Fabrication of 13Cr Stainless Steel Blade Material with Hardness Gradient Using Cladding and Diffusion of Al

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Materials for cutting blades such as for electric razor blades are required to be soft enough for being fabricated into a delicate shape, and after the shaping, to have a sufficient hardness which enables a hard and sharp edge. In order to develop a material that meets these requirements, a new method was explored and succeeded. This method consists of cladding of Fe-13Cr-1.3Mo-0.4C (mass%) martensitic stainless steel with Al, followed by heat-treatment to diffuse the Al into the steel. By choosing an appropriate heat-treatment condition, it is possible to form a layer of Al_2Fe on the surface and a layer of FeAl beneath. In this way, a material with an excellent surface hardness (H_v -11.8 GPa) is obtained. The hardness gradually decreases towards inside as Al concentration decreases reaching the hardness of base material (H_v -5 GPa) at the depth of 10 μm from the surface.

This material is soft enough to be punched into a delicate shape in the as-rolled state. When applied as an electric razor blade, the new material enables a sharp edge and thus the cutting resistance becomes 2/3 of that made of the conventional martensitic stainless steel.

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I. Introduction

The important requirements of cutting tools include: (1) A rigid and sharp blade; and (2) A blade edge that does not chip or break. Accordingly, materials used for blades require a hard surface and a rigid and tough base. Currently, most of the blades are made of hardened and finished steel and their edges are induction-hardened⁽¹⁾⁽²⁾, or clad with martensitic 13Cr stainless steel⁽³⁾⁽⁴⁾. However, induction hardening is difficult to apply to blades of a complicated shape, and 13Cr stainless steel, due to insufficient hardness, cannot ensure a sharp edge. Accordingly, these procedures are inappropriate for producing blades that are delicate in shape and also require sharp edges, such as those in an electric razor.

As a blade material, we previously developed an FeCrNiAl alloy that ensures surface hardness of 19.6 GPa in Vickers hardness (H_v) by forming an alumina layer on its surface and also ensures base material hardness of 4.4 GPa by dispersion of B2-structure particles⁽⁵⁾⁽⁶⁾. However, this material has several drawbacks, such as low processability and unsuitability for mass production.

Accordingly, we explored for other materials of an excellent surface hardness and still suitable for mass production. As a result we have succeeded in developing a new blade material by the following clad and diffusion method. Foils of martensitic 13Cr stainless steel are clad with Al foils and heat-treated to diffuse Al into the stainless steel and thus to form a hard layer of FeAl intermetallic compounds on the surface. Thus-obtained

material has a sufficiently hard surface, and the hardness gradually decreases towards the inner portion while toughness increases. This newly-developed gradient-hardness material enables a sharp edge of less than 1 μm in its radius of curvature, and thus shows a high cutting performance. Among a number of fabrication methods for gradient hardness material explored in the past⁽⁷⁾⁻⁽¹¹⁾, the present method is new and unique. This paper describes the procedure of the new method, microstructures and properties of the obtained material and its cutting performance.

II. Experiment Procedures

1. Sample preparation

First, 0.22 mm thick martensite stainless steel (Fe-13Cr-1.2Mo-0.4C) was annealed at 1023 K for 300 s in Ar atmosphere, and then, on both sides of the stainless steel, 9 μm thick Al foils were clad by cold-rolling, producing 0.2 mm thick three-layer sheets. Before Al was clad, the surface of the stainless steel was subjected to rough surface treatment using a metal brush.

2. Heat treatment for Al diffusion

For Al diffusion, samples were heat-treated by holding for 60 s at temperatures between 1173 to 1323 K, using an electric furnace.

3. Measurement and observation

An X-ray diffractometer (RIGAKU ELECTRIC CO.,

ROTA-FLEX, RAD-rA) was used to identify phases formed by Al-diffusion treatment in the samples, and an X-ray micro-analyzer (EPMA, JEOL, JXA-733) was used to analyze elements in the Al-diffused layer. The cross-section of each sample sheet was polished by emery paper, and then by diamond paste. The hardness of the cross-section was measured by ultra fine micro-Vickers hardness tester (AKASHI, MVK-G3).

A transmission electron microscope (TEM, HITACHI, HU-800 (200 kV)), was used to identify intermetallic compounds formed in the vicinity of the surface. Samples for TEM observation were prepared as follows. First, from the sample sheet, a 10 μm thick and 0.2 mm wide piece perpendicular to the sheet surface was cut by using a cutter (DISCO, DAC-2PH). Next, using a focused ion beam (FIB), the thickness of the sample piece was reduced from 10 μm to less than 0.2 μm from the surface to a depth of 10 μm .

4. Edge performance evaluation

Figure 1 illustrates schematically the outer and inner blades of an electric razor. Edge performance was evaluated by measuring load exerted on the movable inner blade when the movable inner and fixed outer blades cut artificial beards made of nylon fibers 0.15 mm in diameter. Cutting resistance means the load required when the inner blade edge cut an artificial beard placed in the hole of the outer blade. The cutting resistance was measured using a load cell.

