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Investigation of the Machinability of GTD-111 Type Nickel-Base Superalloy During Face Milling

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Abstract

In this paper, the authors investigate the effect of technological parameters on the face milling of GTD-111 type nickel-base superalloys. These alloys are among the most difficult to machine and are widely used as a base material for gas turbine components in the aerospace and energy industries. The aim of this paper is to determine, using the Taguchi method, those parameters that have the greatest influence on cutting force and tool wear. A rotary force meter was used to measure the cutting force and cutting torque, and then the inserts used were examined used under a microscope. Results show that feed per tooth has the greatest effect on cutting forces and tool wear. In order to avoid the formation of edge deposits, it is advisable to use higher cutting speeds and compressed air cooling.

Keywords*: nickel-base superalloy, face milling, cutting force, cutting torque, tool wear, ceramic tool* .

1. Introduction

The literature identifies four types of superalloys: nickel, cobalt, iron and titanium base superalloys [1]. Of these, nickel-base superalloys are mainly used in gas turbines for the aerospace and energy industries because these alloys retain their favourable mechanical and physical properties at high temperatures [2, 3]. These alloys are mainly used in the high temperature zones of gas turbines (HPC – High Pressure Compressor and HPT – High Pressure Turbine) (Figure 1), where operating temperatures reach 1400-1500 °C, operating pressures 40 bar in extremely corrosive environment, and operating speeds exceeding 10 000 rpm [4]. This extremely high temperature is necessary to increase the efficiency of gas turbines because, as with other thermal power engines, efficiency can be increased by increasing the difference between the maximum and minimum temperature of the working medium, which is why today's gas turbines have an efficiency of almost 60% [5].

The superalloys have high thermal strength, poor thermal conductivity, heat and corrosion resistance, but the parts made from them are often produced by cutting, despite the fact that

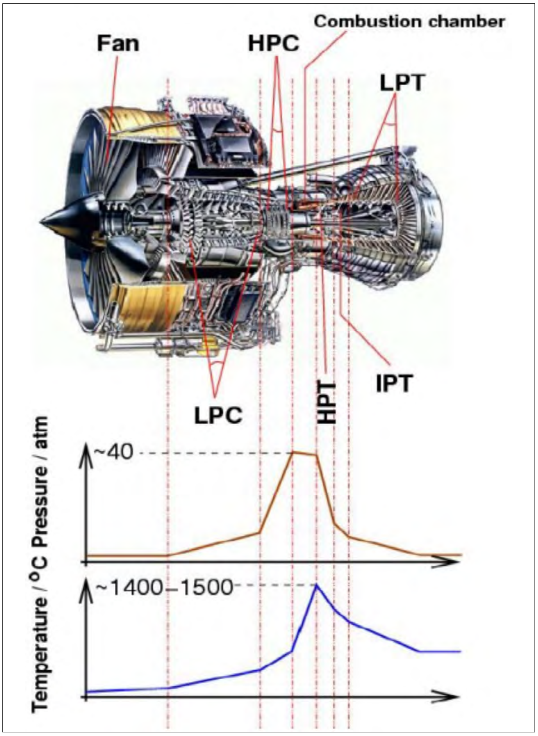

Figure 1. *Gas turbine showing the different zones with temperature and pressure conditions* [8]

their properties make them particularly difficult to machine [6]. In the present paper, the machinability of GTD-111 type Nickel-based superalloy was investigated during face milling, which has a significantly poorer machinability than Inconel 718, which is commonly investigated in today's research. Table 1 shows a comparison of the mechanical and physical properties of GTD-111, Inconel 718 and the widely known C45, presented as a reference material. Because of these properties, machinability of GTD-111 is significantly more difficult than machinability of Inconel 718, which has been generally tested in research, and compared to C45, GTD-111 has more than twice the tensile strength and only a quarter of the thermal conductivity.

