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Sustainable machining of high temperature Nickel alloy – Inconel 718: part 2 – chip breakability and optimization

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ABSTRACT

Global competition, stricter environmental legislation and demands for fulfilling sustainability initiatives, are increasing the pressure on the manufacturing industry, to develop and implement in their production alternative sustainable machining processes. This work focuses on sustainability evaluation and comparison in machining of high-temperature Nickel-based alloy (Inconel 718). Four sustainable machining alternatives (dry, near-dry (MQL), cryogenic and cryo-lubrication (cryogenic + near-dry)) to conventional machining, are evaluated based on the performance models from the Part 1 of the paper and used in the optimization procedure for determining the overall optimum machining conditions. As chip breakability is important machining characteristic, performance-based models of sustainable machining processes, developed in Part 1, are upgraded in this Part 2 of the paper with an additional model for chip breakability. Updated models are used as inputs to the optimization procedure developed, based on the combined overall desirability function. Genetic algorithms (GA) are used to evaluate and optimize the machining process for each cooling/lubrication (C/L) application. Results of the work show that machining performance optimization, when including beside machining parameters also the sustainable alternative cooling/lubrication conditions, can provide further improvement of the processes through tool-life, machined surface quality, chip breakability, productivity and nevertheless power consumption.

1. Introduction

Machining processes constitute a major manufacturing activity that contributes to the growth of the global economy. Recent research and development (R&D) activities in machining processes focus on improved machining performances through advanced tool materials, higher productivity and quality, etc., while addressing environmental and health issues (Sutherland et al., 2008) and the related technologies which are becoming more and more important for achieving cleaner, healthier and safer machining (Westkamper, 2008).

R&D in the field of "machine tool-cutting tool-work material" interactions has resulted in innovations that have enhanced both productivity and quality of machined products, with advances in machine tool and cutting tool technologies. However, the current trend towards higher productivity via high-speed machining (HSM) inevitably leads to higher temperatures in both the cutting tool and the machined component, thus adversely affecting machined product quality. Thermal management of machining operations for enhanced tool-life, reduced cutting forces (energy consumption), improved chip breakability, and machined part quality, etc., is not new. However, the development of cooling and/or lubrication techniques and temperature management of the process, is still considered as a novel and emerging direction to study. Industrial metal cutting applications widely utilize conventional cooling lubrication (C/L) fluids, such as: oils and aqueous emulsions, to counter the extremely high levels of heat generated in the cutting zone during the machining process, even though they are environment unfriendly, health hazardous and relatively costly (Pusavec and Kopac, 2011). It has been reported (Kopac, 2009) that up to 16% of the total machining costs are due to the use of C/L emulsions compared to the tool cost, which is estimated to be around 4% (Klocke and Eisenblätter, 1997; Klocke et al., 1998).

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Simply avoiding the C/L fluids usage and applying dry machining alternatives, with new high performance coated cutting tools, would be a huge process gain from the sustainability point of view (Dubzinski et al., 2004). However, there are certain materials which are extremely difficult to machine, for instance high-temperature Nickel-based alloy (Inconel 718) that presents the core part of this work, and is heavily used in aerospace industry, is hardly machined dry (Weinert et al., 2004). The ability of maintaining properties even at high operational temperatures (jet engines, etc.) is the primary reason these materials are used in aerospace applications (Ezugwu, 2005). These materials have relatively low thermal conductivity, leading to extremely high temperatures in the cutting zone and pose numerous difficulties during machining processes.

These facts, added by the growing awareness of sustainability issues in machining, which have identified conventional oil-based C/L fluids as a major non-sustainable element of the process, have led to new R&D activities on finding alternate cooling and/or lubrication mechanisms. (Davoodi and Tazehkandi, 2014) focused mainly on the possibilities to decrease usage of oil emulsions and approach dry machining. On the other side (Rajemi et al., 2010; Velchev et al., 2014) pointed out that benefits for sustainability should be focused also to the improvement of energy efficiency (Bissacco et al., 2013), while (Jawahir et al., 2006) rise the importance of innovative alternatives in machining processes to make them more sustainable. In this way research continues on finding more efficient machining technologies for difficult-to-machine materials. Therefore, in this paper, four alternatives to conventional flood machining (dry, near-dry (MQL), cryogenic and cryo-lubrication (cryogenic + near-dry)) are undertaken, and best possible solutions are provided by the overall optimization procedure. These four sustainable machining alternatives are special forms of traditional machining processes, which focus on eliminating the flood cooling, or replacing it with alternatives to achieve more sustainable machining. All experimental part of the research and performance-based model development for improved machining performance was described in detail in the first part of paper (Part 1). The developed models will be used in this second part of the paper in the overall machining process evaluation and optimization, for enhancing the machining performance. Some of the results, as work initial results, were reported in Kopac (2009) and are expanded here.

