CIRP Journal of Manufacturing Science and Technology 7 (2014) 71–82

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

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

Chip formation in monocrystalline iron-aluminum

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ARTICLE INFO

Article history:
Available online 5 March 2014

Keywords:
Iron-aluminum
Chip formation
Monocrystal
Intermetallic
Linear planing
Orthogonal turning

ABSTRACT

Iron-aluminum has an excellent corrosion resistance, low density and high specific strength compared to conventional steel. In addition, the raw materials and manufacturing costs of iron-aluminum alloys are relatively low. However, the machinability is challenging. Economical machining of iron-aluminum is currently not possible due to high tool wear. Furthermore the cutting and chip formation mechanisms in machining of iron-aluminum alloys are not fully understood.

To understand the thermomechanical mechanisms in the material separation process the influences of the crystal lattice orientation on the chip formation is analyzed in relation to the cutting direction. Therefore, monocrystalline FeAl specimens are machined, using a simultaneous measuring device existing of a two-color ratio pyrometer, piezoelectric force measurement as well as microcinematographic images. The observed trend is that the segmentation as well as the chip thickness are significantly influenced by the lattice planes engaged in the cut. The causes for the different chip formation mechanisms are ascribed to a change of the slip planes and slip vectors activated in relation to the load on the crystal lattice as well as the orientation of the crystal lattice to the load.

1. Introduction

Intermetallic iron-aluminum alloys in comparison to conventional steel have a high specific strength, stiffness and wear resistance as well as excellent oxidation and corrosion properties, even at higher temperatures [1,2]. Furthermore, the raw materials and manufacturing costs of iron-aluminum alloys are low, especially in comparison to γ-TiAl-alloys which have comparable material properties.

Due to the excellent material characteristics, intermetallic iron-aluminum alloys qualify for many industrial applications, e.g. exhaust gas equipment, petrochemical installations as well as combustion engines and actuations [3–5]. However, the realization of such applications is limited due to the low machinability of intermetallic alloys which leads to high manufacturing costs of the parts.

Machining of iron-aluminum alloys causes higher wear rates of the cutting tool than that of common ferrous materials and cast iron [6]. Therefore, cutting tool macro and micro geometries including substrates as well as process parameters have to be investigated in more detail to increase the efficiency. For this purpose the basic understanding of the cutting and chip formation mechanisms during the process is necessary [7,8].

Preliminary studies [9] show that unequal chip formation mechanisms occur although the process and tool parameters are consistent. The chip shape changes randomly. To investigate the cause of the changing chip formation e.g. in segmented chips [10,11], monocrystalline iron-aluminum with different crystal lattice orientations is machined in a linear planing and orthogonal turning process. The objective is to determine the occurring cutting and chip formation mechanisms in machining of monocrystalline iron-aluminum in dependency of the crystal lattice orientation. For this analysis process forces, temperatures on the chip bottom side as well as high speed camera images are recorded simultaneously. This enables the correlation of chip formation to forces and temperatures as well as to the crystal orientation of the material.

2. Materials and machining

2.1. Material properties of Fe_3Al-alloys

Intermetallic iron-aluminum alloys are a worldwide commonly researched material since the 1930s. They have excellent properties, especially concerning high temperature oxidation-corrosion resistance in aggressive environments [12–14]. Furthermore, they are characterized by a low density, low raw material cost, good

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1755-5817/$ – see front matter © 2014 CIRP.
http://dx.doi.org/10.1016/j.cirpj.2014.01.004

Table 1
Young's modulus in dependency of the crystal orientation [20].

Crystal lattice orientation	[1 0 0]	[1 1 0]	[1 1 1]
Young's modulus [GPa]	63	154	298

wear resistance and convenient fabrication [15,16]. However, low room temperature ductility and poor high temperature creep strength above 600 °C still limit their applications as structural materials [17–19]. This is in the focus of current research on the material itself.

In addition, iron-aluminides show a relatively high elastic anisotropy, as many intermetallic crystals do. The highest degree of anisotropy is determined for crystals near the Fe_3Al composition. The Young's modulus in dependency of the crystal lattice orientation is listed in Table 1. The [1 0 0] crystal lattice orientation is the least elastic and the [1 1 1] is the most elastic orientation. The difference amounts to a factor of 5.

It is noticeable that the material properties of Fe_3Al-based intermetallic alloys with a DO_3 or B2 structure show a yield stress anomaly at an intermediate temperature [2,21]. Král et al. show the critical resolved shear stress in dependency of the temperature for the single crystals Fe-28Al (at.%) as well as Fe-28Al-6Cr (at.%) (see Fig. 1). Below 420 °C the strength of both materials decreases with an increase of the temperature. This is an expected trend for conventional materials. Above about 420 °C the shear stress increases to a local maximum of about $\tau_o = 200$ MPa at 620 °C. With a further increase of the temperature the shear stress decreases again. This trend has been observed for several Fe_3Al-alloys [22,23].

The cause for the yield stress anomaly is not fully understood yet. There is a transformation of the DO_3 to the B2-structure near the temperature anomaly [24]. This was thought to be the cause for the yield stress anomaly. However, present researchers state that the slip systems that are activated during deformation of Fe_3Al-alloys are the main cause for the effect [25,26]. How the slip systems change and for what reason is still a research topic.

