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Measurement and interpretation of residual stresses induced in Ti-17 by machining conditions

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1. Introduction

Ti-17 (Ti-5Al-2Sn-2Zr-4Mo-4Cr) is a "beta-rich" alpha-beta titanium alloy, due to a 8% content in beta-stabiliser alloying elements such as Molybdenum and Chromium. This high-strength and deep hardenable alloy was primarily developed by GE Aircraft Engines [1]. Ti-17 has strength properties superior to those of Ti-6Al-4V. This alloy is used for heavy-section forging up to 150 mm for gas turbine engine components as fan or compressor discs and other elevated-temperature applications demanding high tensile strength and good fracture toughness [2].
Due to their low thermal conductivity, titanium alloys are difficult to machine. The range of feeds and cutting speed providing a satisfactory tool life is very limited [3, 4]. Moreover, the mechanical behaviour, performance and durability of materials are strongly related to the presence and amount of residual stresses [5]. In polycrystalline materials, internal residual stresses raise during mechanical processing, due to the elastic-plastic behaviour of the grains. Each grain is subjected to a local mechanical state: elastic strain (and stress) must be present in order to maintain the compatibility of total strain between neighbour grains [6]. During metal forming, the magnitude and sign of induced stress closely depend on the machining conditions [7]. An adequate selection of these parameters is required to optimise internal residual stresses and, therefore, improve durability and reliability of mechanical parts. In fact, the residual stresses should be distributed in such a way that external load is, as far as possible, counterbalanced.
The purpose of the present work is to identify the main parameters controlling residual stresses due to milling operations on Ti-17. Machining conditions for samples fabrication were defined according to Taguchi method [8]. Procedure and studied parameters are detailed in section 2. Utilization of Taguchi method in the present study is justified, because it requires far less experiments than other more classical experiment designs [9]. Nevertheless, this scheme constitutes a powerful tool providing reliable and efficient interpretations of the physical factors involved in the evolution of the studied parameters [10]. Stress measurements were performed using the classical X-Ray Diffraction technique [11-12] which provides the possibility to explore the residual stress state near to the surface of the material, where cracks often occur during service life [13]. Results obtained are given and discussed in section 3.

2. Testing methodology - Taguchi design for Ti-17 samples milling condition.

Five variables: cutting speed, feed rate, depth of cut, insert type and tool-path strategy were initially considered to affect the magnitude of the residual stresses induced during milling. Two levels corresponding to typical milling conditions [14] were investigated for each factor. Table 1 summarises levels matching with each parameter.

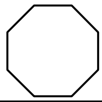
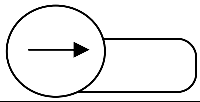
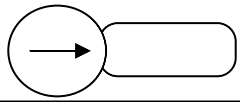
	Level	
Factor	-1	+1
Insert type	S25M 	T25M 
Feed	0.22 mm/rev	0.38 mm/rev
Tool-path strategy	Shifted 	Axis 
Cutting speed	75 rev/min = 14.8 m/min	100 rev/min = 19.8 m/min
Depth of cut	0.5 mm	1.5 mm

Table 1: Levels considered for each studied milling parameter.

Actually, the choice of insert type entails the variation of two linked parameters. The first one is the cutting angle, between the machining surface of the insert and its relief surface, which is about 25° for T25M and 14° for S25M. This is due to the use of two different carbide cutters. The second one is the corner angle, between machined surface and cutting edge. It varies from 45° to 90° when T25M is replaced by S25M.

