G Model
CIRP-1726; No. of Pages 4
ARTICLE IN PRESS
CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx
Contents lists available at ScienceDirect
CIRP Annals - Manufacturing Technology
journal homepage: http://ees.elsevier.com/cirp/default.asp

Fatigue life of machined *Ti6Al4V* alloy under different cooling conditions

Domenico Umbrello (2)[a,*], Giovanna Rotella[b]

[a] Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende, CS 87036, Italy
[b] Department of Computer Engineering, Modeling, Electronics and Systems Engineering, University of Calabria, Rende, CS 87036, Italy

ARTICLE INFO

Keyword:
Cutting
Fatigue
Cooling

ABSTRACT

This paper presents an extensive experimental study on the influence of machining parameters and cooling conditions on the overall fatigue life of a titanium component. In particular, dry, minimum quantity lubrication, cryogenic and high-pressure air jet were compared as cooling/lubrication strategies for the finishing operation. The obtained dog-bone cylindrical fatigue specimens were tested under uniaxial pull–pull cyclic loading in the high cycle fatigue range. An analytical model is proposed to predict the high cycle fatigue strength for the material under investigation demonstrating its effectiveness to reduce the number of tests needed.

1. Introduction

Failure of machined parts due to fatigue is of great concern for components subject to cyclical stresses, particularly where their reliability raises safety issues. It is now well established that fatigue cracks generally initiate from free surfaces implying that products performance is reliant on the surface integrity produced by machining [1,2]. In fact, surface layers experience the heavier load and are also exposed to many environmental factors like oxidation, mechanical and thermal stresses, metallurgical a topographical changes etc. Thus, crack initiation and propagation, can be most of the time attributed to surface conditions after machining [3]. Many researchers verified that machining mainly affects the high cycle fatigue (HCF) strength and the endurance limit strongly depends on the process used and the severity of the involved operations [2,4]. Early fatigue studies focused their attention on the effects of workpiece roughness parameters, while subsequent research pointed out the inadequacy of the sole roughness as an indicator of fatigue strength, highlighting the need to consider the overall surface integrity [2,5]. Javidi et al. [2] underlined the need to define and control two important aspects of the machined surface for fatigue life evaluation: geometric irregularities and metallurgical alterations of the surface and subsurface layer. Among these features, microstructure plays a key role especially considering aerospace components usually made of high strength materials such as titanium alloys. In fact, titanium alloys (e.g. *Ti6Al4V*) are excellent combination of strength, ductility, and high temperature properties, which make them massively used in aerospace. Thus, there has been considerable interest in the high cycle fatigue of such materials. High cycle fatigue for *Ti6Al4V* alloy still results in significant unpredictable failure of engine components, particularly for fan and turbine blades and the most of the high cycle fatigue life is spent to fatigue crack initiation and small crack propagation which is significantly sensitive to the microstructure [6,7]. Thus, the aim of the present work is to study the effects of different machining strategies over the HFC strength of *Ti6Al4V* alloy. In particular, the influence of the obtained microstructure is herein deeply studied at varying of machining parameters and cooling conditions. Fatigue tests have been conducted in order to draw the S–N curves (magnitude of an alternating stress versus the number of cycles to failure) and to evaluate the experimental fatigue strength. In addition, an analytical model has been also calibrated and validated in order to offer a valuable support to machining strategies prior production.

2. Material and methods

The material under investigation is the grade 5 titanium alloy (*Ti6Al4V*). Machining tests were conducted on a Mazak® QuickTurn Nexus 220-II CNC lathe equipped with a self-designed cooling line to supply different cooling and lubrication strategies (Fig. 1a). *Ti6Al4V* cylindrical specimens were turned under dry, high pressure air jet (HPAJ), minimum quantity lubrication (MQL) and cryogenic cooling as shown in Fig. 1(b). Typical dog-bone cylindrical fatigue specimens were obtained by machining at a fixed feed rate (0.15 mm/rev) and depth of cut (0.05 mm) while varying the cutting speed within three levels (30, 50 and 70 m/min). The above mentioned cutting parameters are those suggested by Sandvik Coromant® when a CoroCut® *N123H2-0400-RO 1105 PVD TiAlN* coated insert is used for

* Corresponding author.
E-mail address: d.umbrello@unical.it (D. Umbrello).

https://doi.org/10.1016/j.cirp.2018.03.017

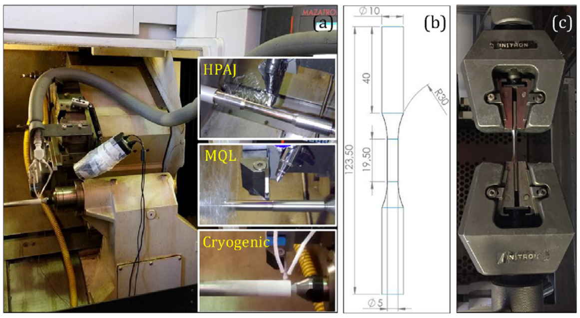

Fig. 1. (a) Experimental set-up for machining test and nozzle configuration for HPAJ, MQL and cryogenic cooling; (b) sketch of dog-bone specimen (dimensions are in mm); (c) fatigue life testing machine.