Figure 2 shows the graph of the specific strength against temperature for commonly used metals. From the figure, it can be seen that nickel-based superalloys exhibit a high specific strength over a wide range of temperatures [7]. It illustrates very well why the machinability of these materials is so difficult and why so many researchers are working on this problem. Due to poor thermal conductivity, the large amount of heat generated during machining cannot escape into the chips and workpiece, and will therefore be concentrated at the edge of the bit. As a result, tools wear quickly and breakages are frequent.

Machining time is very important in manufacturing technology, where there is an increasing demand for cost-effective and environmentally friendly machining methods. This trend is reflected in the spread of high speed cutting (HSC) and hard cutting (HC). Due to the material properties of Nickel-based super alloys, and also due to the technology, high speed steels and brazed insert tools are not suitable to meet the demand, so carbide, ceramic, CBN (Cubic Boron Nitride) and diamond tool materials have emerged in this area.

In most cases, machining of Ni alloys by carbide cutting tools without coatings or with various coatings is carried out due to economic and technological constraints. This is particularly evident in the case of slot and other closed shape milling, for which the ceramic tools needed to machining them have only recently become available on the market and are also very expensive. Indexable end mills are more widely used for machining flat surfaces.

The use of ceramic cutting tools is justified because of their favourable properties, such as high hot hardness, good wear resistance, low thermal conductivity and excellent chemical stability

Table 1. *The mechanical and physical properties comparison of the GTD-111, the Inconel 718 and the C45 steel* [9, 10]

	GTD-111	Inconel 718	C45
Tensile strength R_m (MPa)	1310	965	610
Hardness (HRC)	41.4	36	
Hardness (HB)			230
Elongation A_5 (%)	8	12	16
Density ρ (kg/m^3)	8000	8240	7700
Thermal conductivity λ (W/(m·K))	12.56	11.2	45.35

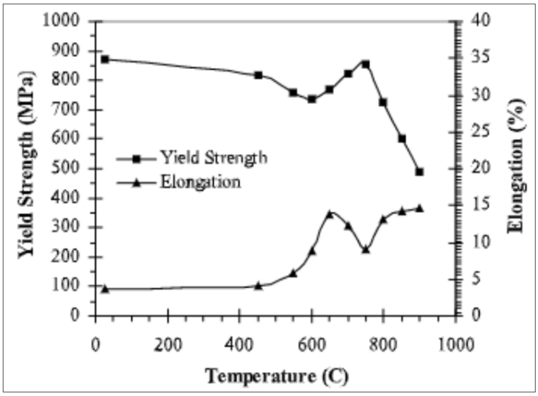

Figure 2. *Temperature dependence of yield strength and elongation of GTD-111.* [11]

[12]. These properties make them a good choice for machining super alloys, as they can be used at the temperature at which these super alloys are already annealing, thus the cutting forces reduces and so the low flexural strength of ceramic cutting tools is not problem.

In this paper, the authors investigate the effects of the cutting parameters used in the slot milling of GTD-111 type Nickel-based superalloy on the cutting forces and inserts failures. The aim is to find the parameter combination that results in the lowest tool load and tool wear.

2. Methodology of the experiment

This chapter describes the machining centre, measuring equipment, cutting tools and the methodology of the design of experimental (DoE).

2.1. Experimental setup

Because hard milling causes extreme demands on the machining centre, a robust and rigid one is required, therefore, the NCT EmL-850D machining centre was chosen. A Kistler 9125A24 type of rotary force meter was used to measure the cutting forces and torques, while a KISTLER 5697 type of signal processing unit was used for signal processing. The results were recorded using DynoWare software and evaluated using OriginPro 2021 software. The experimental setup is shown in **Figure 3**.

In the rotary force meter, the tool can be clamped with a collet chuck, but the face mill requires cylindrical mandrel chuck, so a special intermediate piece was manufactured. The drawing is show in **Figure 4**.