Although a full factorial experimental design could describe all possible conditions for a given set of factor, this will result in a large number (2^5) of experiments. A compact design involving a convenient number of experiments is needed. Taguchi's method constitutes a reliable method to solve the main difficulties encountered. The introduction of orthogonal arrays (O.A.) [15], that represent the possible experimental conditions, provides a standard procedure to analyze the results performed by the adopted experimental design. The first step of designing an experiment with known number of factors in Taguchi's method is to select the most suitable O.A.. This O.A. should be designed to cover all the possible experiment conditions and the factor combination. In the present study, since there are five factors with two levels, the orthogonal array $L_8(2^{5-2})$ that involves 8 trial runs was selected. Table 2 shows an instance of the chosen O.A., with each row representing a trial condition with factor levels indicated in the row. The vertical columns of O.A. correspond to the factors specified in the study.

Eight Ti-17 samples were cut off from the same billet (52 mm in diameter) using a band saw. Specimens were milled according to conditions described in table 2. Machining operations were carried out using a milling cutter of 63 mm diameter and carbide coated inserts. No cooling fluid was used.

Experiment number	Insert type	Feed	Tool-path strategy	Cutting speed	Depth of cut
1	-1	-1	-1	-1	-1
2	-1	-1	-1	1	1
3	-1	1	1	-1	-1
4	-1	1	1	1	1
5	1	-1	1	-1	1
6	1	-1	1	1	-1
7	1	1	-1	-1	1
8	1	1	-1	1	-1

Table 2: Instance of the orthogonal array $L_8(2^{5-2})$.

In order to perform reproducibility tests, the opposite surface of each sample was machined using the same parameters (cutting speed = 75 rev/min, feed = 17mm/min, tool-path strategy: shifted, depth of cut = 1.5 mm and insert type: T25M).

3. Results and discussion

3.1 X-Ray Stress analysis. Copper radiation was used to carry out measurements on the {21.3} lattice planes of Ti-17 α–phase, for 2θ diffracting angles varying from 135.5 to 154.5° by 0.15°

steps. A XRD-3003 PTS Seifert ψ goniometric assembly with a scintillation detector was used. Diffractograms were recorded for sixteen tilt angles ψ varying between –48° to +45° and for azimuth angles ϕ = 0, 45 and 90°. ϕ = 0° direction is parallel to tool-path. Measurements were performed in the center of the milled surfaces of the samples. The X-ray beam output collimator had 3 mm diameter and a 0.2 mm diffracted-beam slit limits the equatorial divergence. The interference profiles were evaluated using "gravity point with fixed low threshold" peak position determination method after background correction.

For stress estimation, the classical $\sin^2\psi$ method was applied [16]. The X-Ray Elasticity Constants (XEC) ½ S_2 and S_1 providing the proportionality between measured strains and calculated stresses have been calculated owing to an elastic self-consistent model based on Kröner and Eshelby assumptions [17-19]: ½ S_2 = 11.71 10^{-6} MPa^{-1} ; S_1 = -2.87 10^{-6} MPa^{-1}.

$2\theta_0$ stress-free Bragg angle is necessary to stresses estimation. It was precisely determined through measurements performed on a powder sample: $2\theta_0\{21.3\}$-α = 139.731°. For these materials state, it was assumed that the $\sin^2\psi$ method could be applied. One of the requirements is ensured by milling which provides very satisfying surfaces profiles exhibiting weak rugosity. Measurements were realized with a Perthometer M1 device: R_a was found close to 0.5 µm. According to Li [20], a deviation between measured and true stress, due to rough surface profiles only occurs beyond a limit of R_a = 6 µm. Therefore, machining conditions chosen prevent any error of that kind. Moreover, in order to use $\sin^2\psi$ method with reliable results, the material should be texture-free with sufficiently small grain sizes to avoid effects of preferred orientation within the irradiated samples volumes. X-Ray Diffraction analysis demonstrated that the crystallographic texture was quasi-isotropic in the analysed alloy. Observations achieved in a Scanning Electron Microscope indicated that the microstructure consists of acicular alpha (platelets) mixed to slightly equiaxed prior beta grains. It is well known that when inclusions, having anisotropic shape, have their principal axis statistically oriented, the homogenised properties remain isotropic [21]. α–phase morphology satisfies this criterion, so that the assumptions used for $\sin^2\psi$ regression are suitable to apply to this alloy.

