CIRP Journal of Manufacturing Science and Technology 7 (2014) 40–47

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

Influence of the lubricoolant strategy on thermo-mechanical tool load

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ARTICLE INFO

Article history:
Received in revised form 9 August 2013
Accepted 6 September 2013
Available online 5 October 2013

Keywords:
Cutting
Optimization
Cooling
Temperature

ABSTRACT

This paper deals with the influence of the cooling strategy on thermo-mechanical tool load during turning of different hard-to-cut materials. The aim is to describe how to control the complex of loads acting on the cutting edge to achieve suitable conditions for different combinations of cutting tool material and workpiece material. As an introduction, measurements and analysis of tool temperature, cutting forces and wear behaviour during turning of TiAl6V4 and Inconel 718 with cemented carbide and high-pressure lubricoolant supply are presented. Based on these results the tool wear behaviour of whisker reinforced cutting ceramics during turning of Inconel 718 with high-pressure lubricoolant supply and conventional flood cooling is evaluated. Additionally this paper presents results of tool temperature, cutting forces and wear behaviour during turning of TiAl6V4 with cemented carbide under cryogenic conditions (LN_2 and CO_2-snow). The results of the tests under cryogenic conditions will be brought in line with the results of the high-pressure coolant supply. Thereby it is possible to qualify the amount of different wear mechanisms onto the total tool wear under different cooling conditions and to show how they can be influenced specifically.

1. Introduction

The use of hard-to-cut materials like titanium and nickel-based alloys as construction material is continuously growing. These materials are widely used for aerospace and turbine components, automotive parts like turbochargers, stationary power plants and medical applications. Therefore the production technology has to deal with the demand for increasing productivity during machining of titanium alloys with an elevated mechanical strength and highly heat resisting nickel-based alloys. However titanium and nickel-based alloys belong to the group of difficult-to-cut materials [1–3]. The machining of these high-temperature alloys is characterized by low productivity and low process stability as a result of their physical and mechanical properties [4,5]. Major problems during the machining of these materials are low applicable cutting speeds due to excessive tool wear, long machining times, and thus high manufacturing costs, as well as the formation of ribbon and snarled chips [6–8]. Under these conditions automation of the production process is limited. Despite considerable improvements in the area of cutting materials and tool coatings, the use of cutting fluid is still necessary when machining difficult-to-cut materials. Therefore a major task is to set up the application of lubricoolant as effectively as possible.

In this context, high-pressure lubricoolant supply is a modern technology with a great capability which is increasingly in demand in industry. The first fundamental investigations were carried out by Pigott and Colwell in the 1950s [9]. Since that time many researchers have demonstrated the huge potential of this technology, especially in machining difficult-to-cut materials [1,10–13]. When using conventional flood cooling the cutting fluid flows uncontrollably around the cutting zone, whereas it is focused directly into the tool-chip interface at high speed when using a high-pressure lubricoolant supply ($p > 70$ bar). Further supply variants are the high-pressure lubricoolant supply onto the flank face, a combined supply onto the flank and rake faces of the tool, or the supply through the cutting insert [13,14]. However it must be considered that the tool-chip contact length decreases when using the rake face side supply variant. If the tool-chip contact area is reduced too much, the generated temperature and mechanical load will act on a small area close to the cutting edge leading to an increased specific tool load [15]. The effects of the high-pressure lubricoolant supply can be summarized as follows:

(a) the reduction of tool wear or the possibility to increase cutting parameters during unchanging tool wear, due to the reduction of chip-tool contact length or friction [16] respectively and reduction in thermal tool load (increase in productivity);
(b) ensure defined chip breakage [17], controlled chip removal, and reliable tool life (increase in process stability).

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1755-5817/$ – see front matter © 2013 CIRP.
http://dx.doi.org/10.1016/j.cirpj.2013.09.001

These effects generally allow an automated manufacturing process of difficult-to-machine materials and an increase in productivity compared to the state-of-the-art. Requirements for this technology are a sealed working room with an extraction system for aerosol mist as well as a high-pressure pump with a filter system. Appropriate high-pressure tool holders with integrated nozzles for directed and focused lubricoolant supply are increasingly available on the market.

The scientific relationships of high-pressure lubricoolant supply are not yet completely analyzed and require further research [17]. Understanding of the fundamental mechanisms is necessary to improve the systematic use of the high-pressure lubricoolant supply and its optimal adjustments (pressure, flowrate, jet alignment, supply method, cutting speed, etc.) considering the background of profitability and energy efficiency. The aim is to evaluate the benefits and possibilities of the high-pressure lubricoolant supply during machining different materials. Therefore new approaches are necessary which allow an estimation of the thermo-mechanical conditions in the shear zones and on the cutting edge. The knowledge of the thermo-mechanical complex of mechanical and thermal loads acting on the tool when using the high-pressure lubricoolant supply allows an estimation of the ability of this technology for different combinations of workpiece and cutting tool materials and enables the choice of appropriate adjustments in the process design.

