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Reduction of built-up edge formation in machining Al- and cast iron hybrid components by internal cooling of cutting inserts

Friedrich Bleicher (3)*, Christoph Pollak, Jens Brier, Anton Siller

IFT – Institute for Production Engineering and Laser Technology, Technische Universität Wien, Austria

Submitted by Gerald Byrne (1), University College Dublin, Ireland

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ABSTRACT

In parallel machining of aluminium and cast iron hybrid components, like in precision boring of crankshaft bearing bores, a tribo-chemical reaction occurs on the rake face of a cutting insert and comes along with significant built-up edge formation. Cooling strategies (external, internal) and the cutting fluid quality show significant influence. The determination of the temperature dependency of the intermetallic compound formation velocity (Fe-Si-C) gives a better understanding of this particular tribo-chemical process. An internal cooling of the cutting insert allows a reduction of the built-up edge effect by reducing the temperature on the rake face.

1. Introduction and motivation

When machining material combinations, in particular workpieces consisting of casted Al-alloys and cast iron materials, a number of distinctive material related effects occur and hamper the straightforward implementation of machining processes. As one of these effects a significant built-up edge formation in precision boring applications is well known. It can be assumed that the formation process derives from the specific chipping behaviour of the material combination due to different material characteristics such as material strength, elasticity, hardness, thermal conductivity and thermal capacity.

As shown in Fig. 1a it can be distinguished between pseudo hybrid and real hybrid material arrangements in assembled components. Pseudo hybrid workpieces are made of the same material in the overall structure while real hybrid assemblies consist of different materials [1].

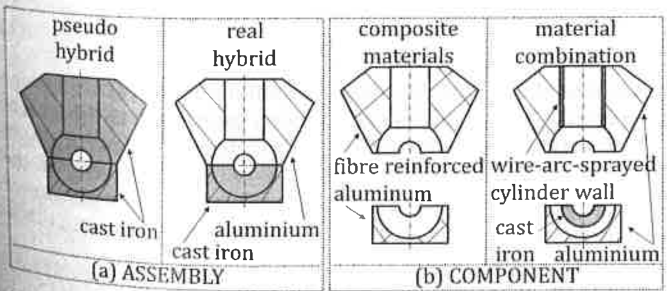

Fig. 1. Definition of (a) assembly and (b) component with aluminium and cast iron parts.

* Corresponding author.
E-mail address: bleicher@ift.at (F. Bleicher).

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If a single component is made of two or more materials it can be distinguished between composite materials and material combinations (Fig. 1b). Composite materials can be regarded macroscopically as a homogenous structure whereas material combinations are a connection of two or more macroscopically different material areas. The latter is usually defined by an intermetallic connection in the interface zone. With respect to the arrangement of the different materials in relation to the feed vector, the machining of material combinations can be noted as serial, simultaneous and parallel machining operations. Fig. 2 exemplarily depicts these different types of machining.

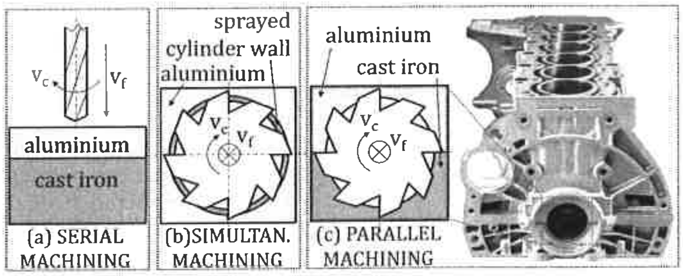

Fig. 2. Serial (a), simultaneous (b) and parallel machining (c).

Parallel machining is defined by machining alternately both materials by one single rotation of a tool. The precision boring of crankshaft bores (Fig. 2c) in a high performance aluminium engine block with reinforcements consisting of cast iron inlets can be regarded as an example for a real hybrid with a 50% aluminium and 50% cast iron cutting process. In [1] parallel machining is regarded to be more challenging in contrast to serial and simultaneous machining due to the different material characteristics and thus different chipping behaviour. Several research activities like in [2,3] are focusing on the investigation of process parameters as well as on tool geometries, which allow an economically relevant processing of hybrid components. The necessity of adjusting machining processes in order to fulfil quality requirements of hybrid components together with the need of an economic and reliable process performance are still counted as challenging topics in machining applications.

2. Tribo-chemical reaction

The major problem in parallel machining (e.g. of crankshaft bores) is besides the alternating load profile which results in different tool deflections, a tribo-chemical reaction which occurs already at an early stage of tool life [4]. An intermetallic compound arises on the rake face due to the presence of iron, silicon and relatively high concentrations of carbon. As shown in Fig. 3 this compound is formed layer-wise causing a continuously increasing built-up edge effect. Additionally, high pressure and temperature during the machining of the cast iron area accelerate the formation of the intermetallic Fe-Si-C reaction. However, the tribo-chemical reaction builds a very stable formation on the rake face which is able to grow steadily. Thus, a significant deviation in the component geometry, the surface quality and finally a highly reduced tool lifetime occur. The displacement of the cutting edge geometry due to the built-up edge formation (see Fig. 4b showing the offset in the cutting edge geometry) makes it almost impossible to meet the tolerances of crankshaft bore diameter (typical range: 15 μm) even using new tools.

