1.

Table 1: Chemical Composition (in %weight) for IN718.

Elements	Ni	Cr	Fe	Nb	Co	Al	Ti	Mn	C
%weight	52.82	19.0	17.0	3.0	1.0	0.8	0.6	0.35	0.08

Cylindric bars (120 mm length and 33 mm of diameter) were produced by DED using the Trumpf TLC 1005. The DED process parameters used were: laser power of 400 W, scan speed of 275 mm/min, and a powder flow rate of 9.8 g/min. A 90° rotating bidirectional scanning strategy was adopted to minimise the residual stress effects and optimise the final surface quality and cooling rate, (Fig. 1b).

Fig. 1. DED Additive Manufacturing Process. a) schematic illustration of the process; b) scan strategy; c) microstructure of processed material IN718.

As shown in Fig. 1c, the as-deposited material (AD) was characterised by a columnar dendritic microstructure. The dendritic growth direction was driven by heat source, and consequently, the dendrites were primarily oriented through the building direction. The dendrites orientation can be related to the influence of the vertical, and horizontal heat flows, as well as to the orientation of the dendrite of the previously deposited layers. Moreover, the use of a continuous laser produced a high concentration of heat which influenced the orientation of the microstructure between the layers. While dendrites tend to grow perpendicular to previous layers, this makes them orientate more towards the direction of the heat source [20]. Due to the rapid heating and cooling the strengthening phases were not able to form, therefore, the produced parts were not suitable for industrial applications because of their low resistance. Consequently, the heat treatment was used to achieve high mechanical properties. The heat treatment, suggested by the standard SAE AMS 5583D [21] and represented in Fig. 2, consists of 3 steps: homogenisation, solution and double ageing. During

the entire heat treatment, the material experiences the dissolution of the detrimental Laves phases, and the formation of the strengthening phases γ' and γ'' , as well as microstructural change (from dendritic to equiaxial).

Fig. 2. Heat treatment carried out on the samples produced by DED; a) description of the heat treatment; b) heat treatment time steps; c) microstructure obtained post-heat treatment.

As shown in Fig. 2c, following the three steps related to the heat treatment (HT) the microstructure of the IN718 changed. In particular, the elongated grains observed in the as-built (AD) sample recrystallised and formed smaller equiaxial grains. Recrystallisation and grain growth have occurred and the precipitation of the different phases, (e.g. γ' and γ'') improved the mechanical behaviour of the material. As results, the higher hardness, the ultimate tensile stress and the reduced elongation are comparable with the Ni-based superalloys manufactured by conventional manufacturing processes such as casting or forging [22].

2.2. Experimental Analysis

The machining experimental tests for both as-deposited and heat-treated material conditions were carried out on a two axis CNC lathe (Mazak, Quick Turn Nexus 200-II) in dry cooling conditions and the experimental set-up of the machining tests is represented in Fig. 3a.

Fig. 3. Machining tests. a) Turning set-up; b) Tool holder and tool used for the test; c) schematic representation of tool details and properties.

The tools adopted (Sandvik Coromant, DNMG 15 06 12-SMR S05F) for the turning tests were a semi-finishing TiAlN insert (Fig. 3c), characterised by rake and clearance angle of 6° and 0° , respectively. The tool was chosen based on Sandvik's advice, due to the CVD multilayer coating used in a wide range of applications where wear resistance is one of the most important factors [23]. Once the tool was chosen, the tool holder (Sandvik Coromant, DDJNR 2525M 15) with an approach angle K_r of 93° was selected (Fig. 3b). To investigate the impact of each cutting parameter on tool wear, the tests were carried out following the Design of Experiments (DoE) reported in Table 2.

Table 2: Experimental Plan (DoE) referred to the machining test.

