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A comparative study of residual stress profiles on Inconel 718 induced by dry face turning

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Abstract

Residual stress profiles induced by different dry face turning conditions are compared employing X-ray diffraction method, Hole-Drilling method and Finite Element Modelling. It is well known that the surface integrity condition has a great influence on the machined parts fatigue life, specially the residual stress profile. This issue is important when machining aeronautical critical parts, even more due to the difficulty of machining of nickel based superalloys, such as Inconel 718. This research work is focused on the identification of the residual stress profile uncertainty of experimental and numerical measurements. For this proposal, several measurements were carried out on a set of Inconel 718 samples machined with different conditions of cutting speed and feed rate under dry conditions. Although residual stress profiles are similar, differences are found between the three measurement techniques used in this study.

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Keywords: Residual stress, Nickel alloy, Machining

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1. Introduction

The development of new materials which excellent mechanical and chemical properties at very high temperatures has been one of the key factors in the evolution of the turbine jet industry by increasing the turbine entry temperature and, consequently, improving the turbine jet performance [1]. However, these types of alloys are very difficult to machine precisely due to their very high resistance and low thermal conductivity. Moreover, in many cases they are employed in aeronautical critical parts, such as turbine

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disks, and the surface integrity induced by the machining processes could influence the functional performance of the part.

Recently, M'Saoubi *et al.* [2] carried out an important and very complete review of the actual research works about surface integrity of machined parts. As they observed, the analysis of the surface integrity greatly depends on the material and its application and, for example, in the case of turbine disks, the residual stress profile induced by the machining processes is one of the most important parameter.

About the 50% of the alloys employed in the manufacturing of turbine jets are nickel-based superalloys [3] and, particularly, Inconel 718 is the most used alloy [4]. Different authors analyzed the influence of different machining processes on the surface integrity of Inconel 718 and especially the residual stresses were studied numerically and experimentally [5-11].

Several techniques were developed to measure the residual stress profile, however, X-ray diffraction and Hole-Drilling are the most widely used techniques when analyzing machined components [12,13]. Each technique has its own error sources and accuracy. Thus, the residual stress measurements could vary depending on the employed technique. For example, even Outeiro *et al.* [5] and Scharman *et al.* [6] determined the residual stresses generated in Inconel 718 specimens under similar turning conditions by X-ray diffraction and Hole Drilling respectively, some differences in the results were observed, probably due to the inherent errors of the applied residual stresses measuring techniques. Consequently, it is considered necessary a comparative study of the measurement techniques under the same test conditions in order to determine their uncertainty.

In the other hand, residual stress prediction using finite element modelling seems to be a promising tool. Torrano *et al.* [14] compared 3 different finite element models with experimental measurements carried out by Hole-Drilling. As numerical models present high computational cost, the analyzed final surface has to be small and therefore, effects of the previous revolutions cannot be considered. Moreover, Arunachalam *et al.* stated [10,11] that the previous revolutions have important influence on the surface residual stress pattern when facing and thus, this aspect needs to be improved. At the same time, input data obtainment is a complex task and in many cases material properties and tribological data have to be taken from bibliography. Consequently, at this stage, finite element modelling can provide basically qualitative data.

The main aim of this research work is to analyze qualitatively the uncertainty between experimental (X-ray diffraction and Hole-Drilling) and numerical methods.

2. Experimental set-up

In this work 50 mm diameter round bars of Inconel 718 (heat treated at 955ºC during 1 hour) were used as raw material. First, disc shape specimens were cut out from the round bar using wire EDM. Then, specimens were prepared by face turning on a CNC machine under the following rough conditions: 40 m/min cutting speed (v_c), 0.25 mm feed rate (f) and 0.25 mm depth of cut (a_p) with conventional cooling.

After this preparation, machining tests were carried out at a constant depth of cut of 0.15mm. During each test, the cutting speed was maintained constant. Table 1 shows the geometry parameter of the employed tool and table 2 shows the testing set conditions.

