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Effects of cutting parameters over turning of UDIMET® 720 superalloy in a broaching process simulation

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Abstract

The nickel-based alloy "UDIMET® 720" has been used for several years to manufacture components in turbomachines. Its physical properties allow it to keep high mechanical strength when subjected to high temperatures. However, those properties also cause its low machinability. Turbomachine design requires the use of rotating parts assembled and submitted to high thermo-mechanical stresses. Fir-tree slots machined by broaching are used to create the bond between turbine discs and blades. Currently, the broaches are made from high speed steel which is restricted to low speed and feed hence limiting the productivity. In order to go faster, a solution is to use carbide tools. However, this material is more sensitive to shock and it is then necessary to precisely identify cutting conditions for the optimal design of broaches. Furthermore, cutting phenomena are different and can affect the machined surface integrity for this critical workpiece.
A large experimental campaign has been done by turning to reduce tool costs and to highlight the effects of cutting parameters on tool wear and machined surface quality. In order to optimize the productivity, the effect of cutting conditions on cutting forces is taken into account. To determine the broach geometry composed of several teeth, the effects of rake angle, cutting edge preparation and clearance angle are presented. In order to simulate the broaching process, a specific test has been designed on a lathe. This allows us to include specific disturbances like interrupted cut, temperature variation, lubrication discontinuity, and difficulty to liberate the chip.

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Keywords: Broaching ; UDIMET® 720 ; Nickel-based alloy ; Surface integrity ; Tool wear ; Machinability

1. Introduction

Increases in air travel bring increased demand for aircraft and engines. Turbomachines are composed of rotating parts made of blades and turbine discs under stressful thermomechanical conditions. Components with high functioning efficiency are made from materials such as nickel-based alloys. They can undergo high strains at high temperatures. However, those materials special properties make them harder to process.

One of the most important operations in the manufacturing of turbo engines is broaching [1]. It produces the desired geometrical shape to position the blades on the disc. The blade-disc interface is highly strained in a critical zone. Thus, the manufacturing process has to be well controlled in order to meet the specifications. It is however a complex operation because of the required positioning tolerances and setting increasing drastically the manufacturing time of turbine discs [2].

Consequently, a high improvement potential lies in the broaching process which has remained unchanged for more than fifty years. Broaches are generally made from high speed steel (HSS). It is a relatively easy to process material with a high toughness making it an ideal material for interrupted cutting processes like broaching [2]. HSS is well known by manufacturers because of the years of experience and feedback on its response under various conditions. However, it has its

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limits in machining high-temperature alloys because of its limited hot hardness [3]. Consequently, the cutting speed has to stay low (2-8 m/min) for the HSS to keep its physical properties [4]. In order to overcome this difficulty making broaching a bottleneck process, the use of tungsten carbide broaches is currently being researched [2,3,4,5]. Tungsten carbide is a very tough material with a good hot hardness allowing cutting speeds up to 20 times those used for HSS [3]. However, tungsten carbide is not very resilient making it difficult to process and re-sharpen. Therefore, study of the interaction between nickel-based alloys and tungsten carbide is needed in order to reduce tool wear or cutting edge chipping of expensive tools, the degradation of turbine discs, and detrimental surface integrity defects.

Because of the cost of investigation (unavailable production mean in laboratory, costly tools, precise positioning tolerances, adjustment time, etc.), publications about broaching are fairly rare. Most of research is limited to Finite Element Modelling [6,7,8,9,10,11,12]. Results are usually quite promising but important choices have to be made in the selection of Johnson-Cook parameters, simulation method (ALE, ILam, etc.), friction model, etc.

This article presents an alternative solution: an orthogonal cutting operation on a lathe. An experimental plan is developed in order to determine the impact of principal cutting parameters on the processing of Udimet® 720 using a tungsten carbide tool. A first set of trials determined a set of parameters to be employed using a full design of experiments. A second experimental effort was made to highlight the impact of clearance angle and the ratio of feed rate to cutting edge radius on the cutting forces. Wear tests were also performed in a discontinuous cutting configuration on a lathe in order to understand and determine optimized parameters to process Udimet® 720 with tungsten carbide tools.