Results of stress analysis are given in table 3, where σ_{11} is the component corresponding to tool-path direction. σ_{22} being the stress component in the surface plane, perpendicularly to tool-path direction. For the purpose of stress tensor calculation, σ_{33} (normal to the milled surface) was considered to be null (plane stress assumption). Shear stress components were estimated. However, they remain in ± 50 MPa domain and weakly vary with machining conditions.

Sample	1	2	3	4	5	6	7	8
σ_{11} [MPa]	-358	-281	-233	-157	-167	-124	-163	-223
σ_{22} [MPa]	-358	-348	-402	-338	-397	-364	-407	-429

Table 3: longitudinal and transverse residual stress components in Ti-17 samples, as a function of milling conditions.

3.2 Results. Mean values of the stresses and the effects of each of five parameters and some interactions were calculated. Due to the choice of a compacted design, most of the interactions are confounded with the main effects of studied parameters. In consequence, second and third order interactions were assumed to be insignificant in comparison to main effects.

Results obtained using Hadamard matrix are given in table 4 for longitudinal and transverse stress components respectively. Let us denote each parameter by a figure (1: insert type, 2: feed, 3: tool-path strategy, 4: cutting speed, 5: depth of cut). Using this representation, the sixth and seventh columns respectively stand for a sum of second order interactions: $I_{24} + I_{35}$ and $I_{25} + I_{34}$.

Reproducibility tests performed on the opposite surface of each specimen showed that the standard error was about ±18 MPa. This deviation can be attributed to either a shifting in machining conditions or data acquisition and treatment processing.

Experiment number	σ_{11} [MPa]	σ_{22} [MPa]	Insert type (1)	Feed (2)	Tool-path strategy (3)	Cutting speed (4)	Depth of cut (5)	I_{24} + I_{35}	I_{25} + I_{34}	Average
1	-358	-358	-1	-1	-1	-1	-1	-1	-1	1
2	-281	-348	-1	-1	-1	1	1	1	1	1
3	-233	-402	-1	1	1	-1	-1	1	1	1
4	-157	-338	-1	1	1	1	1	-1	-1	1
5	-167	-397	1	-1	1	-1	1	-1	1	1
6	-124	-364	1	-1	1	1	-1	1	-1	1
7	-163	-407	1	1	-1	-1	1	1	-1	1
8	-223	-429	1	1	-1	1	-1	-1	1	1
Mean effect [MPa]		σ_{11}	44.0	19.3	43.0	17.0	21.3	13.0	-12.8	-213.3
		σ_{22}	-18.9	-13.6	5.1	10.6	7.9	0.1	-13.6	-380.4

Table 4: Determination of milling conditions main effects on α−phase longitudinal and transverse residual stresses close to the surface of Ti-17 samples.

3.3 Discussion. Longitudinal and transverse stress components were both found highly compressive in Ti-17 α−phase. This result is interesting. In fact, it is well known that during the cutting process, residual stresses are introduced in the material as a result of thermal and mechanical loading. The mechanical loading generally induces compressive stresses due to contact pressure. Conversely, heating of the surface is often associated with tensile stresses. Since thermal conductivity of titanium alloy is low compare to aluminium or steels, the absorbed heat will be retained longer close to the cutting zone. During dry cutting, the part of the material close to the milled surface was heated and elongated more than the bulk material. After matter removal, surface elements remained hotter than the bulk of the specimen. This is due to the fact that cooling mainly occurs from inside because the air is a poor conductor of heat. Therefore, surface elements expand and experience a compressive stress from the bulk material below. This could lead to compressive plastic deformation of the surface layer facilitated by the low yield strength at high temperature and could result in tensile residual stresses close to the surface. The results obtained (see tables 3-4) show that in the case of Ti-17, thermal effects are not sufficient to relax the significant compressive subsurfaces stresses which raise from plastic deformation. The present study is consistent with a previous investigation of residual stresses due to milling of another titanium based alloy: the IMI-834 [7].