Material	# Test	V_c [m/min]	f_r [mm/rev]	Depth [mm]	Cooling Condition	Material Condition
IN718	1	70	0.1	0.5	Dry	As-deposited
	2	90	0.1			
	3	120	0.1			

	4	70	0.2			
	5	90	0.2			
	6	120	0.2			
	7	70	0.1	0.5	Dry	Heat-treated
	8	90	0.1			
	9	120	0.1			
	10	70	0.2			
	11	90	0.2			
	12	120	0.2			

In detail, the experimental campaign includes six tests for each as-deposited and heat-treated material investigated. The cutting depth was kept constant and equal to 0.5 mm, the cutting speed was varied on three levels and the feed rate on two levels. The cutting parameters were chosen considering the range of values suggested by the Sandvik Company. In detail, the feed values, $f_r=0.1$ mm/rev and $f_r=0.2$ mm/rev are within the recommended values when turning superalloys such as IN718. While two cutting speed values within the recommended parameters, $V_c=70$ m/min and $V_c=90$ m/min have been selected. Moreover, an additional value outside the recommended range, $V_c=120$ m/min has been also considered to test the behaviour of the tool at high cutting speeds. The tests were performed in dry conditions, and at a fixed time length necessary to achieve the steady-state region of the forces and the temperatures. A fresh single cutting edge was used for each test, to assure the correct modality and interpretation of the analysis carried out afterwards.

2.3. Analysis

The workability analysis at DED IN718 was carried out in terms of tool wear mechanism using electron microscopy techniques. The tools were analysed with the aid of a Scanning Electron Microscope (SEM) (HITACHI, Tabletop Microscope TM3000) to estimate the tool wear that occurred during each machining test. In particular, the analysis SEM have been carried out to qualitatively evaluate the wear on the cutting edge and machined surface. Furthermore, the principal wear mechanisms, adhesive and abrasive, were analysed and

quantified through Energy Dispersive X-ray Spectrometry (EDX) incorporated in the SEM. Two evaluation criteria, EDX mapping and point analysis, were conducted to visually represent and characterise the amount of material attached to the tool and the potential defects that occurred due to wear. The effect of the cutting parameters, cutting speed and feed rate, were also estimated, to understand the different behaviour of the material in both their configuration and influence on tool wear. Finally, a metallographic analysis was performed to highlight the microstructure alterations occurred across the surface layers.

3. Results and Discussion

3.1. Tool Wear Mechanisms

As a consequence of material behaviour, the machinability of the deposited and treated material can be related to the tool wear. The IN718 is well known as a difficult-to-cut material due to the work hardening, and low thermal conductivity properties. The high pressures induced by the tool on the material surface during machining, cause a hardening effect that makes further machining steps more difficult, and may also cause distortions on the final parts produced [24,25].

Fig. 4. SEM images of tool wear in dry turning conditions considering the material as-deposited (AD) and heat-treated (HT).

In Fig. 4 the comparison of the tool wear at the same cutting time, while different cutting parameters were used, is presented. In the two conditions, heat-treated, and as-deposited, different levels of wear have been found on the tools. The use of the heat treatment on the as-deposited material, together with the variation of the cutting parameters, has clearly influenced the wear and tear of the tool, compared with the one analysed when the material is not heat-treated. Increasing the feed rate, as well as the cutting speed, results in more significant effects in terms of wear are observed. Moreover, the worst wear occurs in the case of heat-treated material since the alloy has acquired superior mechanical properties, compared to the as-deposited condition. In particular, considering the heat-treated condition, the presence of craters on the tool was observed, suggesting excessive tool wear during the machining process. Excluding the presence of the craters, the wear mechanisms are similar for both material conditions (heat-treated and as-deposited), even though their effects are different. The main wear mechanisms observed during the experimental analysis of DED IN718 dry machining, can be grouped into three categories: adhesive, abrasive, and chipping. The adhesive mechanism, as well as work hardening, was responsible for severe notching at the tool nose and the contact length between cutting edge and machined surface. The abrasive mechanism was predominantly due to chip formation, which induced flank wear. The abrasion due to the contact between the tool and machined surface led to chipping, and catastrophic failure, necessitating in the replacement of the tool during the machining of Ni-based alloys. Similar outcomes related to the machining process of additively manufactured Titanium alloy were also found and discussed by Bordin *et al.* [26]. Finally, it was found the chipping was due to the detachment of fragments of the cutting edge, initially triggered by the adhesive wear mechanism. The machined material surface layers adhered to the surface of the