III. Results and Discussion

The clad foils of 13Cr stainless steel and Al were held at temperatures ranging from 1173 to 1323 K for 60 s in air for Al diffusion and then air-cooled (cooling rate: 100 K/s). These Al-diffused 13Cr stainless steel foils were examined for the relationship between heat-treatment temperature and hardness, both for the surface portion and the base material. Figure 2 shows the observation results. The hardness (Vickers hardness) was measured from the direction perpendicular to the cross-section. The surface hardness increases as the heat-treatment temperature increases and reaches maximum with the temperature of 1248 K. The base-material (the martensitic 13Cr stainless

Fig. 1 Schematic illustration of the apparatus for measuring cutting-resistance of electric razor.

Fig. 2 Surface hardness and base material hardness plotted against heat-treatment temperature (held for 60 s at each temperature).

steel) hardness is around 5 GPa for the holding temperature of 1223 K, and it becomes slightly higher for higher holding temperatures ranging from 1173 to 1323 K. The observation shows that, for holding time of 60 s, temperature between 1223 K and 1248 K are appropriate for sufficient surface and base material hardness (H_v) of 5 GPa to be attained.

It is known that the martensitic 13Cr stainless steel, in the annealed condition (held at 1023 K for 3600 s and air cooled), includes carbide, $(\text{Cr, Fe})_{23}\text{C}_6$, dispersed in the α phase, and it shows a hardness (H_v) of around 2 GPa. When heated to 1323 K, the α phase transforms to γ phase and the dispersed fine carbide particles are absorbed into the γ phase. By subsequent fast cooling (such as air-cooling), the γ phase transforms to the martensite phase with a hardness of around 6 GPa⁽¹²⁾. However, in the above heat-treatment for Al diffusion of the present work, carbide absorption is not sufficient since 60 s is too short; accordingly, hardness is rather low ($H_v=4.9$ to 5.3 GPa) and the hardness tends to increase as the heat-treatment temperature increases.

To examine the thickness of the hardened layer of surface and distribution of hardness there, we measured hardness of cross-section of a sample held at 1248 K for 60 s. Figure 3 shows the relationship between distance from the surface and hardness. Between the surface and the depth of 6 μm , the hardness is 11.3 GPa. This 6 μm of the hardened layer is thicker than that obtained by PVD- or CVD-coating method⁽¹³⁾, indicating superiority of the clad-and-diffusion method for fabrication of blade materials. As the depth exceeds 6 μm , hardness gradually decreases and at around the depth of 20 μm , hardness becomes identical to that of the base material. By virtue of the gradual hardness change, hardened layer securely adheres to, and does not peel off from the base material.

EPMA analysis was made on the cross-section of an Al-diffused 13Cr stainless steel foil, to the direction of

depth from the surface for elements in the hardened layer. The result is shown in Fig. 4. It is seen that Al concentration, which is 73 at% at the surface, almost linearly decreases as depth increases, and at the depth of 20 μm ,

Fig. 3 Relation between Vickers hardness and depth from the surface for after 1248 K, 60 s heat-treatment.

Fig. 4 Relation between element concentration and depth from the surface for after 1248 K, 60 s heat-treatment.

it becomes identical to that of the base material. On the contrary, Fe concentration, which is 22 at% at the surface, increases as depth increases and at the depth of 20 μm it reaches 85 at%, which is identical to that of the base material. Cr concentration is lower than that of the base material between the surface and the depth of 10 μm .

To examine surface products formed after 60 s of holding at 1223 K, X-ray diffraction was made. Figure 5 shows the diffraction chart obtained. Peaks, probably due to three intermetallic compounds, FeAl_2 , FeAl and Fe_3Al , are observed, although some of the peaks overlap.

For a further examination of the structural change in the surface layer, specimens 0.2 mm in width were cut vertically from the surface and they were thinned to the depth of 10 μm by focused ion beam (FIB) processing⁽¹⁴⁾. On these specimens, TEM observation was made. Figure 6(a) is the bright field image of the area between the surface and the depth of 7 μm , and Fig. 6(b) is its schematic illustration, in which the observed grains in the area are labeled as (A), (B), (C), (D), (E), (F), (G), (H) and (I). By electron diffraction, it was revealed that the grains (A)-(E) are of FeAl_2 and the grains (F)-(I) are of FeAl . In Fig. 6(c) are shown the diffraction patterns from the grains (A), (C), (F) and (G), where the labels correspond to those of Fig. 6(b). It is seen that the pattern of (A) is indexed as that of the $[12\bar{3}]$ zone of FeAl_2 . Similarly (C) is the $[10\bar{3}]$ zone of FeAl_2 , (F) is the $[001]$ zone of FeAl and (G) is the $[12\bar{3}]$ zone of FeAl .

