Machining aspects of a high carbon Fe₃Al alloy

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Abstract

Iron aluminide alloys containing both ferrous as well as non-ferrous (aluminum) components form unique materials from machining theory and practice point of view. While the cutting tool materials specifically required for their machining are not available, the mechanism of machining of such materials containing ferrous and non-ferrous components has not been adequately investigated. This paper deals with fundamental aspects of chip formation and tool-life in machining of an iron aluminide, Fe₃Al alloy. Microstructural analysis of chips shows that the interaction of chip and tool in the secondary deformation zone, dependent upon the cutting speed mainly determines the mechanism of chip formation. Results of tool-life testing indicate that thermal softening of tool point combined with abrasion is the predominant tool failure mechanism.

Keywords: Machining; Chip formation; Tool-life testing; Iron aluminides

1. Introduction

Iron aluminide alloy based Fe₃Al composition (~16 mass% Al) offers a combination of attractive properties, such as good strength and excellent resistance to oxidizing and resulfidizing atmosphere at elevated temperatures, low density and low cost [1–3]. Some of their potential applications are in coal conversion systems, conventional power plants, catalytic converter substrates, regulator discs in gas turbine engines, heating elements and furnace parts [1,4,5]. Their essential drawbacks are poor room temperature ductility and fracture toughness because of environmental embrittlement [6–8], and poor strength and creep resistance above 600 °C [1]. Beside, the difficulties in their fabrication have dampened the rapid commercialization of Fe₃Al alloys. Many processing routes such as rapid solidification followed by powder compaction or arc melting and drop casting, vacuum induction melting [5] used in their fabrication from high purity raw material are neither cost effective nor amenable to bulk production. To improve their fabrication characteristics, electro-slag remelting of air induction melted cast electrodes was used to produce round ingots free of porosity [9,10]. Efforts are also being made

to reduce their environmental embrittlement susceptibility and to improve their ductility [11–14].

It is certain that to convert aluminides into engineering or industrial products, they need some extent of machining. During machining they have unique implications from the machining theory as well as practice point of view. Since they contain ferrous as well non-ferrous components, there are no specific cutting tools for their machining, as most of the cutting tools are for either ferrous or non-ferrous materials. Secondly, the mechanisms of machining of ferrous as well as non-ferrous materials are known to be different [15–17]. Aluminides containing ferrous as well as non-ferrous components form a special case. Therefore, in the event of lack of available experience and knowledge on machining of these alloys, their efficient machining remains elusive. This paper presents an experimental investigation to understand and model their mechanism of machining and tool-life in machining.

2. Experimental

2.1. Preparation and characterization of aluminide

The iron aluminide alloy required for this work was produced by air induction melting (AIM) followed by electro-slag refining (ESR). A magnesia-lined, medium frequency (2.6 kHz) furnace of 18 kg capacity was used for

Fig. 1. Schematic diagram of orthogonal machining.

AIM. Subsequently, the AIM electrodes were subjected to ESR using $70\text{CaF}_2\text{--}15\text{Al}_2\text{O}_3\text{--}15\text{CaO}$ slag in water cooled steel molds to produce 75 mm diameter ingots.

Chemical analysis was done by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Tensile testing was carried out as per ASTM E8M standard on a BiSS 50 kN servo-hydraulic machine at an extension rate of 0.01 mm/s (strain rate $4.16 \times 10^{-4}/\text{min}$). Hardness values were measured on the C-scale of a Rockwell hardness-testing machine.

2.2. Orthogonal machining

A pipe of 63 mm outer diameter and 2.3 mm wall thickness was made out of the ESR cast ingot for orthogonal machining as shown in Fig. 1. Machining experiments were carried out as per the specifications given in Table 1 and continued till sufficient number of chip samples were available for the study.