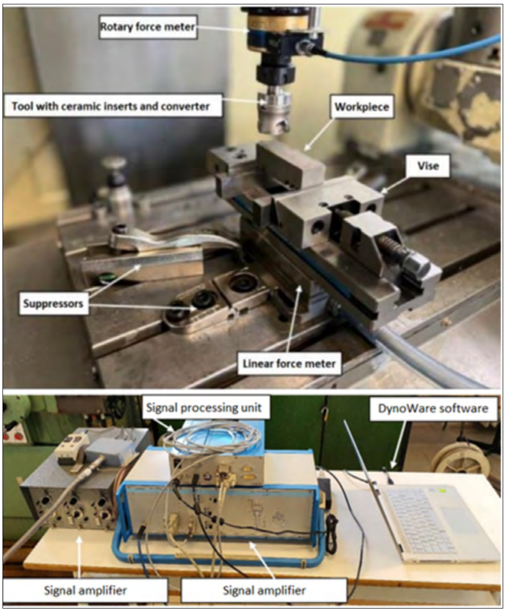

Figure 3. *Experimental setup.*

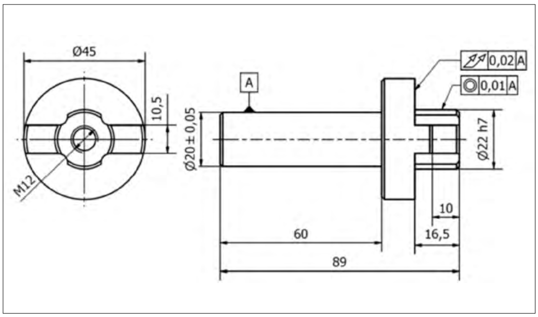

Figure 4. *Drawing of the intermediate piece required to clamp the tool.*

2.2. Tool used for the experiment

A TaeguTec BNGX 0904 CH-E04 ceramic insert and a TaeguTec TFMBN 350-22R09CH Ø40 mm face mill was used for the experiment (**Figure 5**).

2.3. Technological parameters used for the experiment

The experiments were performed according to the Taguchi experimental design, Minitab17® software was used to create the experimental design. The defined factors and levels are shown in **Table 2**, and the experimental design shown in **Table 3.** The choice of the technological parameters used was based on the manufacturer's recommendation.

During the experiments, down-milling was used, because when machining with ceramic tools, especially in difficult-to-cut materials, climb milling is harmful, as the tooth tries to cut the maximum chip thickness, which results in impact stress on the tool, which will break down faster due its low bending strength. In the case of down milling, the cut starts with zero chip thickness, essentially the tool is slightly milling into the material, resulting in a higher cutting zone temperature.

Table 2. *Milling factors and levels defined in the experimental design*

Milling factors		Levels		
		1.	2.	3.
A	Cutting speed v_c (m/min)	600	900	1200
B	Feed per tooth f_z (mm/tooth)	0.15	0.25	0.35
C	Depth of cut a_p (mm)	0.5	0.75	1

Figure 5. *The cutting tool holder and insert used for the experiment.*

Table 3. *The experimental design*

No. of experiment	a_p (mm)	f_z (mm/fog)	v_c (m/min)
1.	0.5	0.15	600
2.	0.5	0.25	900
3.	0.5	0.35	1200
4.	0.75	0.15	600
5.	0.75	0.25	900
6.	0.75	0.35	1200
7.	1	0.15	600
8.	1	0.25	900
9.	1	0.35	1200

The chip removal curve was determined empirically at a value of 70°. The associated cutting width was 16,5 mm. The machined length was 130 mm for each experiment.

3. Results

This chapter presents the results of experiment. Experiments 3., 6. and 9. are flawed, because the relationship between the cutting speed and the feed rate was not calculated, so during machining it was observed that the feed rate was higher than the cutting speed, which resulted in damage to the tool body as observed in **Figure 6.** Thus, experiments 3., 6. and 9. cannot be evaluated.

3.1. Cutting forces and torques

The cutting forces in the „z" direction measured during the experiments are shown in **Figures 7–9**, while the cutting torques are shown in **Figures 10–12**.