tool, smearing the tool surface layer, causing the removal of the coating layer and faster tool wear [27]. It is conventionally accepted that tool wear during the machining of a Ni-based alloy, such as IN718, is mainly determined by the adhesion mechanism. Tool failure, however, is largely driven by the phenomenon of chipping due to adhesion, and subsequent abrasion between the tool and the workpiece surface layers [28,29]. As a result, all the wear mechanisms occurring during the machining tests are highlighted and discussed in this work.

Fig. 5. Wear mechanisms occurred on the tool tip during the machining process ($V_c=120$ m/min; $f_r=0.2$ mm/rev) a) and b) as-deposited, c) and d) heat-treated.

According to Fig. 5, three main regions found on the tool faces were identified by low magnification images acquired during the SEM analysis. The first region, highlighted in purple, (Fig. 5a) corresponds to the area where the adhesive wear mechanism mainly

occurred, due to direct contact between the cutting edge and the workpiece. This zone, where the formation of the chip began, was subject to high forces and represented the trigger point of the wear of the cutting edge. The second region, highlighted in green, (Fig. 5a, Fig. 5c), corresponds to the delaminated coated area of the tool, where the adhesion mechanism and subsequently the abrasion, led to the loss of the surface coating layer. Therefore, the internal part of the tool remained uncovered. The second region was caused by the damage of the coating layer during the machining due to the rubbing of the chip on the tool surface. It can be noted that the area was characterised by the adhered workpiece material due to the chip that formed and rubbed the tool surface. The third region was represented by the undamaged zone of the tool, where the coating and, consequently, the insert integrity was not affected by the machining process. Finally, the other two regions were discovered on the tool tip. The first region was represented by the area where the chipping phenomenon occurred and is highlighted in yellow (Fig. 5b), while the second area, highlighted in blue, was represented by the presence of craters (Fig. 5c, Fig. 5d), due to the detachment of a substantial part of the flank face.

3.2. Adhesive Wear Analysis

Since the greatest wear mechanism of the coated tools during Ni-based superalloys turning is adhesion ones, it is appropriate to evaluate the different levels correlated to the different cutting parameters during the machining tests. The study of adhesive wear mechanism was carried out through the use of two different approaches, based on the Energy Dispersive X-Ray Spectroscopy (EDX) analysis. To better investigate the adhesive wear mechanism, an initial qualitative evaluation through an EDX map was carried out by a localised analysis, which provided information about the chemical nature and amount of the material observed on the tool surfaces.

Fig. 6. EDX zone mapping of the rake face of the tool; a) as-deposited (AD); b) heat-treated (HT).

The IN718 is a Ni-based alloy characterised by the presence of a considerable number of elements within the alloy. Therefore, it is possible to know the area affected by the adhesive wear mechanism evaluating the quantity of material present on the insert surface. As shown in Fig. 6a and Fig. 6b, the region near the flank face was mainly characterised by a high

percentage of Ni, Cr, Nb and Fe. These are the main constituent elements of the IN718 alloy, suggesting that a large region of the tool surface was affected by adhesive wear. On the contrary, the unaffected region was mainly characterised by a high concentration of Al and Ti that are elements of the protective coating of the tool. Focusing on Fig. 6b, it is possible to notice that there was a significant amount of heat-treated workpiece material smeared on the tip tool, suggesting that both the adhesion and abrasion were remarkable. Moreover, to better characterise, quantify, and compare, the different amount of smeared material on the tool tip, localised EDX analyses were, therefore, carried out and the results are reported in Fig. 7 and Table 3.