Table 1. Tool geometry

Tool nose radius (mm)	Rake angle (°)	Clearance angle (°)	Position angle (°)	Inclination angle (°)
4	0	7	30	0

Table 2. Experimental test planning

Measurement set	Test	Cutting speed, v_c (m/min)	Feed, f (mm/rev)	Depth of cut, a_p (mm)
SET_1	Test Set_1	30	0.15	0.15
SET_1	Test Set_2	70	0.25	0.15
SET_1and SET_2	Test Set_3	30	0.15	0.15

As it can be seen in table 2, two different measurements set were carried out. In SET_1 residual stress profiles were measured on the same specimen at the same distance from the center (figure 1a) using both X-ray diffraction (A) and Hole-Drilling method (B). This method was applied in the three machining tests sets. In SET_2, three measurements of residual stress profiles, using the X-ray diffraction method, were carried out (figure 1b) in the same specimen. This allowed evaluating the homogeneity of the residual stresses field.

Hole-Drilling technique measurements were made applying the Integral Method, which is appropriate to calculate non-uniform stresses. Gauge installation and Hole-Drilling procedures were carried out following the NPL good practice guide [15], using EA-06-031RE-120 target strain gauges and making the hole with three-axis PC controlled machine.

X-ray diffraction technique measurements were made using a portable Proto_iXRD machine and employing the next parameters: radiation Mn Kα, diffraction angle of 151° in the plane {3 1 1}, irradiated area of 2 mm diameter spot and the $\sin^2\psi$ method. In order to measure the residual stresses profiles, material layers were removed by electropolishing.

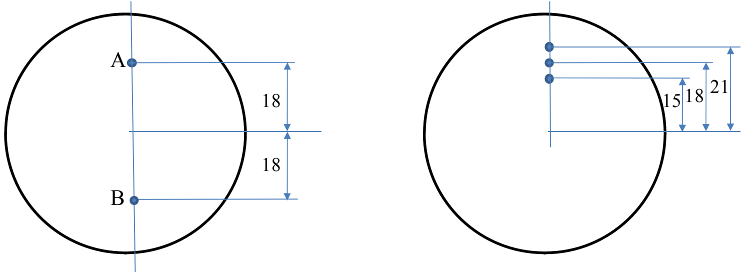


Fig. 1. (a) SET_1 Measurement points; (b) SET_2 Measurement points

3. Numerical model

Considering the results of the previous research work conducted at Mondragon University [14], where different finite element models were compared, the commercial software DEFORM 3D was selected. The numerical model used in this work was composed by DEFORM 3D chip formation elastic-plastic model, figure 2a, and a relaxation model, figure 2b [14]. The input data were taken from bibliography [16] and are shown in table 3. Once the chip is obtained with the first model, the tool is removed in the relaxation model and new boundary conditions are defined, both mechanical and thermal. The residual stress extraction points are shown in figure 2c. As it can be seen, the data line is in the middle of the machined surface and the points are taken along the depth direction. Due to the small area of the final surface obtained by the chip formation model the interpretation of the simulation results has to be carefully analyzed.

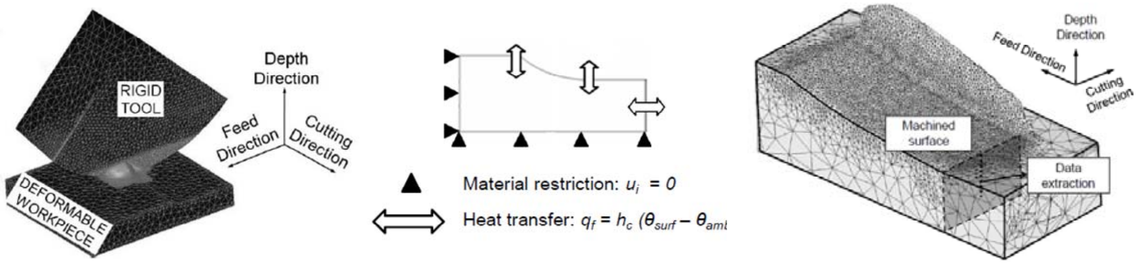


Fig. 2. (a) 3D chip formation model; (b) Relaxation model boundary conditions; (c) Data extraction points for residual stress.

