DISCUSSION MEETING ON THE DEVELOPMENT OF INNOVATIVE IRON ALUMINIUM ALLOYS

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Turning and Grinding of Iron-Aluminium Alloys

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Abstract: Intermetallic iron-aluminum alloys offer mechanical and chemical properties qualifying them for many demanding applications e.g. turbo-chargers, turbine blades and valves. Such products are mainly manufactured by turning, milling and grinding. The performance of these processes is investigated in this work for FeAl- and FeAlCr-alloys by means of the influence of the material properties and the machining parameters. Experimental analyses show that tool wear increases by 10- to 100-fold when machining FeAl-alloys with a geometrically defined cutting edge in comparison to the machining of conventional steels. According to this, different process parameters and tool substrates must be investigated to define an optimised machining process in cutting iron-aluminides. By this reason, the wear mechanisms and process forces in turning are investigated for different alloy compositions in the present work. Additionally, the basic understanding of material removal in iron-aluminides by geometrically undefined cutting is investigated to establish an efficient grinding process. Therefore the cutting forces, radial tool wear and workpiece quality must be studied. The objective is to determine process parameter with low tool loading and to find a substrate with low tool wear. During grinding with cubic boron nitride grinding wheels, determined maximal cutting forces of $F_n$ and $F_t$ should not be exceeded in order to diminish grinding wheel wear and to preserve the workpiece quality, i.e. to avoid workpiece subsurface damage.

Introduction

Machining of iron aluminides causes higher wear rates of the cutting tool than that of common ferrous materials and cast iron [1]. Therefore iron aluminides are rated as “difficult-to-cut” materials. Nowadays FeAl-alloys are machined with standard tools and low process parameters. Their wide industrial application due to their good mechanical and chemical properties, e.g. high corrosion resistance, is still limited by the lack of productive machining processes. Therefore, different substrates and process parameters have to be investigated. For this purpose the basic understanding of tool wear and chip formation mechanisms during turning and grinding is necessary [2, 3]. In external turning an investigation of tool wear for two cutting materials and the influence of various FeAl-based alloys on the process forces are done. Due to the excessive tool wear, grinding operations can be more economic for finishing operations. By this reason, the influence of the specific material removal rate and the cutting speed on process forces, tool wear and workpiece quality are investigated during grinding of FeAlCr with cubic boron nitride grinding wheels.

Experimental Setup
The turning experiments are performed on a lathe Gildemeister CTX 520L. The process forces are measured with a Kistler dynamometer 9257B during machining. The tool wear mechanism is analysed by scanning electron microscopy (SEM). Furthermore, energy dispersive X-ray (EDX) spectroscopy is used for the determination of adhesion. To analyse the influence of the alloy composition and the cutting speed on the machining process with cubic boron nitride (CBN) and uncoated carbide tools (HW), a binary FeAl- and two ternary FeAlCr-alloys are used.

**Influence of the Alloy Composition and Cutting Speed on Cutting Forces and Tool Wear in External Turning**

**Process forces.** By force measurements during turning of the rejective FeAl materials dynamical changing process forces are determined. The diagrams of the cutting force $F_c$ show that significant high cutting forces are applied to the cutting tool (Fig. 1). A specific cutting force $k_e$ is calculated more than twice higher compared to C45E steel. At a cutting speed of $v_c = 20 \text{ m/min}$ the mean cutting force $F_c$ varies between 200 N and 250 N, but decreases with a higher cutting speed of $v_c = 300 \text{ m/min}$ on a mean cutting force $F_c$ between 125 N and 200 N. Highest mean cutting forces $F_c$ are determined at a low cutting speed in Fe-14Al-3Cr, whereas the lowest mean cutting force $F_c$ is measured at a high cutting speed in Fe-14Al. However, the mean cutting force progression for the three different iron-aluminium alloys is at a higher cutting speed lower. This is due to the high plasticity and low flow stress of the FeAl material at the chip formation zone. These results correlate with the findings of a changing chip formation and solidification during the chip formation process [4]. Furthermore, at a cutting speed of $v_c = 300 \text{ m/min}$ the dynamic behaviour of the cutting forces $F_c$ is decreasing related to a cutting speed $v_c = 20 \text{ m/min}$. With increasing cutting speed the maximal cutting force $F_{c,max}$ decreases from partially up to $F_{c,max} > 500 \text{ N}$ to 250 N. This might be caused by the material microstructure, especially by inhomogeneous grain sizes or by grain boundary hardening, but will be studied in future investigations.