As the tool moves along the hoop direction, three components of cutting forces are generated in the cutting zone between tool and workpiece. The cutting force in the hoop direction is usually the largest and has the most significant effect on the residual stresses in a milled surface. Therefore, it is reasonable to expect the largest stress in the cutting direction, which corresponds to transverse stress (σ_{22}). Results given in tables 3-4 agree with this point of view, the feeding residual stress component (σ_{11}) being weaker than the transverse one.

In order to increase the reliability of structure elements, it is actually better to have compressive subsurface stresses. The analyse of the results for the longitudinal stresses (see figure 1) shows that the main factor managing the raising of compressive residual stresses is the temperature reduction during the matter removal process. Hence, as demonstrated in figures 1-a, 1-b and 1-c, the parameters increasing the temperature in the machined surface tend to reduce the amount of compressive longitudinal stresses. It is the case for example, when cutting speed or chip surface increase. In fact, chip surface enlarges proportionally to feed and depth of cut. The main effect of each of these parameters on longitudinal residual stresses is about 40 MPa.

According to figure 1-d, while chip surface is kept constant, longitudinal compressive stress state decreases with the octagonal shaped insert. This is attributed to an augmentation of the cutting edge length in contact with the machined piece, combined to a reduction of chip thickness. Temperature of the milled surface increases in these conditions. This confirms that a combination of high feed with a low depth of cut is appropriate to generate high compressive stresses.

