FABRIC CUTTING APPLICATION OF FeAl-BASED ALLOYS

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ABSTRACT

Four intermetallic-based alloys were evaluated for cutting blade applications. These alloys included Fe₃Al-based (FAS-II and FA-129), FeAl-based (PM-60), and Ni₃Al-based (IC-50). These alloys were of interest because of their much higher work-hardening rates than the conventionally used carbon and stainless steels. The FeAl-based PM-60 alloy was of further interest because of its hardening possibility through retention of vacancies. The vacancy retention treatment is much simpler than the heat treatments used for hardening of steel blades.

Blades of four intermetallic alloys and commercially used M2 tool steel blades were evaluated under identical conditions to cut two-ply heavy paper. Comparative results under identical conditions revealed that the FeAl-based alloy PM-60 outperformed the other intermetallic alloys and was equal to or somewhat better than the commercially used M2 tool steel.

INTRODUCTION

Iron-based alloys are commonly used [1] as cutting edges for all types of cutting applications including fabric and paper. The primary reasons for using carbon steels include: (1) they are heat treatable to high hardness levels, and (2) they are inexpensive materials. However, the heat-treated steel cutting edges lose their performance from the softening that results from the heat generated at the cutting interface. Thus, it is desired to

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examine an alternate cutting blade material that does not derive its cutting properties from heat-treated microstructures. The purpose of this paper is to describe the use of an FeAl alloy for fabric and paper cutting applications. A cutting blade testing facility and the data from the cutting experiments will be presented in comparison to other possible materials and M2 tool steel blades currently used.

BACKGROUND

The intermetallics are attractive as possible cutting edge materials because of their significantly higher work-hardening rates [2] as compared to carbon and stainless steel (Table 1). The data in Table 1 shows that the work-hardening rate of Ni_3Al is four times that of carbon steel. The work-hardening rate normalized for shear stress for FeAl is the highest among all of the intermetallics, and it approaches seven times that of carbon steel.

In addition to the highest work-hardening rate, the FeAl-based intermetallic alloys also show a significant increase in hardness from the retention of constitutional and thermal vacancies. The vacancy-hardening data [3] for FeAl-based intermetallics are shown in Fig. 1. This figure also shows that not only can high hardness be achieved from vacancy hardening, but the treatment to achieve it is reasonably simple. For example, the vacancy hardening in FeAl can be achieved by simply heating the work piece to $\geq 700^\circ\text{C}$ followed by air cooling.

MATERIALS AND CUTTING BLADE PREPARATION

Four different materials were chosen for this study. These included two Fe_3Al -based alloys (FAS-II and FA-129) [ref. 4], one FeAl-based alloy (PM-60) [ref. 5], and a Ni_3Al -based alloy (IC-50)[ref. 6]. Compositions of these alloys along with the commercially used M2 steel blade are given in Table 2. It is to be noted from Table 2 that the M2 steel has essentially the same iron content as Fe_3Al -based alloy FAS-II. However, the alloying content of M2 steel has been replaced by the equivalent amount of aluminum

Table 1. Work-hardening rate^a of polycrystals^b (at axial strain of 0.1)

Material	Work-hardening rate (normalized with respect to the shear modulus, G)	Reference
NiAl	$G/15 - G/38$	Dymek et al. (1992)
FeAl+	$G/7$	Baker and Nagpal (1993)
Zr ₃ Al	$G/10$	Schulson (1984)
Ni ₃ Al	$G/12$	Weihs et al. (1987)
Al ₃ Sc	$G/15$	Schneibel and George (1990)
Al ₆₆ Mn ₆ V ₅ Ti ₂₃	$G/15$	Zhang et al. (1990)
Al ₆₇ Ni ₈ Ti ₂₅	$G/19$	Turner et al. (1989)
Low-carbon steel	$\approx G/50$	U.S. Steel (1964)
301 Stainless steel	$G/40$	Brickner and Defilippi (1977)
Cu, Al, and Ni	$G/30 - G/40$	Feltham and Meakin (1957)
Cu ₃ Au, Ni ₃ Mn, and Ni ₃ Fe	$G/23 - G/38$	Schulson (1984)

^aFor the intermetallics generally obtained from compression tests at room temperature.

^bFurnace cooled after annealing.

plus chromium in FAS-II. All other intermetallics are of quite different composition than the M2 steel.

Each of the intermetallic alloys was prepared as small heats by a different process.