2.3. Scanning electron microscopy (SEM) of chips

Chips produced during orthogonal machining were mounted in epoxy molds and polished on the polishing

Table 1

Experimental specifications for orthogonal machining

Machining process	Turning			
Cutting speed (m/min)	14.8	22.6	35	82
Feed rate (mm/rev)	0.122	0.122	0.122	0.122
Cutting tool	Grade K20 (brazed carbide)			
Coolant	None			

papers and polishing cloth so as to investigate longitudinal cross-sections of chips. The chip samples thus prepared were etched using a solution of $33\%\text{HNO}_3 + 33\%\text{CH}_3\text{COOH} + 33\%\text{H}_2\text{O} + 1\%\text{HF}$ by volume. To prevent charging of non-conducting resin in SEM, a thin film of gold was deposited on these specimens using vacuum deposition technique. The chip samples were analyzed under a 25 kV JEOL scanning electron microscope.

2.4. Tool-life testing

Tool-life tests were carried out as per ISO specification no. ISO 3685E (1977) on a lathe using uncoated as well as coated carbide inserts. The uncoated carbide inserts were of TTR grade (equivalent to ISO P30-P40) and coated carbide inserts were of TK35 grade (equivalent to ISO P30-P40).

Fig. 2. Details of cutting tool used in the tool-life testing.

Table 2
Cutting parameters during tool-life testing

Cutting parameters	Coated carbide (TK35)			Uncoated carbide (TTR)	
Cutting speed (m/min)	9.5–52.7			9.24–37.2	
Feed rate (mm/rev)	0.122	0.122	0.122	0.122	0.199
Depth of cut (mm)	0.25	0.5	0.8	0.7	0.7
Tool failure criterion	0.6 mm width of flank wear land				
Coolant	Chemical emulsion of oil with water mixed in ratio (1:100)				

Details of cutting tool and other experimental specifications are shown in Fig. 2 and Table 2, respectively.

3. Results and discussion

3.1. Microstructure and mechanical properties of the aluminide alloy

Microstructure of the aluminide alloy prepared for this work containing two phases viz. Fe_3Al (73%) and $\text{Fe}_3\text{AlC}_{0.5}$ (27%) is shown in Fig. 3. The results of chemical and mechanical characterization of the material are depicted in Table 3.

3.2. Scanning electron microscopy of chips

Micrographs of typical chips produced in orthogonal machining under varying cutting conditions are shown in Fig. 4a–d. It is observed that the chip formation mechanism in these materials is a combination of a number of distinct processes with the following prominent features:

Fig. 3. Microstructure of undeformed aluminide alloy (400 $\times$).

Table 3
Chemical composition and room temperature mechanical properties of aluminide alloy

Alloy composition		Mechanical properties	
Al (wt.%)	16.2	UTS (MPa)	478
Cr (wt.%)	2.35	YS (MPa) (0.2% proof stress)	391
C (wt.%)	1.06	Elongation (%)	2
Fe	Balance	Hardness (R_c)	41

- Chip formation begins with an initiation of a minor crack from the chip outer surface that results in imparting a saw tooth profile (STP) to the outer surface of the chip.
- Geometry of the STP and its prominence depends primarily on the cutting speed. At lower cutting speeds of 14.8 and 22.6 m/min, chip segments appear to be triangular in shape (see Fig. 4a and b). Whereas, at higher cutting speeds of 35 and 82 m/min, chip segments are of approximately trapezoidal in shape.
- Profile of the inner surface of chip also changes with the cutting speed. Chips produced at lower cutting speeds of 14.8 and 22.6 m/min show presence of gross secondary fracture (see Fig. 4a and b). However, this is not so in the case of chips at higher cutting speeds and the chip inner surface appears to be smooth instead (see Fig. 4c and d).
- The extent of deformation or elongation of grains and their alignment with the direction of cutting also varies with the cutting speed. In chips at lower cutting speed, grains appear to get severely stretched or elongated in the direction of shear. The grains also appear to lie along a curvilinear path of very large radius (refer Fig. 4a–c). But at higher cutting speeds, the grains undergo sever stretching so that they break into elongated globular grains. These grains tend to lie along a curvilinear path of relatively smaller radius (see Fig. 4d).
- A closer observation of micrograph in Fig. 4 reveals that in a majority of instances, the minor fracture initiated at the chip outer surface usually gets inhibited when an inter-phase boundary is encountered as indicated by arrows.
- Thus, it can be concluded that the mechanism of machining differs mainly based on the cutting speed as two distinct chip formation mechanisms appear to be operating in these materials at higher as well as lower cutting speeds.