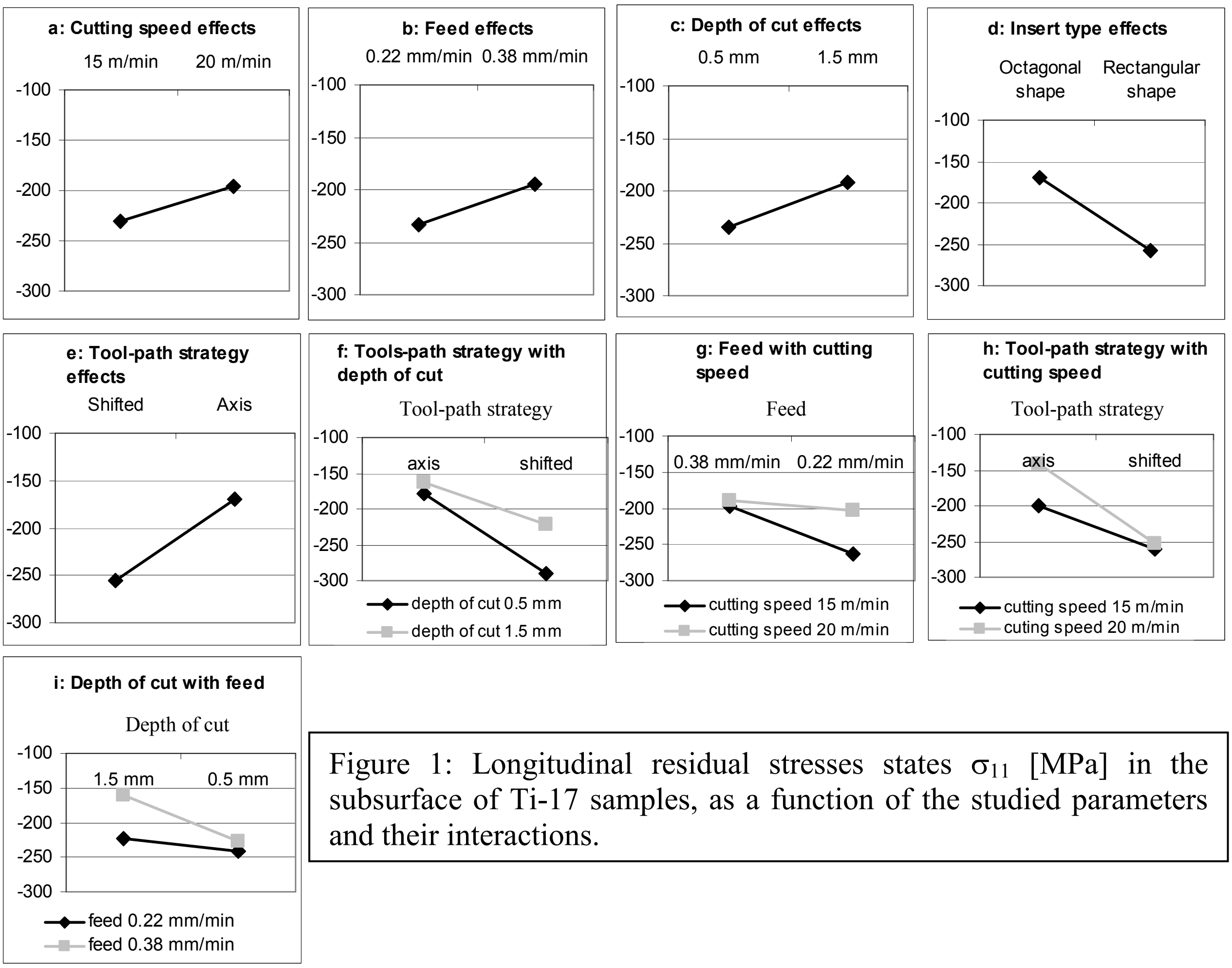


Figure 1: Longitudinal residual stresses states σ_{11} [MPa] in the subsurface of Ti-17 samples, as a function of the studied parameters and their interactions.

Figure 1-e shows that the milling in axial position of the tool increases longitudinal stress by about 90 MPa. This is due to an increasing of the real feed of the cutting edge which induces a higher chip surface. Moreover, in this particular case (i.e. axial tool-path), machining induces more shocks due to a fewer number of cutting edge in contact with the milled surface than in the case of the shifted tool-path.

Fractional experiment designs due to Taguchi's method entails a mixing of two first order interactions in the considered case (see tables 4). The interaction terms involving parameters having weaker main effects are often neglected. A first coupling is given with figures 1-f and 1-g. Fig. 1-f indicates that the satisfactory residual stresses states obtained with a shifted tool-path are improved by a lower depth of cut. According to figure 1-g, it is better to associate low cutting speed with low feed in order to increase the amount of compressive stresses.

The second coupling of interactions was drawn on figures 1-h and 1-i. It seems that a higher feed associated to a large depth of cut or the combination of a high cutting speed during machining with bad shock conditions (axial tool-path) leads to a higher temperature in the subsurface of the milled part. Thus, the longitudinal stresses do not reach their optima in these conditions.

Table 4 shows that transverse stress component remains almost constant over the range of the five examined milling parameters.

4. Conclusion

Residual internal stresses due to milling conditions were investigated in Ti-17, using the classical non destructive X-Ray Diffraction technique. Experiences were designed according to Taguchi's method.

Under typical and representative machining conditions, high compressive longitudinal and transverse stresses were measured in the subsurface of every specimens. The raising of compressive stresses in Ti-17 demonstrates that thermal loading has weaker effects than mechanical loading, even in dry milling. This is good from a fatigue in service-life point of view because the presence of tensile residual stresses often impair the correct functioning of a machined part.
Over the range of the five milling parameters considered, transverse stresses were found almost constant.
Among the explored factors, insert type and tool-path strategy were found to significantly affect residual stress states in feed direction. Conversely, results demonstrate that cutting speed, feed and depth of cut chosen have weaker effects on the amount of residual stresses induced. Nevertheless a combination of high feed and low depth of cut generates satisfactory compressive stress states in the subsurface of the milled material.

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