**Figure 1. Influence of alloy composition and cutting speed on the cutting force in external turning.**
At higher cutting speeds the flow stress is decreasing, which reduces the dynamic variation of the cutting force $F_c$. In fast consecutive cutting of single grains with the tool a lower dynamic alternation during the material separation is determined. Consequently, a high cutting speed is advantageous in turning iron-aluminides, but leads to increasing tool wear in uncoated cemented carbide. Therefore, the use of a CBN substrate could effect a better tool wear behavior.

Wear mechanisms. The thermo-chemical stability of the substrate has an important influence on the wear mechanisms. Due to the highest dynamical load on the tool, the alloy Fe-16Al-5Cr (wt%) has been chosen to analyse the tool wear. The wear characteristics after a cutting length of $l_c = 35$ m using CBN and carbide turning tools are compared at two different speeds, as shown in Fig. 2.

A high thermal load of the tool is expected because of the low heat conductivity of iron-aluminides. CBN tools offer superior high temperature strength than carbide tools during the cutting process with cutting speeds above $v_c = 100$ m/min. The CBN tool shows no abrasion or diffusion on the flank face. On the rake face material adhesion can be identified by the EDX-analysis. In contrast, carbide tools show widespread adhesions and abrasive wear of the substrate. At further investigations with higher cutting speeds CBN tool failure will be determined by cutting edge chipping, but not by crater wear. The main reason for this is the higher susceptibility due to its brittleness compared to carbide tools.

![Figure 2. Influence of the cutting speed on wear mechanisms of CBN and carbide tools.](image)

Conclusions. The turning processes with different alloy compositions show a highly dynamic variation of the cutting force $F_c$ at a cutting speed of $v_c = 20$ m/min. However, the dynamic variation decreases with increasing cutting speed. The machining of the alloys should be done at a cutting speed of $v_c = 300$ m/min. Uncoated cemented carbide tools wear faster, because of thermal induced adhesion and cutting edge chipping. Thus, solid carbide tools have limited tool life under these conditions. In contrast, CBN tools show a better wear behaviour at the investigated cutting speeds.
Influence of Material Removal Rate and Cutting Speed on Grinding of Fe-26Al-4Cr (at\%) with a CBN grinding wheel

Experimental Setup

Peripheral grinding experiments are carried out on a Blohm Profimat 307 grinding machine. The cutting tool is a CBN grinding wheel with metallic bond system and a mean grain size of $d_g = 126$ µm. Both, cutting material and metallic bond system were chosen due to their high thermal conductivity and high wear resistance. The specific material removal rate is varied from $Q'_w = 0.5$ mm$^3$/mms to 2 mm$^3$/mms, set through the variation of the tangential feed rate $v_f$. The cutting speed is set from $v_c = 30$ m/s to 80 m/s. The normal and tangential cutting forces, $F_n$ and $F_t$, as well as the grinding wheel radial wear $Δr$ are measured at the three different specific material removal rates $V'_w = 9$, 90 and 180 mm$^3$/mm. The different specific material removal rates $V'_w$ are adjusted by the depth of cut $a_c$, the feed travel $I_f$ and the width of cut $a_p$. The workpiece quality is analyzed at $V'_w = 180$ mm$^3$/mm through the roughness $Ra$ and $Rz$, and the subsurface quality, i.e. subsurface crack formations.