Fig. 7. EDX spot analysis of the rake face of the tool ($V_c=120$ m/min; $f_r=0.2$ mm/rev); a) as-deposited material (AD); b) heat-treated material (HT).

Table 3: EDX result in %w of the EDX point analysis carried out.

EDX Spot	Ni [%w]	Cr [%w]	Nb [%w]	Fe [%w]	Ti [%w]	Al [%w]
1	0.59	0.01	0.03	0.22	74.36	24.79
2	48.98	21.48	5.11	21.03	2.86	0.54
3	9.21	2.45	1.57	3.02	59.64	24.11
4	43.39	20.7	6.43	28.05	1.19	0.24

As shown in Fig. 7 and highlighted in Table 3, the EDX spots 2 and 4 show high concentrations of Ni, Cr, Fe. Conversely, in the EDX spots 1 and 3, these values were

drastically lower, highlighting a greater concentration of Al and Ti that characterised the substrate tool elements. Considering the concentrations of the constituent elements of the workpiece material evaluated by the EDX spots 2 and 4, no drastic change was appreciable when the same machining parameters (cutting parameters, depth of cut) and same conditions were used (dry). However, since there are craters for the heat-treated material, it is possible that the higher forces caused a greater adhesion of material. Consequently, an EDX spot near the cutting edge, would have given much higher concentrations of the elements compared to the case of the as-deposited material. This effect could be due to the temperatures reached during the machining process, lower than the case of heat-treated material, which almost certainly inhibited the adhesive wear mechanisms [26]. An increase in the cutting parameters highlighted a larger area of adhesion material, correlated to the higher forces that occurred during the turning tests. Furthermore, for the as-deposited material, the phenomenon of crater formation was not observed, regardless of the cutting speed or feed rate used. Therefore, the main wear mechanism was characterised by the adhesive wear. On the contrary, concerning the heat-treated material, the adhesive wear mechanism occurred in the very early stages of the turning process, leaving the uncoated substrate exposed to an extended contact with the piece and chips scroll, causing deeper wear and consequently a shorter tool life.

3.3. Abrasive and Crater Wear Mechanisms

During the chip formation, the hard inclusions in the workpiece material pressed into the friction surface, which caused an abrasive wear mechanism that generated scratches, due to the rubbing of the insert surface. Moreover, the chip sliding eroded the rake face of the cutting tool causing the crater formations. This type of tool wear is common during the machining of the difficult-to-cut material, and generally does not seriously compromise the tool life until it becomes significant enough to trigger and cause cutting-edge failure [30,31].

The optimum tool life during the machining process, could also be identified by evaluating the optimal length and depth of crater wear, before the tool leads to the failure of the product characteristics due to the compromised machined surface [32]. Therefore, a study of the presence of craters offers very useful information on the degradation of the cutting insert and consequently on the life of the tool.

Fig. 8. SEM analysis of the crater wear ($f_r=0.2\text{mm/rev}$).

As shown in Fig. 8, the wear mechanism is completely different for the two cases analysed (i.e. machining of as-deposited and heat-treated IN718). Concerning the tools employed in machining the as-deposited material, the abrasion wear along the chip formation area was mainly found, with a presence of high chipping wear region. While in the case of the heat-treated material, all the tools showed severe damage of the tip characterised by the formation of significant craters. These results suggested that the tool was not strong enough to support the high localised pressures developed in this area during the cutting process. This consequently resulted in the detachment of part of the coating and thus led to tool failure. It is important to highlight that the tool used to machine the heat-treated material with the lowest

cutting speed (i.e. 70m/min) did not show significant damage as observed for the other cases, but mostly coated material removed. This suggests that the wears mechanism, with the consequent crater formation, was not mainly driven by the feed rate, but also depended on the cutting speed. In fact, for low cutting speed values, there was frequent chipping of the cutting edge. When the cutting speed of the tool increased the crater formation on the rake face that led to the critical condition where the failure of the tool happened. Considering the tool life, the use of low cutting speed has a positive impact on this when the IN718 is machined, after the application of a heat treatment due to the higher hardness of the material. While the as-deposited IN718 also showed a better machinability when higher cutting speed and feed rate were used due to the higher ductility of the material.