In all cooling/lubrication (C/L) cases, the cutting fluid is generally directed to the cutting zone. There are different approaches on how to get as close as possible to the cutting zone that is affected with the highest cutting temperature during the machining process. For the sake of clear understanding, the delivery for each of the cooling/lubrication fluid is quickly reviewed (from the part 1 of the paper) and shown in Fig. 1. C/L strategies are collected through four scenarios:

1. In dry machining no C/L fluid was used.
2. In MQL, oil mist is oriented to the rake face with the nozzle B.
3. In cryogenic case, LN_2 is oriented to the rake face (nozzle B) and the workpiece (nozzle A).
4. In cryo-lubrication, simultaneous delivery of LN_2 and oil mist is performed. LN_2 is directed to the flank face via nozzle C and the oil mist is directed to the rake face via nozzle B.

Nozzle A was oriented towards the workpiece surface before the actual cut, to cool down the workpiece material before coming to the machining zone. Nozzle B and C were used to deliver C/L fluid to the rake or/and flank face of the cutting insert.

The outline of the paper is as follows: In Section 1, a short introduction of the problem along with a summary of observations

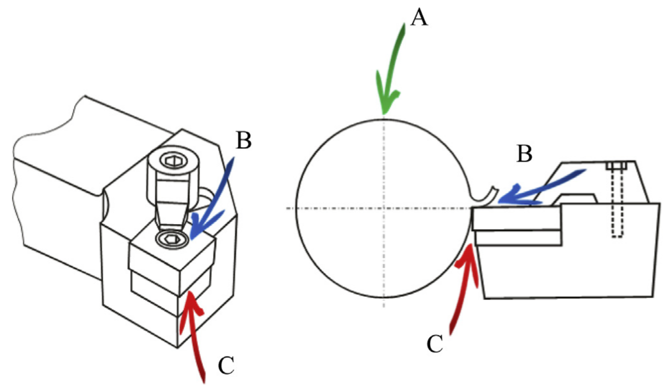

Fig. 1. Direction of cooling/lubrication application (3D view and its cross-section).

from Part 1 is discussed. In Section 2 performance models from Part 1 of the paper are briefly presented, followed by the chip breakability analysis and its modeling covered in Section 3. In the next section, Section 4, the overall machining process optimization procedure is performed using genetic algorithms (GA) methodology, giving optimum machining parameters and C/L conditions. The results and conclusions of this work are presented in Section 5.

2. Process models

Response surface modeling methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems (Montgomery, 2005) in which a response of interests is influenced by several variables and the goal is to optimize these responses: using Grey–Taguchi method in milling (Kopac and Krajnik, 2007), overall fitness function in grinding (Krajnik et al., 2005), etc. RSM also quantifies relationship among one or more measured responses and the vital input factors (Sarıkaya and Güllü, 2014).

In order to study the effects of the cutting parameters and cooling/lubrication application in machining of Inconel 718, a second-order polynomial RSM mathematical model was applied (Equation (1)) to evaluate the parametric effects on the various machining criteria and optimization of the machining process.

$$y_k = \alpha_{k,0} + \sum_{i=1}^{4} \alpha_{k,\,1\ldots4} x_{ki} + \sum_{i=1}^{4} \alpha_{k,\,5\ldots8} x_{ki}^2 + \sum_{i=1}^{4} \times \sum_{j=i+1}^{4} \alpha_{k,\,9\ldots14} x_{ki} x_{kj} + \varepsilon \quad (1)$$

where $x_1, \ldots, x_4$ stand for input parameters: cutting feed rate (f), cutting speed (V_c) and depth of cut (a_p), while the forth input is cooling/lubrication (C/L) condition. Response variables in Equation (1) are presented by y_k. Responses that are considered in this work are $k = R_a$, VB_{max}, KW_{max}, C_{in}, and F_c, F_f, F_r. This represents seven respective models. The terms $\alpha_{k,0}$, $\alpha_{k,1\ \ldots\ 4}$, $\alpha_{k,5\ \ldots\ 8}$, and $\alpha_{k,9\ \ldots\ 14}$ are the second-order regression coefficients that cover linear terms, quadratic terms and interactions between input parameters, respectively. The modeling is in detail covered in Part 1 of this work (Pusavec et al., 2014).

2.1. Graphical representations of the models

The performance models were developed for R_a, VB_{max}, KW_{max}, and F_c, F_f, F_r, in Part 1 of this work. Graphical representations of the models are shown in Figs. 2 and 3. While the process has four input