The findings that the layer between the surface and the depth of 2 μm is composed of FeAl_2 grains and that the portion deeper than 2 μm is composed of FeAl grains agree well with the results of the EPMA analysis shown in Fig. 4 that Al concentration is around 68 at% at the depth of 2 μm and is around 50 at% at the depth of 5 μm . Although the deeper portions could not be observed, the Al concentration of 30 at% at the depth of 10 μm as seen in Fig. 4 suggests that Fe_3Al phase exists there. Figure 7 illustrates schematically the layer-structure obtained by cladding and diffusion of Al.

Al and Fe atoms should diffuse mutually to form the intermetallic compounds. Using the data of D_0 and Q available⁽¹⁵⁾, diffusion coefficient of Al in Fe and that of Fe in Al at 1223 K are calculated to be $1.6 \times 10^{-14} \text{ m}^2/\text{s}$ and $2.06 \times 10^{-11} \text{ m}^2/\text{s}$, respectively. These values show that

Fig. 5 X-ray diffraction pattern of a clad alloy held at 1223 K for 60 s.

Fig. 6 (a) Electron micrograph of the cross-section of near surface of the clad held at 1223 K for 60 s. (b) Schematic illustration of the micrograph (a). (c) Diffraction patterns from the (A), (C), (F) and (G) in Fig. 6(b). (A) [123] of FeAl_2 (C) [103] of FeAl_2 (F) [001] of FeAl (G) [123] of FeAl

Fig. 7 Schematic illustration of layer structure obtained.

Fe atoms diffuse into the Al layer is much faster than Al atoms diffuse into the matrix, and that actually the intermetallic compounds FeAl_2 , FeAl , and Fe_3Al are formed by the 1223 K–60 s heat-treatment mainly as a result of diffusion of Fe atoms into the 9 μm thick Al layer. Meanwhile, Al atoms diffuse into the matrix to a depth of 20 μm from the surface.

Edge performance was evaluated by measuring cutting resistance using a tester introduced to the inner blade of an electric razor. As described in Experimental Procedures, the load, required when inner and outer blade edges cut an artificial beard, is regarded as cutting

Fig. 8 Cutting-load on blade material plotted against edge angle of the inner blade.

resistance. Figure 8 shows cutting resistance measured by a load cell. Though the cutting resistance also depends on the edge angle, the cutting resistance of the blade made of the newly-developed material is 35% lower than that made of the martensitic 13Cr stainless-steel only, regardless of edge angle.

Figure 9 shows the results of optical microscope obser-

Fig. 9 Edge-shape of the sliding surface after grinding. (a) Al-cladded stainless steel heat-treated at 1223 K for 60 s (the edge is sharp). (b) Conventional stainless steel only (many abrasive leavings are left).

vation made on the edges to make clear the reason of the difference in performance. The photographs show the sliding-surfaces of inner blades. (a) is of the newly-developed present material, and (b) is of the martensitic 13Cr stainless steel only. The upper flat portion is the sliding-surface that comes in contact with the outer blade. The eaves-like protrusion observed at the edge of the martensitic stainless steel blade is formed during grinding of the blade surface due to the insufficient hardness of the material (*i.e.* $Hv=5.4$ GPa), and hinder the edges from becoming sharper, thus increasing cutting resistance.

In contrast, the blade of the newly-developed gradient-hardness material has sufficiently high surface hardness ($Hv=9.8$ GPa), and no eaves-like protrusion remains; accordingly, the edge is sharper, leading to lower cutting resistance. Thus, high surface hardness ensures edge sharpness, enhancing cutting performance.

IV. Conclusion

A gradient-hardness material for the blade application was developed by the clad-and-diffusion method. In this method, Al foils are cladded to both sides of a Fe-13Cr-1.2Mo-0.4C martensitic stainless steel sheet, and Al is diffused into the stainless steel by heat-treatment, which forms FeAl intermetallic compounds near the surface. The optimum heat-treatment condition was found to be holding for 60 s at 1248 K. The microstructures and the properties of thus obtained material are as follows:

(1) Al concentration gradually decreases in the portion between the surface and the depth of approximately 10 μm. The upper most layer between the surface and the depth of 2 μm consists of $FeAl_2$ and the next layer between 2 μm and 10 μm in depth consists of FeAl. The FeAl changes to Fe_3Al around the depth of 10 μm. Below the depth of more than 20 μm, Al concentration becomes identical to that of the base material.

(2) The surface hardness is 11.8 GPa and decreases gradually towards the base material hardness of 5 GPa.

(3) A blade made of this gradient-hardness material shows an excellent performance as an electric razor inner blade. Because of the excellent surface hardness no protrusion remains at the edge after grinding, thus leading to a sharp edge. The cutting resistance of an electric razor blade made of this material is 2/3 of that made of the conventional stainless-steel.

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