FAS-II

This composition was a water-atomized powder that was produced by Ametek Specialty Metal Products Division (Eighty-Four, Pennsylvania). The powder was hot-extruded in an evacuated carbon steel can at 1100°C to a round bar. The can was removed and the bar was flattened and rolled at 1100°C to a thickness of 6 mm, which was subsequently warm-rolled at 650°C to a final thickness of 1.5 mm. Optical microstructure of this sheet [Fig. 2(a)] showed coarse grain microstructure with elongated Al₂O₃ particles. The Al₂O₃ particles came from the water atomization process.

Fig. 1. The hardness of FeAl versus the square root of the constitutional and thermal vacancy concentration. Each data point was measured at room temperature after different quenching temperatures. Aluminum concentrations are in atomic percent [3].

FA-129

This composition is a cast alloy. An air-melted ingot of 76 mm diam was hot-extruded at 1100°C to a sheet bar of 19 mm thickness. The sheet bar was hot-extruded at 1100°C to a thickness of 6 mm and warm-rolled to a final thickness of 1.5 mm. Being a cast and rolled sheet, this sheet microstructure showed large grain size (125 μm) with a few particles of niobium carbides [Fig. 2(b)].

PM-60

This FeAl-based alloy was also a cast and processed alloy. A 76-mm-diam air-melted ingot was canned in a mild steel can and hot-extruded into a 19-mm-thick sheet bar

Table 2. Chemical compositions of intermetallic blades and
M2 tool steel blade used commercially

Element	Alloy, weight percent				
	FAS-II	FA-129	PM-60	IC-50	M2
Mn	--	--	--	--	0.35
Fe	81.87	77.66	73.45	--	80.09
Al	15.9	15.90	26.0	11.3	--
Cr	2.20	5.50	--	--	4.00
Mo	--	--	0.42	--	5.16
Nb	--	1.0	--	--	--
Zr	--	--	0.1	0.6	--
C	--	0.05	0.03	--	0.86
B	0.01	--	--	0.02	--
O	0.25	--	--	--	--
N	0.004	--	--	--	--
Ni	--	--	--	88.08	0.20
Si	--	--	--	--	0.36
W	--	--	--	--	6.53
V	--	--	--	--	2.09
Co	--	--	--	--	0.36

at 1100°C. The sheet bar with the carbon steel can was hot-rolled at 1000°C to a thickness of 6 mm, which was finished rolled at 800°C to a final thickness of 1.5 mm. The thin carbon steel can oxidized during the heating cycles of the hot-rolling process. This sheet showed a very large grain microstructure [Fig. 2(c)].

IC-50

This alloy was prepared at Allegheny Ludlum Corporation (Brackenridge, Pennsylvania) by a direct sheet casting process. In this process, the alloy sheet was directly cast from liquid melt by overflowing the melt over a rotating wheel. Since the cast thickness was of near-net thickness, it was used in the as-cast condition. The alloy is single phase with large grain size and shows the cast dendritic features [Fig. 2(c)].

Fig. 2. Microstructure of blade materials: (a) FAS-II, (b) FA-129, (c) IC-50, (d) PM-60, and (e) M2 tool steel.

M2 Tool Steel

This is a commercially produced steel with a very fine grain microstructure [Fig. 2(e)] The microstructure is fully martensitic with spheroidal particles dispersed throughout.

The blade shape used (Fig. 3) for the Eastman cutting machine [7] was electrodischarge machine cut from the sheets of each of the four intermetallic alloys. The blade blanks were flattened at 1000°C between Inconel platens prior to machining the cutting edge. Four blades were fabricated from each of the alloys. The microhardness of the flat section of the four intermetallic alloy blades and that of the M2 tool steel are compared in Table 3. All of the intermetallic alloys showed similar but less than half the hardness of the M2 tool steel blade. The larger scatter in data for the M2 tool steel is probably a result of whether the spheroidal carbide was included or not in the indented area.

BLADE TESTING FACILITY AND TEST PROCEDURES

A blade testing facility shown in Fig. 4 was built at the Oak Ridge National Laboratory (ORNL) to test the blades in a consistent manner. The test facility consisted of a cutter acceleration apparatus, a base track assembly, and a cutting track assembly.

The blades cutting performance was evaluated for cutting denim fabric and thick paper. Before testing, each blade was sharpened with a new Eastman medium grit belt (this sharpening feature is built in the Eastman cutter). Before each cutting experiment, the Eastman machine was pulled by a 2.27-kg (5-lb) drop weight to move it along the track without any fabric. The purpose of this step was to calibrate the system as well as to evaluate the friction between the cutting machine and the track. In all cases, it took 1.95 to 2.05 s for the machine to travel a distance of 1.5 m (5 ft).