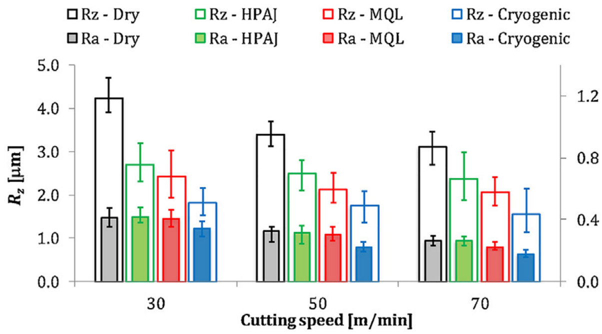

Fig. 2. Mean surface roughness (R_a) and mean surface roughness depth (R_z) on machined samples under dry, HPAJ, MQL and cryogenic cooling conditions (the error bars indicate data dispersion).

profiling. The cutting tool was mounted on a *RF123H25-2525BM* tool holder supplied by the same manufacturer providing rake and clearance angles of 0° and 7°, respectively. Tool wear effects were limited by allowing fresh cutting tool at each test. The HPAJ and the MQL tests were performed applying respectively air and vegetable oil emulsion through an external nozzle to the cutting zone at the pressure of 7 bar (with a rate of 60 ml/h for the MQL). In contrast, the cryogenic coolant (LN_2) was applied at the pressure of 12 bar through two nozzles (with a diameter of 2 mm) to the cutting region. After machining, several samples for each cutting and cooling conditions were sectioned, mounted on a resin holder, then polished and etched in order to measure the grain size on the machined surface using an optical microscope (with 1000× magnification). The etchant employed is the Kroll's reagent (92 ml of distilled water, 6 ml of nitric acid and 2 ml of hydrochloric acid) that is recommended for etching nonferrous materials and *Ti* alloys. A fresh etchant was used for each sample and the immersion time was around 20 s. The remaining specimens were then used for the fatigue life tests and for measuring the surface roughness.

The surface roughness was measured using a confocal white light 3D surface profilometer. Fatigue tests were performed on a servo-hydraulic testing machine at 20 Hz (Fig. 1c). The tests were carried out under load control (sinusoidal waveform) at room temperature. The pull–pull fatigue test was performed with a positive stress ratio ($R = \sigma_{min}/\sigma_{max} = 0.1$) so that the specimen is tested always under tensile load as suggested by the standard *ASTM E466*. The fatigue limit has been evaluated by using the step by step method which has been widely adopted for materials, such as *Al* or *Ti* alloys, that are less, or not, sensitive to load history (no influence on the fatigue limit) [8,9]. The test is useful to obtain the fatigue limit for a given number of cycles. At the first step, the specimen is tested for a given stress σ and for a fixed number of cycles. If the specimen fails at the first step, then it is not considered for the evaluation and the initial stress σ is reduced by $\Delta\sigma$. In contrast, if failure does not occur (e.g. the specimen does not fail at $N_{limit} = 10^7$ cycles) the fatigue test is relaunched for the same specimen by increasing the stress of $\Delta\sigma$. The procedure is repeated until the rupture of the sample, which defines the end of the test at a corresponding failure stress σ_n. Thus, the fatigue limit is calculated using Eq. (1) [9].

$$\sigma_D = \frac{N_{failure}}{N_{limit}}(\sigma_n - \sigma_{n-1}) + \sigma_{n-1} \quad (1)$$

3. Results and discussion

3.1. Surface roughness

The surface roughness was measured for each test five times at different locations along the surface. The tendencies for the mean surface roughness (R_a) and mean surface roughness depth (R_z) are shown in Fig. 2. As an overall trend, R_a and R_z are always below 0.4 µm and 5 µm respectively for each cooling condition indicating a good surface finish that generally helps retarding the initiation of cracks under cyclic loads [10]. Both R_a and R_z decrease when the cutting speed increases. The R_a values for cryogenic machining were found to be consistently superior to those obtained in dry, HPAJ and MQL conditions. In contrast, there is little difference between the other cooling strategies at 30 m/min and 50 m/min. At 70 m/min MQL produced better surface quality with lower R_a values. Furthermore, dry machining led to the worst R_z measures wile within the cooling strategies, the cryogenic one produced the best surface quality. The roughness results were also helpful to understand the role of the residual stresses. In fact, it is well known that residual stresses play a significant role on the fatigue life when R_a values is higher than 2.5 µm while small values of R_a correspond to negligible surface residual stresses [1]. Furthermore, it has also been demonstrated that rapid residual stresses relaxation takes place in the early stages of fatigue cycling, with a reduction of more than 50% during the first few cycles [1]. Finally, it has been proved that with small values of R_a (below 2.5 µm) cracks initiate due to persistent slip bands or at grain boundaries [1]. Also R_z plays a key role for the overall fatigue behavior. In fact, as stated by Carvalho Pereira da Silva et al. [11], when R_z reaches values bigger than 2 µm, it can be considered as semi-circular surface notches with radius approximately equal to the R_z reducing the fatigue strength accordingly.

3.2. Microstructure

The mechanical properties, as fatigue life of machined *Ti* components can strongly depend of the induced microstructure such as grain size, shape, and grain boundary arrangements [4]. Thus, the microstructure was analyzed and the grain dimensions were measured on each machined surface at twenty different locations with three repetitions for each testing conditions. The results show that the original microstructure of equiaxed primary α grains and intergranular β grains was always present although grain refinement takes place in all performed tests (Fig. 3).

In particular, the equiaxed grains are stretched and deformed following the cutting direction, becoming smaller with increasing the cutting speed due to the higher plastic deformation induced by the cutting tool action. Also the cooling strategy plays an important role on grain refinement after the machining process since it clearly shows that the cooling conditions can influence the final microstructure of the machined product. Indeed, the cryogenic fluid delivered into the cutting zone lead to avoid any recovery phenomena due to the high temperature, therefore the induced plastic deformation and consequently the smaller grains were preserved. These results also confirm the potential of the cryogenic cooling to generate a stronger machined surface due to smaller grains and, consequently, harder surface which results in a product less prone to crack initiation [12].