Based on the measurement results shown in **Figures 7–12**, it can be concluded that, in general, the cutting forces and torques increase in a linear relation to the increase in the depth of cut and feed per tooth. The lowest tool load is observed in experiment 1, while the highest is observed in experiment 5. It can be concluded that the feed per tooth has the greatest impact on the tool load.

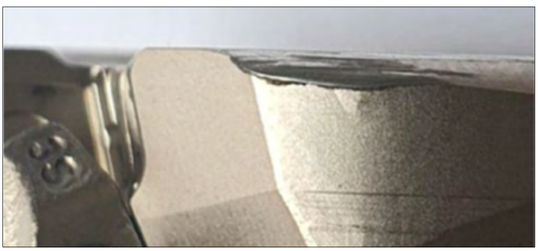

Figure 6. *Damaged tool body.*

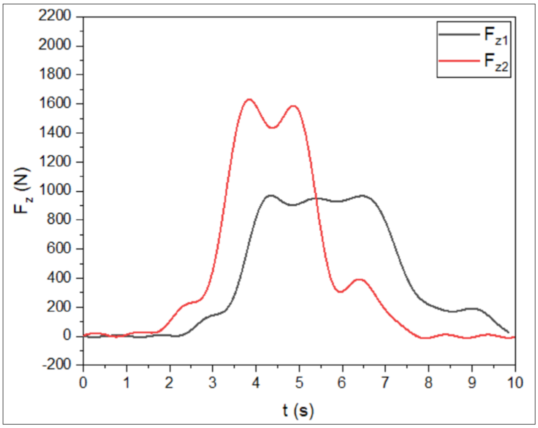

Figure 7. *Cutting forces F_z measured in the Experiments 1-2. as a function of machining time.*

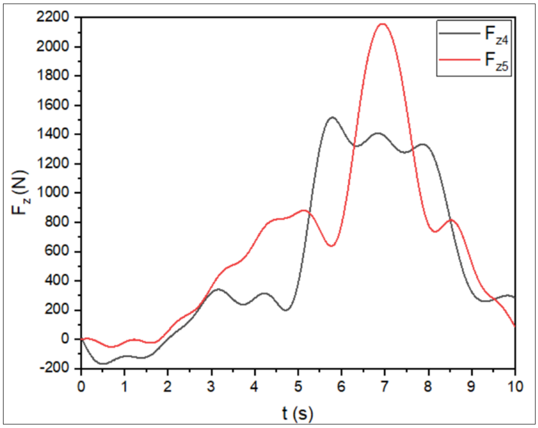

Figure 8. *Cutting forces F_z measured in the Experiments 4-5. as a function of machining time.*

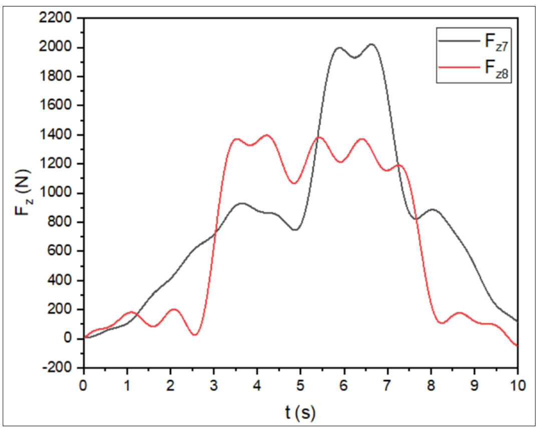

Figure 9. *Cutting forces F_z measured in the Experiments 7-8. as a function of machining time.*

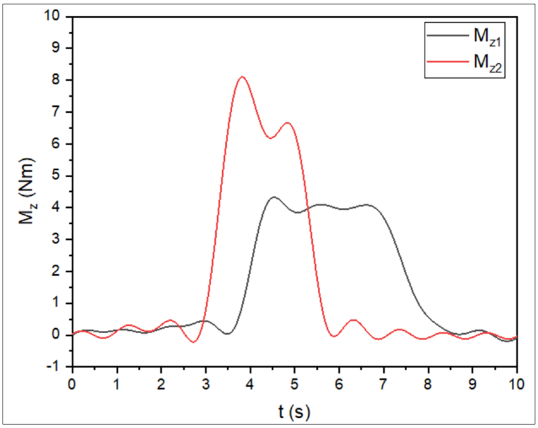

Figure 10. *Cutting toques M_z measured in the Experiments 1-2. as a function of machining time.*

