DIFFUSION COUPLE BETWEEN HIGH-STRENGTH WEAR-RESISTING ALUMINUM BRONZE AND MACHINING TOOLS MATERIALS①

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ABSTRACT Diffusion couples of tool materials (prepared from commercially available high speed steel and YW1 carbide tools) and the wear-resisting aluminum bronze (KK) were prepared by casting to study the diffusion pattern and phase formation sequence in order to clarify the diffusion wear of the tools during the turning of the wear-resisting aluminum bronze. Optical micrographs show that good contact was obtained at the tool material-KK interface. After annealed at 900 ℃ for 6 h, strong inter-diffusion across the interface was observed. Microprobe analysis was used to study the elemental distribution across the interface and X-ray diffractometry was used to study the phases formed at the interface.

Key words wear resistance aluminum bronze tool materials diffusion

1 INTRODUCTION

Aluminum bronze is an important engineering material. Its excellent physical, mechanical, anti-corrosion and wear-resisting properties make it become one of the most versatile engineering materials that work under a high stress. Our research group developed a special type of high strength, wear-resisting bronze (KK). Compared to the traditional commercial aluminum bronze, it has better mechanical properties such as tensile strength and impact toughness, and tribological behaviors[1-4]. In the past few years, KK enjoys a great success in engineering parts industry and finds wide applications in elevator, machine manufacturing and metallurgical industries. However, unlike the traditional bronze, when machining KK parts, a higher cutting force must be used and thus the temperature involved during machining is very high, thus lowering the service life of the machining tools. In order to make the manufacturing of the KK engineering parts more efficient, a study of the wear mechanism of the cutting tools was carried out by our group.

Diffusion is one of the most significant phenomena that can be found during the machining process. It not only affects wear mechanism and the service life of the machining tools, but also affects the surface quality of the finished work pieces, especially in the high speed machining. During the high speed machining, the tremendous cutting force causes serious plastic deformation and results in an intimate contact between the tool and the work piece. Meanwhile a large amount of energy will be dissipated on a small area near the rake and frank surface of the cutting tool and thus that particular area will be raised to a very high temperature. This high temperature will accelerate the interdiffusion between the tool and the work piece, therefore diffusion wear is one of the major tool wear mechanism during high speed machining[5]. It is not easy to directly study the effect of diffusion on the actual contacting interface between the tool and the work piece since the work piece materi-

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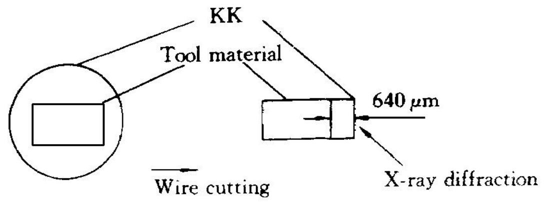

Fig.1 Schematic diagram showing fabrication of X-ray diffraction sample

3 RESULTS AND DISCUSSION

3.1 Microstructure

The polished sample surface was etched by 5 g $FeCl_3$ + 5 mL HCl + 1 g CrO_3 + 100 mL H_2O, which is sensitive to KK only and will not reveal the microstructure of either HSS or YW1. Figs. 2(a) and 2(b) present the optical micrographs of HSS + KK and YW1 + KK diffusion couples, respectively. The contact interface is clean and tight. At the HSS + KK interface a transition layer is found, which indicates that a new phase has been formed (details concerning this new phase will be discussed in another paper), but there is no such layer can be observed in Fig.2(b). Actually, nothing special can be seen visually from Fig.2(b). The microstructure of KK is composed of α (bright phase), β (dark phase), κ (small particles). The HSS used in this study is composed of martensites, carbides and maybe some residual austenite. The carbide contents near the interface are obviously less than those in the rest of the HSS body. At 900 ℃, some of the carbides become less stable and decompose into carbon and metals. The high contents of these unreacted elements enhance the diffusion driving force. The carbon diffuses into KK and reacts with Al to form Al_4C_3, so there is a relatively high carbon content at the interface, as shown in Fig.3, and less carbide content near the boundary of the HSS side. Table 2 lists the free energies of formation for some carbides at room temperature and 1 500 K[4,5]. It is thus clear that Al_4C_3 is a stable carbide when compared with carbides of tungsten, molybdenum and iron.

Table 2 Free energies of formation for some carbides at room temperature and 1 500 K[6,7]

Carbide	$-\Delta G_f$(298 K) / (kJ·mol^{-1})	$-\Delta G_f$(1500 K) / (kJ·mol^{-1})
Al_4C_3	203.6	153.3
Cr_7C_3	223.4	254.3
Fe_3C	-19.0	4.9
Mo_2C	23.5	-
TaC	142.2	137.8
TiC	180.0	167.1
WC	37.3	34.8
W_2C	24.5	-

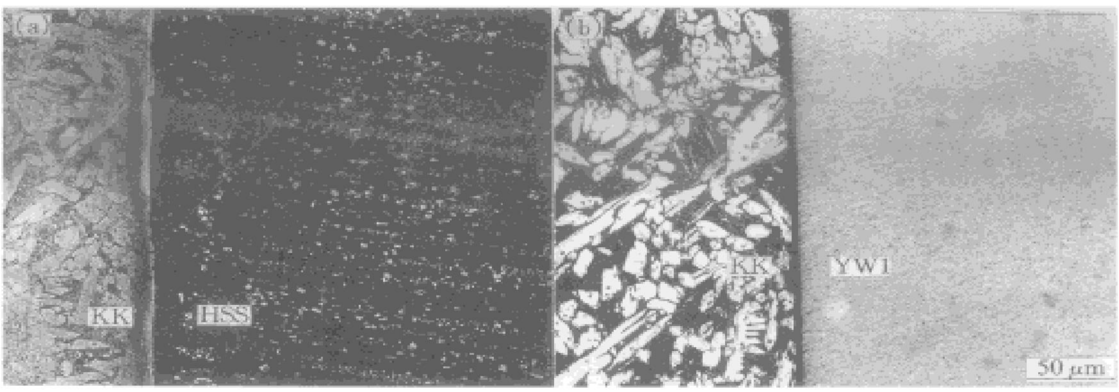

Fig.2 Optical micrographs of diffusion couples
(a) —HSS + KK; (b) —YW1 + KK

Table 3 Typical chemical compositions of tool materials and KK near interface(%)