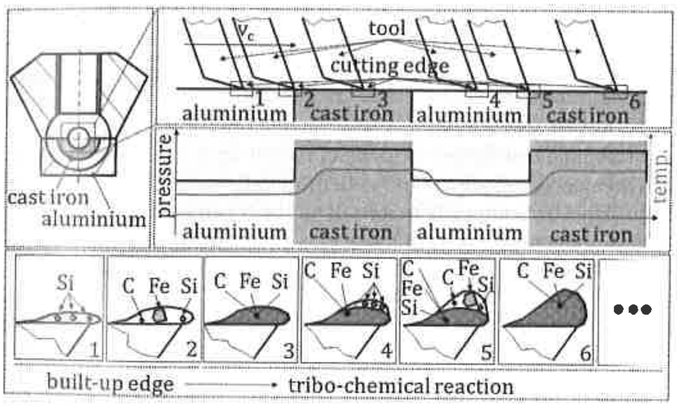

Fig. 3. Tool path of two rotations, mechanism of the tribo-chemical reaction in case of aluminium/cast iron parallel machining.

The contamination ("ageing") of the cutting fluid plays a crucial role in the occurrence of tribo-chemical reactions [5]. For investigating these effects initially cemented carbide cutting inserts with Ti-Al-N coatings and an ester-containing coolant Oemeta Hycut ET46 have been used in experimental tests (process parameters shown in Table 1). Furthermore, two different conditions of ester-containing coolants have been taken under consideration. Both cooling lubricants have been emulsions based on the same ester-based oil Hycut ET46 but with different pre-processing and therefore different contamination levels. Fig. 4 shows the respective areas on the rake face of two hereby differently used cutting inserts where the tribo-chemical reaction has already taken place.

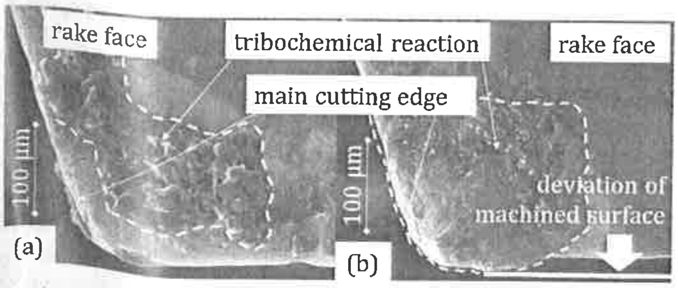

Fig. 4. Cutting insert machined with (a) lowly and (b) highly contaminated cutting fluid Hycut ET46 (EPMA with secondary electrons).

The cutting fluid deployed for the insert in Fig. 4b contained more ageing products, determined by high performance thin layer chromatography, than the one in Fig. 4a. However, it can be derived that the higher the cutting fluid is contaminated by particles and fractions of hydraulic oil, the faster a particular tribo-chemical reaction layer formation grows. The pressure load at the rake face combined with the heat energy flow during the machining and as a result the temperature level at the cutting edge are the main factors for enabling this tribo-chemical reaction. In addition, the quality of the cutting fluid can be regarded as an appendant factor. Due to the requirements for machining processes with respect to the needs of a large-scale production like productivity and economic efficiency there are restrictive limitations given when optimizing cutting parameters. Hence, there is no option to considerably reduce the pressure loads on the rake face with respect to subsequent industrial applications. The reduction of the temperature level at the cutting edge can be expected as an appropriate approach to avoid the tribo-chemical reaction. In order to determine the relationship between temperature and the chemical reaction it is crucial to classify, at least roughly, the formation of the reaction processes regarding its thermodynamic nature. Fig. 5a depicts the result of a differential thermal analyze (DTA) with 5 K/min heating rate carried out with a mixture of a material composition consisting of 85% iron, 10% silicon and 5% carbon [mass/mass]. The percentage of this material mixture was determined in the tribo-chemical reaction products on the cutting tool (Fig. 4b) by the electron probe micro analyser (EPMA).

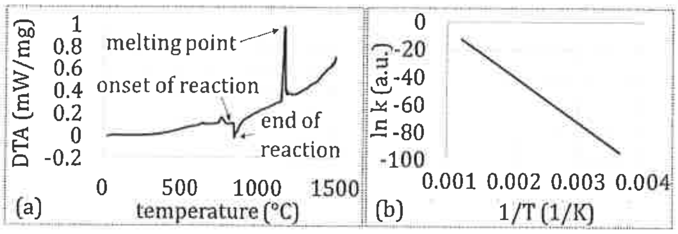

Fig. 5. (a) DTA-measurement (5 K/min heating rate) and (b) Arrhenius plot of a Fe-Si-C (85%-10%-5%) mixture at ambient pressure.

The DTA-graph shows a significant temperature level with an exothermic reaction. Thus it can be anticipated that if a process overruns a particular temperature level, an intermetallic reaction starts and evolves a stable tribo-chemical formation. By varying the heating rate (10 K/min, 20 K/min) the activation energy E_A could be determined in the range of approximately 280 kJ/mol [6]. Based on these results the corresponding Arrhenius plot (Fig. 5b) was created with the Arrhenius equation (formula (1)) using a pre-exponential factor A, a gas constant R and a temperature T. The graph illustrates the dependency of the reaction velocity k by the temperature T.

$$k = A*e^{-E_A/RT} \qquad \ln k = \ln A - \frac{E_A}{RT}*\frac{1}{T} \tag{1}$$

It should be noted that the local conditions at the cutting edge can correspond to a significantly higher pressure than the level of 1 bar. Hence, it can be expected that a higher level of pressure will usually lower the onset temperature value. However, for the experimental investigation of the cutting process the qualitative characterization seems to be sufficient to achieve a first approach.

3. Internal cooling of the cutting zone

Besides conventional external cooling strategies like flood cooling new strategies such as atmospheric-pressure plasma jet [7], solid lubrication [8] and cryogenic cooling [9] are described in the literature. Additionally, there are some different internal cooling strategies well known concerning the cutting fluid itself and the kind of delivery. The latter can be defined by open loop [10] or closed loop [11] systems. Fig. 6 gives a schematic overview of the state of the art in cooling strategies considering the impact of the