Fig. 3. Eastman cutting blade.

Table 3. Microhardness data of the flat and cutting edge section locations of various blades used in this study

Alloy designation of blade	Microhardness (dph) ^a	
	Flat location away cutting edge	Cutting edge ^b
M2 tool steel ^c	736 ± 51	829 ± 38
FAS-II	326 ± 9	315 ± 15
FA-129	305 ± 18	315 ± 8
PM-60	320 ± 5	387 ± 19
IC-50	316 ± 7	341 ± 12

^a100-g load.

^bAfter testing.

^cEastman blade.

RESULTS AND DISCUSSIONS

Test results on the blades of three alloys (FAS-II, PM-60, and IC-50) are compared in Fig. 5. These results were developed by cutting two-ply heavy-duty paper with a constant load of 1.59 kg (3.5 lb) over a distance of 1.5 m per cut. Ten runs were made for each blade. The cutting time for each blade is plotted as a function of the number of runs (Fig. 5). The data show that for the initial pass, the cutting time for each blade was

Fig. 4. View of the blade testing facility at the Oak Ridge National Laboratory.

Fig. 5. Comparison of relative performance of FAS-II, PM-60, and IC-50.

equivalent. However, upon subsequent passes, the performance of the PM-60 blade was superior to the other blades produced from the other material (i.e., cutting time was faster).

In the next experiment, all four of the alloys were compared with a commercial M2 tool steel Eastman blade (Fig. 6). These tests were run using a 2.72-kg (6-lb) force as opposed to 1.59 kg (3.5 lb) in Fig. 5.

Fig. 6. Comparison of aluminide blade with the M2 Eastman blade under identical conditions.

The results in Fig. 6 again show that PM-60 is the best performer of all the intermetallic alloys that were tested in this study and is equal to or even better than the commercial M2 tool steel Eastman blade.

The blades, after the cutting data described in Fig. 6, were sectioned for microhardness and microstructure of the cutting edge. The microhardness (Table 3) of the cutting edge of M2 tool steel increased by nearly 13% from its sheet hardness. In comparison, the hardness of PM-60 increased by nearly 21%. The other three alloys (FAS-II, FA-129, and IC-50) showed only minor changes. It is not quite clear if the

increase in hardness of the cutting edge is a result of work hardening from the sharpening process or from the paper cutting process. This can be determined by measuring the hardness of the blades after sharpening but before testing. However, at this time, this information is not available. Photomicrographs of the cutting edges of all five blades are shown in Fig. 7. Comparison of the cutting edge with sheet microstructure (Fig. 7 versus Fig. 2) showed no observable differences in any of the materials after ten cuts.

It is well known that the frictional forces result in temperature rise of several hundred degrees at the cutting edge. While frictional forces can increase the cutting edge temperature, the cutting forces (acting on a small area of the cutting edge) can deform the cutting edge. The deformation from the cutting forces will increase the cutting edge surface (from edge flattening) and, thus, require increased cutting forces and thereby decrease the cutting velocity. In the case of temperature rise, the microstructure with starting high hardness through the hardening process can overtemper and soften to a point where it can deform from the cutting forces. The increased temperature at the cutting edge can also lower the alloy flow stress and, thus, increase deformation for the same cutting forces. Thus, the combined effect of increased temperature, which causes a decrease in flow stress, and edge deformation from the cutting forces, which increases the cutting edge area and requires even high cutting forces, continue to dull the cutting edge and increase its time of cutting for the cutting length and the applied force.

It is believed that in the case of FAS-II and IC-50, their lower hardness caused their rapid dulling (Fig. 5) through the deformation process from the cutting forces. However, once deformed, the cutting forces increased as reflected by a significant increase in cutting time for the same distance, but no further increase in time was observed from cut No. 2 to No. 10. Such a behavior reflects that the work-hardened cutting edges of FAS-II and IC-50 may also perform well. The exceptional behavior of PM-60 is believed to result from the fact that it increased its hardness through a combination of two mechanisms. First, work hardening (note it has the highest work-hardening rate, Table 1) from the edge

Fig. 7. Microstructure of the cutting edges after ten cut runs for: (a) FAS-II, (b) FA-129, (c) PM-60, (d) IC-50, and (e) M2 steel.

deformation by the cutting forces. Second, the increase in the cutting edge temperature followed by in-situ air cooling prior to the subsequent cut resulted in vacancy hardening. It is postulated that a combination of the two mechanisms, but preferably the vacancy hardening during each cut is the reason for essentially no change in cutting time of PM-60 blade (Fig. 5).