3.4. Surface Integrity

The surface integrity of a processed product depends on all the process variables, as well as on the material and geometry of the workpiece. Furthermore, the characteristics of the tool, and its wear during the machining process can significantly affect the surface integrity of a machined component [33]. Generally, surface integrity is analysed by different techniques. For this reason, the surface roughness (S_a) of each machined sample was measured using a ConScan microscope and the results are reported in Table 4. These results present useful information on a possible correlation between the tool wear and the surface quality evaluated [34].

Table 4: Surface Roughness S_a (μm) measured on the machined samples.

Material	$f_r=0.1 \text{ mm/rev}$			$f_r=0.2 \text{ mm/rev}$		
	$V_c=70 \text{ m/min}$	$V_c=90 \text{ m/min}$	$V_c=120 \text{ m/min}$	$V_c=70 \text{ m/min}$	$V_c=90 \text{ m/min}$	$V_c=120 \text{ m/min}$
As-Deposited	1.06	0.85	0.92	1.23	1.12	1.20
Heat-Treated	0.86	0.69	0.93	1.54	3.72	3.6

Analysing the values reported in Table 4, the use of the low feed rate (0.1mm/rev) allowed to achieve lower value of surface roughness due to the considerable limited tool wear. Regardless the material condition, the measured values showed the same trend and the use of low cutting speeds resulted in low surface roughness and better surface quality. Material such as Ni-based superalloys are normally machined at low cutting speeds to preserve the integrity of the tool as much as possible. Moreover, the use of the most suitable cutting parameters, while maintaining high-quality standards, is also advantageous because it reduces the processing times and the associated costs. Focusing on the surface roughness measured on the samples machined at feed rate equal to 0.2mm/rev, the effect of higher feed rate was quite clear. As also revealed by the SEM analysis of the tool, the high feed rate combined with the material condition (i.e. heat-treated) affected the surface roughness because of the significant tool wear. Furthermore, the increase of the cutting speed from 70m/min to 120m/min triggered the tool failure with negative consequences in terms of surface quality as highlighted by the higher surface roughness. Therefore, the use of the high cutting speed to machine the heat-treated IN718, was not suitable to enhance the manufacturing performances since the tool life, as well as the surface quality of the part, are significantly compromised. Consequently, when higher values feed rate are used (equal or higher than 0.2mm/rev) the material condition plays also a key role, indeed limited surface roughness was achieved when the as-deposited material was machined and no catastrophic tool failures were observed.

Fig. 9. ($V_c=90$ m/min; $f_r=0.2$ mm/rev) microstructure beneath the machined surface. a) as-deposited material; b) heat-treated material.

SEM images were acquired and analysed to evaluate the microstructural alteration due to the machining process, and to assess the different effects of the tool wear on machined surface and within the plastically deformed region. The low magnification SEM images represented in Fig. 9, show elongated and deformed grains along the cutting speed direction. In detail, two regions within the affected layer can be identified due to the severe plastic deformation induced by the turning operation. The first region, characterised by grains that were deformed along the cutting direction, mainly represented the affected region. The second region was the one immediately below the material removed by the tool and it was characterised by fine grains and significant plastically deformed material. On the other hand, several slip bands