Table 3. Input parameters

PARAMETER			**Part (Inconel 718)**	**3.1.1. Tool (P10)**	3.1.2. **PARAMETER**		**3.1.3. Values**
3.1.4. **MATERIAL**	3.1.5. Plasticity 3.1.6. Johnson-Cook Law	A (MPa)	1241	Rigid	**CONTACT**	Thermal conductance (K i)(W$\cdot$m$^{-2}\cdot$K^{-1})	10e8
		B (MPa)	622	Rigid			
		n	3.1.7. 0.6522	3.1.8. Rigid		Heat Partition coefficient *(Γ)*	0.5
		C	0.0134	Rigid		Friction coefficient *(μ)*	0.23
		m	1.3	Rigid		Friction energy transformed into heat *(η)*	1
	Inelastic heat fraction *(β)*()		0.9	Rigid			
	Density *(ρ)* (kg$\cdot$m^{-3})		8221	10600		Emissivity *(ε)*	0
	Elasticity	Young *(E)*(N$\cdot$m^{-2})	3.1.9. 2.12e11	3.1.10. Rigid			
		3.1.11. Poisson (ν)	3.1.12. 0.294				
	Conductivity *(k)* (W$\cdot$m$^{-1}\cdot$K^{-1})		3.1.13. 12 (293K) 3.1.14. 24 (1173K)	3.1.15. 25			
	3.1.16. Specific heat *(c)* 3.1.17. (J$\cdot$Kg$^{-1}\cdot$K^{-1})		3.1.18. 440(293K) 3.1.19. 680(1173K)	3.1.20. 200			
	3.1.21. Expansion		3.1.22. 1.2e-5(293K) 3.1.23. 1.7e-5(1193K)	3.1.24. Rigid			

4. Results and discussion

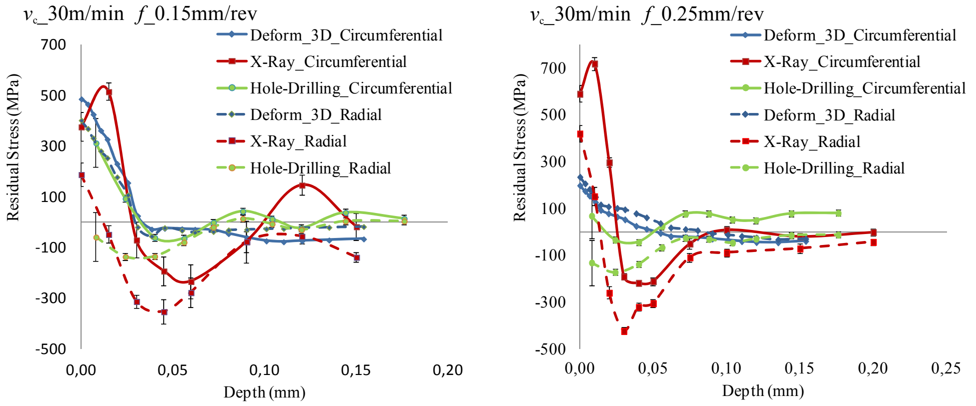
Figures 3 and 4 show the predicted and the measured (XRD and Hole-Drilling) residual stress profiles in the circumferential direction (cutting direction) and radial direction (feed direction). First of all, it is worth mentioning that some differences have been spotted in the results obtained with Hole-Drilling method compared with the previous work [14]. Although in both studies the material employed was Inconel 718, the format and consequently the microstructure were different.

When analyzing the obtained results, it has to be taken into account that the surface stress value cannot be considered due to Hole Drilling technique limitations and only the stress profiles along the measured depth can be compared.