When the tests were run with higher pulling force (nearly double for data in Fig. 6 versus data in Fig. 5), the cutting resistance increased with a significant increase in cutting time for the first cut. The competing mechanisms of hardening through blade deformation from cutting forces and softening through frictional heat (with the exception of PM-60), for different alloys being different results in the scatter observed in Fig. 6. Once again, PM-60, which hardens from both deformation and heating (vacancy hardening) has shown lowest cutting time. Furthermore, the cutting time appears to have stabilized after the eighth cut. These results, along with the proposed idea, suggest that the PM-60 blade has the strong potential of maintaining its cutting edge for long periods of cutting without dulling. Over a period of time, the M2 tool steel, which is extremely hard to start with, will soften from the martensite tempering by the frictional heat of the cutting process without work hardening (because of its low work-hardening rate, Table 1) and will result in blade dulling.

Since the temperature of the cutting edge increases from the frictional forces of cutting, the strength and hardness at temperature may also be an important consideration in comparing the performance of different materials.

SUMMARY AND CONCLUSIONS

Four intermetallic-based alloys were evaluated for cutting blade applications. These alloys included Fe₃Al-based (FAS-II and FA-129), FeAl-based (PM-60), and Ni₃Al-based (IC-50). These alloys were of interest because of their much higher work-hardening rates than the conventionally used carbon and stainless steels. The FeAl-based PM-60 alloy was of further interest because of its hardening possibility through retention of vacancies. The

vacancy retention treatment is much simpler than the heat treatments used for hardening of the M2 tool steel blades.

Blades of intermetallic alloys were tested for their comparative performance by using a commercially used fabric cutter known as a Eastman cutting machine. A blade testing facility was designed and built at ORNL for using the Eastman cutting machine for cutting trials. All of the blades were the same configuration and were sharpened to the same level by the same process. Cutting efficiency was tested by measuring the time to cut through two-ply heavy paper over a distance of 1.5 m per cut. The change in cutting time with the number of cuts was measured and compared between the intermetallic alloys and with the commercially used M2 tool steel blades. The following conclusions are possible:

1. The cutting time for the PM-60 alloy blade was the least and remained unaffected with the increased number of cuts. However, for the Fe_3Al - and Ni_3Al -based alloys, the cutting time increased rapidly after the first cut.
2. The comparative testing of intermetallic blades with the commercially used M2 tool steel blade showed PM-60 to be equal to or somewhat better than the M2 tool steel blade.
3. The competing mechanisms of deformation from cutting forces and the softening through heat of the cutting process are considered responsible for cutting edge dulling in most materials. The unaffected cutting time of PM-60 with the number of cutting passes for the low cutting speeds is believed to result from vacancy hardening from the heat of cutting followed by air cooling during each pass. Under high cutting speeds, PM-60 can harden by even small deformation from the cutting forces (because of its very high work-hardening rate) and from vacancy hardening. Thus, PM-60 has a potential of cutting for long periods of time without dulling.

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REFERENCES

1. *Metals Handbook, Properties and Selection: Irons, Steels, and High-Performance Alloys*, 1, Tenth Edition (Materials Park, OH: ASM International, 1990) p. 757.
2. E. M. Shulson, *Physical Metallurgy and processing of Intermetallic Compounds*, eds., N. S. Stoloff and V. K. Sikka (New York: Chapman & Hall, 1996), p. 56.
3. Y. A. Chang, L. M. Pike, C. T. Liu, A. R. Bilbrey, and D. S. Stone, *Intermetallics*, 1 (1993) 107.
4. V. K. Sikka, *SAMPE Quart.*, 22 (1991) 2.
5. M. R. Hajaligol, "Polymer Atomization of Iron Aluminide," for publication in *Proc. International Symposium on Iron Aluminides: Alloy Design, Processing, Properties & Applications*, San Antonio, TX, February 16-19, 1998.
6. V. K. Sikka, "Oxidation and Corrosion of Intermetallic Alloys," *Intermetallics for Structural Applications*, eds. G. Welsch and P. D. Desai (West Lafayette, IN: CINDAS, Purdue University, 1996), p. 1.
7. Eastman Blue Streak II, Model 629, Eastman Company, 779 Washington St., Buffalo, NY 14203, U.S.A.