3.3. Model of chip formation at lower cutting speeds

Characteristic features of the chip formation mechanism at lower cutting speed are (see Fig. 4a and b):

- Minor crack initiation on the chip outer surface.
- Inhibition of the minor fracture mainly by grain boundaries.
- Generation of a triangular-shaped chip segment.
- Initiation of gross secondary fracture on the chip inner surface.

Fig. 4. (a–d) Micrographs of chips obtained at various cutting speeds.

At the lower cutting speeds, a minor fracture is initiated on the outer surface of the chip where the normal stress on the shear plane is very low [16]. Further, the minor fracture propagates to a certain distance as facilitated by compressive stresses on the shear plane [17] and usually gets terminated near grain boundaries (indicated by arrows in Fig. 4a). It has been evident that in aluminides, grain boundaries have greater fracture resistance than the bulk material [9] hence they could form common sites for inhibition of the minor crack. Thereafter, rest of the material on the shear plane is removed by shear type deformation wherein the shear plane takes a curvilinear path. This could be mainly due to the larger restraint imposed on the movement of chip material due to heavy sticking friction along the tool face. Consequently, a triangular shaped chip segment (or STP) is generated on the chip outer surface. Another effect of severe sticking of chip material on the tool face is generation of a gross-secondary shear along the chip inner surface (see Fig. 4a and b) and formation of a built-up-edge (BUE) on the tool face. Occurrence of a BUE on the tool face was found to be very common while machining at low cutting speeds. It may be appreciated here that the aluminum contents of the material (about 40%) although advantageous for mechanical properties, leads to strong adhesion on the tool face. Therefore, cutting of such materials could involve cutting forces of very high magnitude. A conceptual model of chip

formation mechanism at lower cutting speed is presented in Fig. 5.

3.4. Model of chip formation at higher cutting speeds

Characteristic features of the chip formation mechanism at higher cutting speed are (see Fig. 4c and d):

- Major crack initiation at the chip outer surface.
- Generation of a trapezoid-shaped chip segment.
- Severe deformation of grains and their alignment along the shear direction.
- Intense secondary shear along the chip inner surface and formation of a white band.

A major crack is initiated at the chip outer surface and propagates to a larger depth towards the tool nose at higher cutting speeds. This could be due to higher void formation facilitating the propagation of gross fracture at higher cutting speeds. Other grains in the primary deformation zone get stretched to an extent that they break and elongated globules of these grains along with voids (see Fig. 4c and d) lie along a curvilinear path in the thickness of chip. This indicates that the deformation during machining takes place again along a curvilinear shear plane.

Along the chip–tool interface, the temperature is comparatively higher while machining at higher cutting speeds.

Fig. 5. Model of chip formation at lower cutting speeds.

It results in a reduced restraint (sticking) on chip material along the tool face leading to the formation of trapezoidal chip segments. Although, the gradient in chip velocity along the thickness of chip is lower as compared to that of machining at lower cutting speeds, it is sufficient to cause minor sticking of chip on the tool face. Due to the poor heat conductivity of the aluminide alloy [18], intense localized heating as well as shearing occurs in the chip material close to the tool face, usually called as *secondary shear* [19,20]. The intensely sheared layer appears as a white layer along the chip inner surface in the chip microstructure (see Fig. 4c and d). Thus, reactions at the chip–tool interface play an important role in governing mechanism of chip formation in aluminide alloys. A conceptual model based on the above discussion depicting machining characteristics of aluminide alloys at higher cutting speeds is shown in Fig. 6.