In general, the residual stress profiles obtained experimentally in the present and the previous works

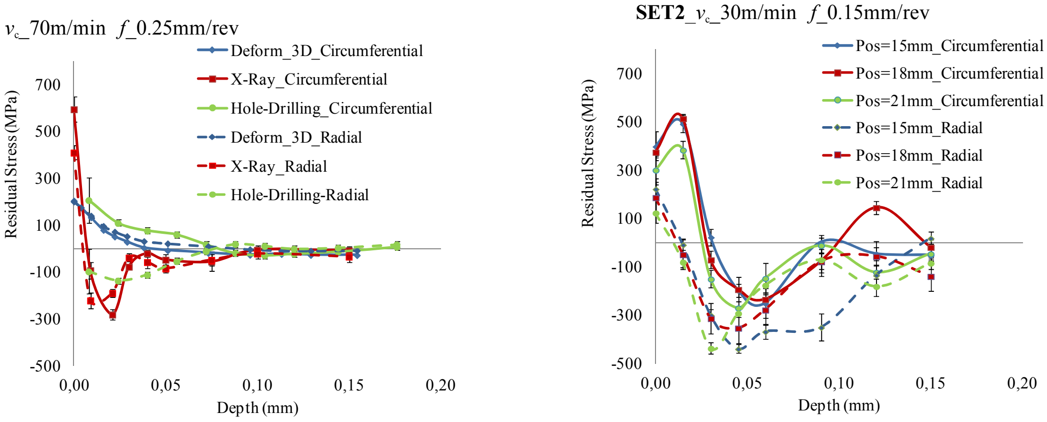
[14] for different cutting conditions show similar qualitative results, being more tractive near the surface and more compressive in the sub-surface layers. Analyzing figure 3 and 4a in more detail, it can be observed that Hole-Drilling measurements and numerical results show that by increasing the feed, stress profile near the surface becomes less tractive and sub-surface stress profile becomes more compressive. In the other hand, by increasing the cutting speed the stress pattern near the surface becomes even more tractive and sub-surface stress pattern becomes less compressive. However, X-ray diffraction measurements do not show this trend.

Figure 4b presents the residual stress profiles for Test set 3 using measurement SET_2. Analyzing the obtained results, it can be said that similar results were achieved in the different measured points and the residual stress field is quite homogenous along the machined surface. More specifically, residual stresses in the inner diameter are more tractive as Arunachalam *et al.* states [11], but the stress gradient between the outside diameter and inside diameter is not as pronounced as they observed.



a) b)

Fig. 3. a) Residual stresses for v_c =30 m/min and f= 0.15 mm/rev; (b) Residual stresses for v_c =30 m/min and f= 0.25 mm/rev



a) b)

Fig. 4. (a)Residual stress for v_c=70 m/min and f=0.25 mm/rev. (b) Cutting and feed direction residual stress profiles obtained in SET_2.

5. Conclusions

Results of residual stress values depend on the employed measurement technique. Consequently, the analysis of experimental residual stress data should be more qualitative than quantitative. In the present study case, Hole-Drilling measurements and numerical results show a good qualitative correlation, however, great differences were noticed between X-ray measurements and numerical results. Authors consider that more repetitions of X-ray diffraction measurements should be done to confirm their validity.

Residual stress profiles obtained experimentally in the present and the previous works for different cutting conditions show similar qualitative results, being more tractive near the surface and more compressive in the sub-surface layers.

Accuracy discrepancy between numerical results and empirical measurements could be originated by at least two reasons: (I) the input data such as material properties and tribological data should be properly identified and (II) the traditional residual stress prediction model used in the present work is not able to reproduce all the complexity of machining. Moreover, the validation of the numeric results accuracy is limited by the inherent uncertainty of the used measurement technique.

Finally, it has been observed that for the same cutting parameters the residual stresses field on the surface and sub-surface layers is quite homogenous, being more tractive in the inner diameter.

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