**Process forces.** In Fig. 3 it is determined that the tangential and normal forces, $F_n$ and $F_t$, increase degressive with the specific material removal rate $Q'_w$. However, the tangential and normal forces, $F_n$ and $F_t$, decrease with the cutting speed $v_c$ at higher specific material removal $V'_w$.

![Graphs showing the influence of specific material removal rate $Q'_w$ on forces and cutting speed $v_c$.](image)

**Figure 3.** Influence of the specific material removal rate $Q'_w$ and cutting speed $v_c$ on the process forces in grinding of Fe-26Al-4Cr (at\%) at different specific material removal $V'_w$. 

**Process:** pendulum grinding  
**Workpiece material:** Fe-26Al-4Cr (at\%)  
**Dressing process:** tool: diamond wheel  
**Coolant:** mineral oil  
**Cutting material:** B126  
**Bonding:** metallic  
$v_c = \text{var.}$  
$\Delta r = \text{var.}$  
$a_c = 50$ µm  
$Q'_w = \text{var.}$  
$U_d = 2$  
$a_p = 10$ mm  
$d_g = 0.9$  
$a_{ed} = 2$ µm  
$\alpha = 0.9$  
$\nu = 2$  
$\phi = 2$ µm

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By an increasing feed rate \( v_f \) the chip thickness \( h_{cm} \) rises and therefore the specific material removal rate \( Q'_{w} \). This leads to higher tool wear and hence, by increasing specific material removal \( V'_{w} \), to decreasing cutting forces.

**Grinding wheel radial wear \( \Delta r \).** Measurements of the grinding wheel radial wear \( \Delta r \) were performed at specific material removal of \( V'_{w} = 9 \), 90 and 180 mm\(^3\)/mm by means of graphite imprints. The depth of the imprints was determined by tactile measurements. At cutting speeds below \( v_c = 80 \) m/s radial wear increases from \( \Delta r = 0 \) \( \mu \)m at \( V'_{w} = 9 \) mm\(^3\)/mm to \( \Delta r = 3 \) \( \mu \)m at \( V'_{w} = 180 \) mm\(^3\)/mm after a cutting time \( t_c = 90 \) s. At \( v_c = 80 \) m/s wear remains at \( \Delta r = 2.5 \) \( \mu \)m for all specific material removal values. Lower radial wear at higher cutting speeds can be explained due to smaller equivalent chip thicknesses which results in lower cutting forces and finally in a higher tool life.

**Workpiece quality.** The quality of the ground workpieces was evaluated by SEM micrographs and polished cross sections of the workpiece. Only at a cutting speed of \( v_c = 80 \) m/s and a specific material removal rate of \( Q'_{w} = 0.5 \) mm\(^3\)/mms the ground surface of the workpiece was free from cracks. The cross sections of the workpieces ground at \( v_c = 50 \) m/s and \( V'_{w} = 90 \) and 180 mm\(^3\)/mm exhibit cracks, which extended up to a depth of 770 \( \mu \)m from the workpiece surface. The roughness of the ground surface varies from \( Rz = 2.5 \) to 5 \( \mu \)m (\( Ra = 0.35 \) to 0.6). The lowest roughness was measured at a cutting speed \( v_c = 80 \) m/s and \( Q'_{w} = 0.5 \) mm\(^3\)/mms and the highest at a cutting speed \( v_c = 50 \) m/s and \( Q'_{w} = 2 \) mm\(^3\)/mms. This can be explained with the higher grain overlap at higher cutting speeds. The micro hardness for all ground surfaces without thermal damage remains constant at 389 HV 0.1 \( \pm \) 12.5 HV 0.1, up to a workpiece depth of 2 mm.

**Conclusions.** At a cutting speed of \( v_c = 80 \) m/s and a specific material removal rate of \( Q'_{w} = 1 \) mm/min by a feed rate of \( v_f = 600 \) mm/min neither a hardening, by e.g. recrystallization below the workpiece surface, nor a thermal damage while grinding occurred. It can be concluded that the temperatures during grinding must be underneath the recrystallisation temperature of about 545°C [5].

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