Another alternative for achieving process cooling using lubricoolants is cryogenic cooling of machining processes. This holds great potential for further reducing tool temperatures. Cryogenic cooling in machining technology involves the use of media with extremely low temperatures. The best known cryogens are liquid hydrogen (boiling point: 20.268 K = −252.882 °C), liquid nitrogen LN_2 (boiling point: 77.35 K = −195.80 °C), liquid oxygen (boiling point: 90.18 K = −182.97 °C) and dry ice (sublimation point 194.5 K = −78.5 °C). Liquid nitrogen and dry ice are frequently used for cooling during cutting processes due to their good availability and relatively safe handling. The advantages of cryogenic cooling include reduced cutting temperatures and thus significantly lower levels of tool wear and higher cutting parameters. An additional advantage of cryogenic cooling is the fact that the media completely gasifies during machining, thereby leaving components, chips and machine interiors clean and dry.

Cutting tests using cryogenic cooling were carried out in the early 1960s, and research in this area has continued until today. Most of this research work focuses on cryogenic cooling when cutting steel materials. When carrying out longitudinal external turning on austenitic steel using LN_2 cooling, a tool life can be achieved that is four times longer than that attained using conventional flood cooling [18]. Due to the properties of highly creep-resistant alloys, cryogenic cooling also holds great potential when cutting these alloys for reducing thermally induced wear mechanisms. Analyses undertaken when carrying out longitudinal external turning on TiAl6V4 have shown that the use of LN_2 cooling instead of conventional flood cooling can reduce tool wear to a fifth [19]. Particularly at higher cutting speeds the greater cooling effect from cryogenic cooling becomes apparent. The reduction in tool wear when using LN_2 cooling instead of conventional flood cooling enabled the high surface quality with sharpened cutting edges to be achieved for a considerably longer time [20].

To find suitable lubricoolant strategies to improve the machinability of titanium and nickel-based alloys it is necessary to exactly understand the thermo-mechanical tool load acting on the cutting edge during machining of these alloys. Denkena et al. showed the effects of the cutting edge geometry on thermo-mechanical tool load during cutting of steel [21]. The topic of this paper is the influence of different cooling strategies.

2. Workpiece materials

2.1. TiAl6V4

Titanium alloys are characterized by their high specific strength, which they can maintain up to temperatures of approximately 600 °C [4,5,7]. Compared with nickel-based alloys, titanium alloys offer a significantly lower density with a marginally lower strength. The density of TiAl6V4 is $\rho = 4420\ kg/m^3$ at 25 °C whereas the density of Inconel 718 is nearly twice as high, $\rho = 8190\ kg/m^3$ [22]. However, the high-temperature strength and the maximum operating temperature of titanium alloys are lower than those of nickel-based alloys. Therefore titanium alloys are used, for example, in the low- and middletemperature areas of aerospace engines. For many years the percentage of components made from titanium alloys as well as fibre-reinforced titaniummatrix composites has been increasing. Therefore a raise in productivity during machining of titanium alloys is becoming more important.

The machinability of titanium alloys is poor due to their mechanical and physical properties. The tensile strength is high; the elongation at break is low. One important physical characteristic concerning their machinability is the low thermal conductivity of titanium alloys, which is just 10–20 per cent of the value for steel. As a consequence only a minor portion of the heat generated during cutting is led away through the chips. Accordingly the heat that has to be led away through the tool is 20–30 per cent higher during machining of titanium alloys compared with 42CrMo4 steel [23]. A comparison of the thermal conductivity versus temperature for different workpiece materials is shown in Fig. 1. Besides the elevated thermal tool load, titanium reacts with the most cutting tool materials [12,16]. The combination of high thermal tool load and high reactivity of titanium alloys leads to major diffusion wear on the tools [24].

2.2. Inconel 718

Inconel 718 is a very tough, high-temperature nickel-based alloy which is resistant to corrosion and belongs to the group of hardenable nickel-based alloys. The hardenable nickel-based alloys gain their strength properties during the heat treatment process (solution annealing followed by artificial ageing). In the heat treatment process intermetallic phases and carbides precipitate from the matrix [28]. Hardenable nickel-based alloys are mainly used in the aerospace industry. Furthermore they are used for parts of stationary gas turbines which are exposed to high dynamic mechanical loads during high working temperatures [2]. The tensile strength of Inconel 718 is about 1375 N/mm^2 at room temperature. At 650 °C it decreases only by approximately 20 per cent to 1100 N/mm^2 [29].

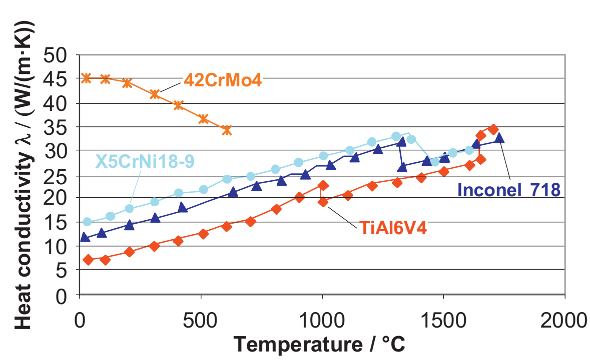

Fig. 1. Heat conductivity of different materials [22,25–27].