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ScienceDirect

Procedia CIRP 14 (2014) 54 – 59

www.elsevier.com/locate/procedia

6th CIRP International Conference on High Performance Cutting, HPC2014

High Performance Machining of Profiled Slots in Nickel-Based-Superalloys

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Abstract

Broaches made of high speed steel (HSS) are state of the art for the production of complex slots in turbine discs, but they are increasingly reaching their limits in machining difficult to machine materials. The application of carbide as cutting material is a very promising approach for broaching tools and could have a significant impact on productivity. In this case, the lower fracture toughness of cemented carbide compared to high speed steel is a challenge. One effect is increased chipping of the cutting edge. Therefore, in the following paper, the influences of the carbide grade as well as the tool micro and macro geometry and cutting parameters on tool life were investigated. An analogy test set up was applied that allows a free orthogonal cut with a single cutting edge. Finally, a comparison between the productivity of HSS broaching, cemented carbide broaching and trochoidal milling was drawn.

Keywords: Cemented carbide broach, Broach design, Nickel-based-alloys

1. Introduction

Broaching is the standard machining operation for manufacturing complex profiles and has a wide field of application in automotive and aeronautic industries. This is due to the fact that by broaching high requirements on quality, regarding geometry and shape, as well as surface roughness and integrity can be fulfilled [1]. In addition to high quality demands on the components, the materials to be processed are often very demanding. Especially for turbine discs mainly high-temperature resistant super-alloys are employed and must be machined, such as Inconel 718 [2,3,4]. In turbine discs profile slots are the default feature to realize plug connections between the turbine disc and the blades [3]. This type of connections finds application in stationary gas turbines and air craft turbines. Typical geometries of the complex shaped profiles are dovetail and fir tree profiles.

Standard tool grade for broaching nickel based alloys is high speed steel (HSS). HSS as a cutting material is relatively easy to process, which is an important requirement for the production of complex broaching tools. Besides, the high toughness of HSS is ideal for the use in interrupted cutting during broaching. However, due to the low temperature resistance, HSS has its limits in machining high-temperature alloys. Applicable cutting speeds for HSS broaches are v_c = 2-5 m/min and are thereby, relatively low compared to other machining processes. In addition, the consistent development of super alloys leads to a strong reduction of tool life of HSS broaches.

Therefore, more flexible, alternative technologies for the production of complex slots have been discussed intensively in turbo machinery industry [5,6,7,8,9]. Within the scope of technology with defined cutting edge, milling is a promising option. Different cutting strategies are thinkable, such as trochoidal milling or slot milling with ceramics. Feasibility and performance of the trochoidal milling will be discussed later in this paper by means of a benchmark comparison with broaching.

Processes for pre-machining of slots, such as grinding, water-jet cutting and wire EDM machining, are catching up [7,8,9]. Wire EDM and water-jet cutting are very flexible and

doi:10.1016/j.procir.2014.03.061

benefit from the fact that, compared to cutting technologies, they are less dependent on the work piece material properties. Wire EDM even has a high potential for a finishing operations [5]. However, the introduction of these processes in aerospace industry requires extensive technical approval processes, which in addition are very time and cost intensive.

Therefore, high potential lies in the improvement of the standard broaching process. In order to use existing resources, such as machine tools and expert knowledge of the broaching process, the further development of cemented carbide broaching technology is recommendable. An application of cemented carbide as cutting material could have a significant impact on productivity. Due to higher thermal resistance of carbide, the substitution of HSS by cemented carbide offers the possibility to increase cutting speed in broaching significantly.

Broaching tools can be detailed into roughing, finishing and calibration section. In a first step, it would be feasible to realize the roughing process based on carbide, while still maintaining the finishing operation with HSS. This way finishing operation would not change and thereby approval process for the roughing operation would be simplified. In a second development step, finishing with cemented carbide broaches could be conceivable to use full potential of the carbide broaching technology. However, the lower fracture toughness of cemented carbide compared to HSS might causes chipping of the cutting edge. In order to counteract chipping, both the cutting material as well as the micro and macro geometry of the cutting tools have to be adjusted to the broaching process.