At room temperature Fe_3Al-based intermetallic alloys with a DO_3 structure have a slip plane and a slip vector of $\{1\ 1\ 0\}\ \langle 1\ 1\ 1\rangle$ [2,21,25]. High temperature deformation of Fe_3Al single and polycrystals in the DO_3 structure regime suggests the thermally activated operation of the $\{1\ 1\ 2\}\ \langle 1\ 1\ 1\rangle$ in addition to the $\{1\ 1\ 0\}\ \langle 1\ 1\ 1\rangle$ slip system near the peak-stress temperature [27,28]. In rolling deformation studies in the DO_3 regime, the combined action of the $\{1\ 1\ 2\}\ \langle 1\ 1\ 1\rangle$ and $\{1\ 1\ 0\}\ \langle 1\ 1\ 1\rangle$ slip systems provide the best fit for texture evaluations in the 500–560 °C range [24]. However, an increased transition of the $\langle 1\ 1\ 1\rangle$ to $\langle 1\ 1\ 0\rangle$ as well as $\langle 1\ 0\ 0\rangle$ slip directions in slip systems are observed [2].

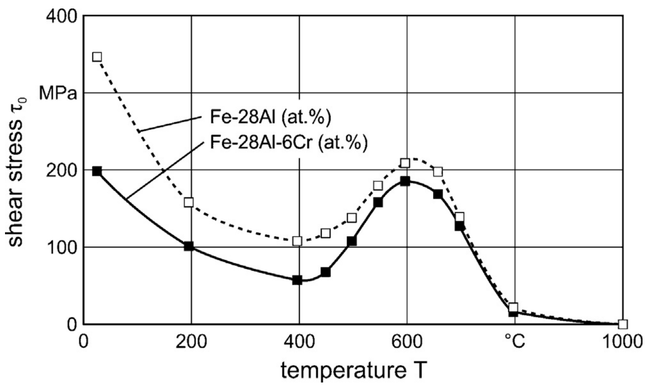

Fig. 1. Thermal dependence of the critical shear stress of Fe-28Al (at.%) monocrystals [22].

2.2. Machining of iron-aluminum

Currently there is only little knowledge available regarding the machinability and the basic chip formation mechanisms of FeAl-alloys. Some authors report about their experiences in machinability gained by the preparation of specimen. Pocci refers to a better machinability in extruded profiles in contrast to powder metallurgical production and casting with an alloy containing 24 wt.% aluminum [29].

Woodyard investigated the machinability in milling of Fe-28Al-Cr [30]. By milling without coolant ductile smearing on the machined surface is determined. Uncoated carbide tools show a fast tool wear by chipping and buildup edges. The analysis of the chips showed a ductile chip formation with shear bands and a discontinuous chip compression. The application of water and oil as coolant leads in dependency of cutting speed to different chip thicknesses and chip compressions.

Chowdhuri et al. showed the influence of cutting speed on the chip formation [31]. At a low cutting speed triangular chip segments are generated joined by secondary crack formation on the chip bottom side. On the chip top side cracks are interfered by grain boundaries. Already at a cutting speed of $v_c = 35$ m/min changes in mechanisms occur. The crack formation appears on the chip top side and the chip segments show rather a trapezoid form. The grains are deformed and adjusted along the shear plane.

Denkena et al. investigated grinding and turning of FeAl-alloys [9,32,33]. The material removal mechanisms for grinding were investigated by single grain cutting. In turning the tool wear as well as chip formation has been researched with respect to a variation of cutting speed. Based on the results in grinding operations, the cutting speed should be limited to $v_c = 20$ m/s. At higher speeds, an increasing grain wear is observed. In turning, TiAlN-coated tools show a better tool life compared to TiB_2 due to the higher thermal stability. The lower thermal stability in TiB_2 causes a fast progressing dissolution of the coating and a removal of the substrate by oxidation and diffusion. The chip formation and its microstructure are unsteady. It is shown that the chip formation changes within different grains.

3. Experimental setup

3.1. Material characteristics

The material used in the experimental cutting investigations is a ternary iron-aluminum (Fe_3Al) alloy with 26 at.% aluminum and 4 at.% chrome (Fe-26Al-4Cr). The alloy composition leads to good mechanical properties and a high corrosion resistance in relation to binary FeAl-alloys [34,35]. Chrome increases mainly the ductility and the corrosion resistance [36,37]. This intermetallic material has a body-centered cubic structure with DO_3-arranged phases [26]. The monocrystalline material was produced by directional solidification from liquefied material using the Bridgman method. Three different cylindrical monocrystalline workpieces were manufactured with varying orientation of the crystal lattice.

The crystal lattice orientations [1 0 0], [1 1 0] and [1 1 1] are oriented parallel to the workpiece axes. Their exact orientations are determined by an X-ray diffractometer type Seifert XRD 3003 TT by GE Sensing and Inspection Technologies. In addition, the lattice planes {1 0 0}, {1 1 0} and {1 1 1} of the crystals are determined by reflections on the lattice characterized by pole figures (see Fig. 2).

The hardness of Fe-26Al-4Cr is determined in relation to the crystal lattice orientation. Table 2 lists the measured mean values of the hardness HV1 on the perimeter of a cylindrical specimen in dependency of the lattice planes. No significant difference could be determined.