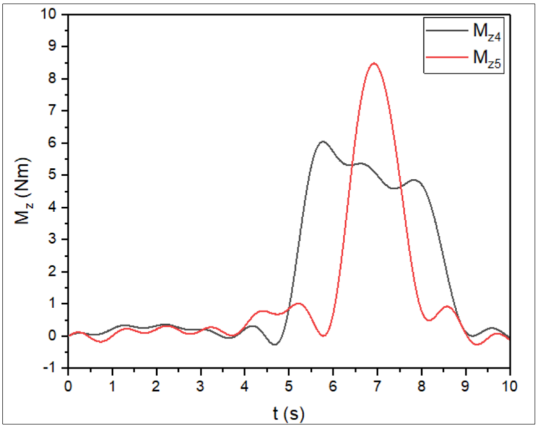

Figure 11. *Cutting toques M_z measured in the Experiments 4-5. as a function of machining time.*

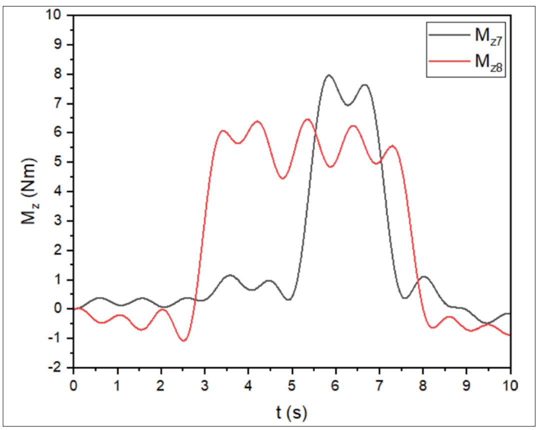

Figure 12. *Cutting toques M_z measured in the Experiments 7-8. as a function of machining time.*

3.2. Investigation of cutting inserts

Photographs of the inserts used during machining are shown in **Figure 13**. During the machining process the formation of built-up edge along the tool edge was typical, and some wear was also observed. One insert is broken, most likely due to impact effect during machining.

The built-up edge rate could be greatly reduced if compressed air cooling was used to improve chip separation. Holes are provided in the tool body for this purpose, but the machine centre used for the research is not suitable for such cooling. Experience shows that higher cutting speed is preferable.

4. Conclusion

In this research, the authors investigated the machinability of GTD-111 type Nickel-based superalloy during face milling. Using Taguchi-method, an experimental plan was prepared and the applied cutting forces and torques were measured during the experiments. The authors have stated the following conclusions:

- it is advisable to check the correctness of the experimental design before carrying out the experiments;
- of the technological parameters, the feed per tooth has the greatest impact on the machining process;
- it is advisable to use a higher cutting speed to avoid the formation of built-up edge;
- compressed air cooling is recommended when machining with ceramic tools.

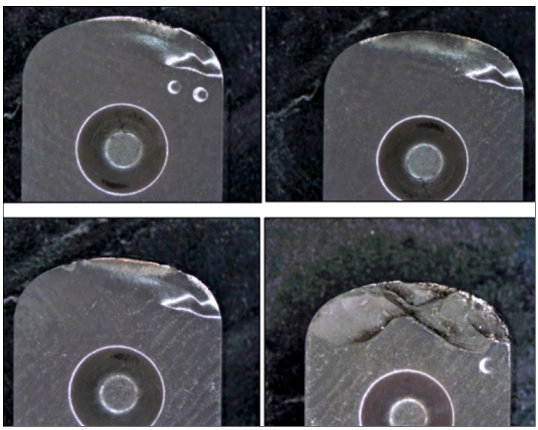

Figure 13. *The cutting inserts used during experiments.*

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