2. Materials and methods

2.1. Udimet® 720 LI

The material used in this study is the nickel-based alloy Udimet® 720 Low Interstitial. It is a superalloy close to Inconel 718 but with a higher tensile strength at high temperatures. The chemical composition of this alloy is given in Table 1.

Table 1. Composition of Udimet® 720 and Udimet® 720LI [14].

Elements	Ni	Cr	Co	Ti	Mo	Al	W	B	C
U720	Base	18.0	14.8	4.98	3.04	2.49	1.25	0.03	0.02
U720LI	Base	16.3	14.7	5.02	3.00	2.57	1.31	0.02	0.01

The Face-Centered Cubic structure (FCC) of the γ matrix offers a greater resistance at temperatures close to the melting point. The γ matrix is reinforced by precipitation of the intermetallic coherent γ' phase, as well as carbides and borides that precipitate during the solidification or during previous heat treatment [13].

The Udimet® 720 LI by comparison to "classical" Udimet® 720 has a lower carbon, chromium and boron concentration allowing better metallurgical stability at high temperature and particularly to reduce the sigma phase formation [14].

2.2. Experimental means

Broaching is not adapted for trials. It is an uncommon production method. It is also slow and the setting will greatly impact the quality of obtained results [1]. Moreover, the principal parameters are included in the tool, only the cutting speed can be modified. It is then necessary to have one broach per experiment.

A solution to overcome those difficulties is to mimic a broaching configuration on a lathe as seen on Fig. 1. The similarity between orthogonal cutting and broaching allows us to extrapolate the data while reducing the experimental cost. Turning tools have fixed rake and clearance angles but the feed rate can be modified in order to test different conditions with the same tool. The experimental approach has been realised on a Genymab 900 lathe (P_{max} = 30 kW, C_{max} = 2200 Nm, N_{max} = 2500 rev/min). The tool was mounted directly on a three-component dynamometer Kistler 9129.

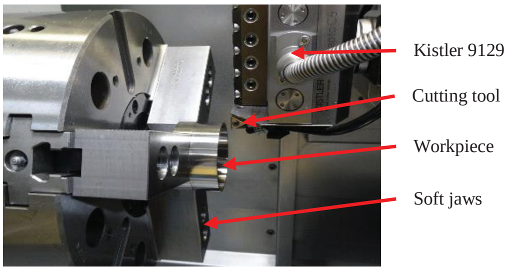

Fig. 1. Experimental setup for an orthogonal cut.

A tubular workpiece of 3 mm width was chosen. This configuration enables constant contact on the tool clearance face during the machining. A large diameter (77 mm) compared to a small tube width (3 mm) allows us to limit the speed variation on the cutting edge to 8 %. Soft jaws were machined to reduce the workpiece runout during trials. The carbide turning tools used for the experiments were TCMX 16 04 08 and TNMA 16 04 08. They were then modified to meet our requirements.

2.3. Methods

The influence of principal machining parameters such as cutting speed, feed rate, cutting edge radius, rake and clearance angles was studied using multiple complete designs of experiments. The literature on broaching nickel-based alloys with a tungsten carbide tool can be summarized in Table 2.

Table 2. Summary of parameters used to broach nickel-based alloys.

Reference	Material	Vc [m/min]	f [µm/tooth]	γ [°]	α [°]
[2]	Inconel 718	10-40	50-75	0-15	3
[3]	Inconel 718	10-30	50-75	0-15	3
[5]	Inconel 718 Allvac718plus	12-36	70	-12	3
[11]	Inconel 718	5-50	20-100	0	3

The influence of clearance angle and the ratio of feed rate to cutting edge radius on the cutting force was studied on titanium by [17,18,19] and on steel by [20,21]. However, little research addresses Udimet® 720. The wide range of parameters chosen for those trials is made to observe the evolution of cutting