3.5. Tool-life testing

Tool-life testing was carried out as per the details given in the experimental procedure using coated as well as uncoated

Table 4

Tool-life equation and Taylor's exponent as a function of depths of cut tool material: coated carbides

Depth of cut (mm)	N	C	Tool-life equation
0.25	−0.851	278	$VT^{0.851} = 278$
0.5	−0.864	149	$VT^{0.864} = 149$
0.8	−1.79	341	$VT^{1.79} = 341$

carbide tools. Fig. 7a shows development of flank wear land on the coated carbide insert of grade TK35 when machining Fe_3Al at a constant feed rate (of 0.122 mm/rev) and varying cutting speeds and depths of cut. Limiting flank wear land length of 0.6 mm is taken as the tool failure criterion the test according to ISO 3685E (1977) as mentioned earlier. Fig. 7b is a natural logarithmic plot of tool-life, the time required to reach the tool-life criterion at a given cutting speed and depth of cut versus cutting speed while machining with coated carbide inserts. Coefficients of tool-life equations are also mentioned in the figure as well as Table 4 for various depths of cut. It is observed that the tool-life is greatly influenced by the cutting speed as well as depth of cut. From the Taylor's

Fig. 6. Model of chip formation at higher cutting speed.

Fig. 7. (a–b) Cutting performance of a coated carbide insert while machining Fe_3Al at different speeds and depths of cut.

tool-life equation, the tool-life ‘T’ in minutes is given by the following equation [21]:

$$VT^n = C \quad (1)$$

where V is the cutting speed, n the Taylor’s exponent and C the constant. After rearranging Eq. (1) we get

$$T = \left[\frac{C}{V} \right]^{1/n} \quad (2)$$

It is seen from Eq. (2) that as the value of n increases the exponent of cutting velocity V decreases indicating that the tool-life is less dependent on this variable. It is evident from the present results in Fig. 7b and Table 4 that the magnitudes of Taylor’s exponent are very high (0.8–1.79) as compared

to the steels and cast irons (0.18–0.28). Therefore, it is clear that the accelerated flank wear while machining aluminides may not be due to abrasive wear.

It is known that as the depth of cut increases, the normal pressure on the tool point increases if the thermal conductivity of work material is not sufficient to carry the heat generated during machining, heat concentrates at the tool point leading to the tool failure by accelerated thermal abrasion and plastic deformation. The thermal conductivity of Fe_3Al is very poor and varies from 15 to 17 $\text{W m}^{-1} \text{K}^{-1}$ as temperature changes from 25 to 600 °C [18]. Therefore, most of the heat generated in machining confines to the cutting zone. Especially at higher cutting speeds, this effect being prominent, temperature dependent softening of

Fig. 8. (a–b) Cutting performance of uncoated carbide insert while machining Fe_3Al at different speeds and feed rates.

the tool material may take place causing accelerated flank wear.

The cutting performance of an uncoated carbide tool (grade TTR) at a depth of cut of 0.7 mm and at different feed rates is shown graphically in Fig. 8a and b. The corresponding tool-life equations and their coefficients are given in Table 5. Again, it is observed that an increase in the feed rate has the same effect on the tool-life as that of the increase in depth of cut. At higher feed rate, tool-life appears to be independent of cutting speed. Therefore, the high flank wear rate again may not be due to abrasion alone but due to the combined effect of thermal softening of the tool material and abrasion.

Table 5

Tool-life equation and Taylor's exponent as a function of depths of cut tool material: uncoated carbides

Feed rate (mm/rev)	N	C	Tool-life equation
0.122	-0.447	56.79	$VT^{0.447} = 56.79$
0.199	-0.676	74.1	$VT^{0.676} = 74.1$

4. Concluding remarks

- Interactions at the chip–tool interface dependent upon the cutting speed play a vital role in determining the mechanism of chip formation in aluminide alloys.
- Characteristic features of chip formation mechanism at the lower cutting speed are—inhibition of minor fracture by grain boundaries, formation of triangular-shaped chip segments due to high restraint on the chip–tool interface and gross secondary fracture.
- At higher cutting speed the mechanism of chip formation involves—generation of trapezoid-shaped chip segments due to less restraint at chip–tool interface, alignment grains in the direction of shear and intense secondary shear along the chip inner surface leading to the formation of a white band.
- Very high values of Taylor's exponents indicate that the cutting speed is not a dominant factor influencing tool-life of coated as well as uncoated carbide tools. Therefore, thermal softening of aluminides due to their poor thermal conductivity combined with abrasion could be the main reasons for accelerated flank wear during machining.

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