formation were observed on the heat-treated machine samples. The main tool wear phenomenon observed, however, in the as-deposited samples was adhesion material, thus suggesting greater ductility of the material that was removed by the tool. As shown in Fig. 9, the as-deposited IN718 was characterized by layers of plastically deformed material, while in the heat-treated sample the formation of a very thin white layer occurred. As reported in the work of Capellini *et al.* [35], the phenomenon could be linked to the main parameters such as the cutting speed, the feed rate, and tool wear involved in machining. The flank wear is usually related to the cutting speed; therefore, high speed causes an increase in flank wear. Furthermore, Polvorosa *et al.* [36] have analysed the relationship between the grain size and the flank wear. In their study on the face turning of Ni-based superalloys, the authors estimated qualitatively and quantitatively the tool wear mechanisms when the material with two different grain sizes, fine and coarse was machined. The results obtained explain that the finer microstructure induces a greater flank wear phenomenon. The comparisons between the quantities of the chemical elements present on the cutting tool carried out by Polvorosa *et al.* [36] give information on the nature of the wear mechanisms, mainly adhesive, and indicate that the combination of the microstructure of the material and the cutting parameters greatly influence the flank wear phenomenon. This causes an intense, localised, thermo-mechanical stress that can lead to surface modification. Furthermore, although most of the heat is generally trapped and dissipated by the chip, a significant part is usually kept by the workpiece due to the low thermal conductivity properties that characterise the Ni-based superalloy. The accumulation and slow dissipation of the heat could further affect the machined surface [37]. Consequently, the higher tool wear during the machining of the heat-treated IN718 could lead to significant heat conduction in the workpiece. This is supported by the formation of a discontinuous chip, sufficient to induce the formation of a white layer on the surface below the machined area (Fig. 9b). This condition did not occur in the case of the

as-deposited material, where the formation of a continuous chip (enhanced heat dissipation) and higher ductility, did not create the conditions for triggering the phenomenon (Fig. 9a).

4. Conclusions

In this study the principal tool wear mechanisms occurred during the dry turning process of Ni-based superalloy IN718 produced by DED were investigated and discussed. The samples produced by AM process were also heat-treated to evaluate the effect of the heat treatment on the tool wear. Moreover, the surface quality of the machined parts was also assessed by measuring the surface roughness and through SEM microstructure analysis. Wear is strongly linked to the machinability of the material and in particular to the material condition (as-deposited or heat-treated). The main outcomes are listed below:

- In general, the main tool wear mechanisms observed in both material conditions were the adhesive wear and the abrasive wear.
- Concerning the heat-treated IN718, the formation of craters on the rake face of the tool during the first stages of machining at high cutting speed caused significant wear which led to a rapid tool failure. Consequently, as suggested by the surface roughness analysis, the final quality of the machined part was compromised by increasing the cutting parameters.
- Concerning the as-deposited IN718, the cutting tools mainly exhibited adhesive and abrasive wear. The phenomenon explanation is due to the poor mechanical properties and better ductility of the as-deposited IN718. A limited chipping phenomenon was noticed due to the increase of the cutting parameters. However, chipping did not affect the final quality of the machined part as also suggested by the surface roughness analysis.

- An analysis of the alterations occurred beneath the machined surface was carried out to estimate the effect of the cutting parameters and the tool wear on the quality of machined parts. In both cases (as-deposited and heat-treated), elongated and orientated grains along the cutting direction were observed, which suggested a possible work hardening of the material due to the plastic deformation induced.

The work carried out indicates that the machinability of the IN718 produced by DED and heat-treated is comparable with the material produced by the conventional manufacturing processes such as casting or forging. Consequently, the use of cutting parameters far from the ones recommended by the tool manufacturer leads to severe wear and, therefore, a rapid failure of the cutting tool. The as-deposited material, on the other hand, can be processed at high speeds without affecting the quality of the product. Consequently, the industries can benefit from this study in terms of adopting new manufacturing strategies, such as performing the heat treatments downstream of the machining operations, in order to reduce the tool wear and consequently the costs and the waste during the production process.

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