2. Investigation in analogy process for broaching with cemented carbide

2.1. Work piece material

The investigations were carried out using Inconel 718, representing one of the standard materials for turbine discs. It was delivered in solution annealed condition. To achieve aircraft industry requirements it underwent a three-stage heat treatment.

1. Solution annealing – heating to 980 °C, maintaining the temperature (60 min) and then cooling in air.
2. Aging 1 - heating to 720 °C, keeping the temperature (480 min) and then cooling in the furnace to 55 °C
3. Aging 2 - heating to 620 °C, maintaining the temperature (480 min) and then cooling in air.

Fig. 1 shows the microstructure in a cross section after heat-treatment. After the heat treatment the material had a hardness of 45 HRC. This corresponds to the material specification as required by turbine discs industry.

Fig. 1: Microstructure of solution annealed and double aged Inconel 718, HRC 45

2.2. Experimental test setup

Due to its physical and mechanical properties, nickel based alloys such as Inconel 718 are ranked among difficult to machine materials [2,4]. Dominant types of tool wear for broaching nickel based alloys with cemented carbide is material adhesion and the appearance of chipping [6]. Hence, a cemented carbide grade has to combine a high abrasion resistance and compressive strength and at the same time high bending strength and fracture toughness to resist against micro cracking. However, these are conflicting requirements. It is well known that the cobalt content of cemented carbide grade has a significant influence on abrasion resistance and the fracture toughness [6]. Therefore in this investigation the cobalt content of the cemented carbide grades was varied between 6 % (WC-6Co) and 10 % (WC-10Co) to determine the impact on tool wear mechanism, Table 1. By grain size the grades are associated to the group of fine hard metals [2]. The WC-6Co grade has a higher hardness than the WC-10Co grade but at the same time it has lower fracture strength.

Table 1: Composition and properties of the used WC-Co carbide grades [2]

	Chemistry			Grain size	Fracture toughness	Hardness
	WC	CrC_2	Co	[µm]	[N/mm^2]	HV
WC-6Co	~94		~6	1-2	2200	1650
WC-10Co	~89	~0.5	~10	>1	2500	1600

Table 2: Cutting parameters tool geometry and tool grade

Cutting parameters		Tool geometry		Grade
f_z	v_c	γ	r_β	
[mm]	[m/min]	[°]	[µm]	
0.050	10	6	30	WC-6Co / WC-10Co
0.050	20	6	30	WC-6Co / WC-10Co
0.075	10	6	30	WC-6Co / WC-10Co
0.075	20	6	30	WC-6Co / WC-10Co
0.075	20	0	30	WC-10Co
0.075	20	12	30	WC-10Co

Besides tool grade, cutting parameters and tool geometry were varied as shown in Table 2. First the investigation focused on the influence of cemented carbide grade and varying cutting parameters on tool life, while the tool geometry was kept constant. Second, after determining the best tool grade and cutting parameter, the rake angle was varied between 0°, 6° and 12° to discuss the influence of the tool micro geometry on tool life.

Due to the fact that broaching tools are cost intensive an analogy process, based on a single cutting edge test, was chosen for machining investigation. This allows testing varying cemented carbide grades for a wide range of cutting parameters under acceptable expenses.

The analogy test setup was developed for fundamental cutting investigations and was already introduced in former studies [10,11]. It was installed on a Forst broaching machine tool of the type 8x2200x600M/CNC. It allows testing of single cutting edge in a free orthogonal cut and with a translational movement between tool and work piece, as demonstrated in Fig. 2. Therefore an Inconel 718 sheet metal work piece (dimensions: length l = 40 mm, thickness t = 35 mm and width w = 3.9 mm) was mounted into a work piece fixture. In order to avoid the generation of burrs, a cast iron sheet was clamped