Position	Al	Cu	Fe	W	Co	Ti	Ta	C
KK Side	9.66	82.91	2.00	0.24	0.15	0.00	0.62	4.42
YW1 Side	0.29	2.91	0.26	80.72	1.05	5.70	4.16	4.91

The microprobe used in this study is not good enough for quantitative analysis of C, therefore the C content mentioned here is for reference only.

mainly due to the presence of Al which destabilizes the carbides near the interface and there is a strong tendency of the formation of aluminum carbide, thus enhancing the driving force for the diffusion of C. Nevertheless, the activation energy for the C diffusion is very low compared to those of metal atoms since during diffusion process C atoms occupy interstitial sites[8], while other metallic elements take up vacancies.

3.3 X-ray diffraction analysis

Results for the X-ray diffraction analysis of HSS + KK and YW1 + KK diffusion couples are listed in Tables 4 and 5, respectively. As we can see from these tables, Al_4C_3 are present near the contact interface in both of the HSS + KK and YW1 + KK diffusion couples, thus confirming the argument we made earlier that aluminum carbide has been formed at the interface. In addition, Al_9Co_2 can be seen at the interface of YW1 + KK diffusion couple also. This can explain the relatively high concentrations of C and Co and the two small Al peaks near the boundary (Fig. 4). Tables 4 and 5 also tell us that Al_7Cu_2Fe is always present, since the KK aluminum bronze contains 3 % to 5 % Fe, we cannot tell whether this phase is a product of diffusion or it is from bronze itself. Anyway, the Al plateau found in Fig.4 is probably an exhibition of this Al_7Cu_2Fe phase or other high Al content phases such as Al_4C_3. This is possible because the C content in that region shows two small peaks also.

Table 4 X-ray diffraction analysis near interface of HSS + KK diffusion couple

Position	Depth of KK layer/ μm	Phases
1	640	α-Cu, γ_2, Al_7Cu_2Fe
2	224	α-Cu, γ_2, Al_7Cu_2Fe, $Al_4C_3^*$
3	60	α-Cu, γ_2, Al_7Cu_2Fe
4	20	α-Cu, γ_2, α-Fe
5	0	α-Fe, WC, Al_7Cu_2Fe, $AlCu_3$

1) γ_2 is a solid solution of $AlCu_3$;
2) * only 3 ~ 4 major peaks match.

Table 5 X-ray diffraction analysis near interface of YW1 + KK diffusion couple

Position	Depth of KK layer/ μm	Phases
1	640	α-Cu, γ_2, Al_7Cu_2Fe
2	228	α-Cu, γ_2, Al_7Cu_2Fe
3	100	α-Cu, WC, $Al_9Co_2^*$, $Al_4C_3^*$, γ_2
4	25	α-Cu, Al_9Co_2, Al_7Cu_2Fe, γ_2
5	0	WC, Co, TaC, α-Cu*

1) γ_2 is a solid solution of $AlCu_3$;
2) * only 3 ~ 4 major peaks match.

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als continuously flow away from the tool surface and thus the contacting time between them is relatively short, the effect of diffusion may not be significant enough to be detected and analyzed. Diffusion couples of KK and tool materials (M2 high speed steel, and YW1 carbide tool materials) was prepared to exaggerate the inter-diffusion and phase formation during the actual cutting. By choosing suitable annealing temperature and annealing time, it is possible to obtain the diffusion pattern and phase formation sequence that occurs at the contacting interface. Thermodynamically, this diffusion couple experiment is an exaggeration of the actual machining interface; it is meaningful to compare these results. One major difference between the actual machining process and the diffusion couple experiment is that during the actual machining there is an infinite supply of fresh work piece materials due to the continuous flow of work piece material to the surface of the tool materials but it is not the case for the diffusion couple experiment. Besides, the tremendous pressure exerted on the actual machining interface is much larger than those experienced at the diffusion couple interface.

2 EXPERIMENTAL METHODS

2.1 Experimental materials

Two of the most common turning tools were chosen for carrying out the experiment. They are commercially available and ready to use M2 high speed steel (HSS) and YW1 carbide tools. The work piece is the KK aluminum bronze. The chemical compositions of these materials are listed in Table 1.

2.2 Experimental method

A casting method was used to prepare the diffusion couples. Tool materials were cut into 6 mm × 6 mm × 4 mm pieces. After they were polished and degreased they were cleaned with acetone and methyl alcohol. Then each of these pieces was fixed in a cylindrical metal mold (inner diameter 30 mm × 60 mm in length) and ready for the casting. The cast cylindrical samples were then machined to d 15 mm × 20 mm and annealed at 900 ℃ in a sealed, evacuated capsule for 6 h. The annealed samples were quickly air cooled to room temperature to avoid any further inter-diffusion. The microstructure was examined by optical microscope. Contact interface was examined by scanning electron microscope (SEM). Electron microprobe analysis (EMPA) with energy dispersive spectroscopy and wave-length dispersive spectroscopy (EDS and WDS) was used in chemical analysis.

For the preparation of the X-ray analysis samples, in addition to the above steps, part of the annealed samples were carefully cut through the KK materials by spark machining. Care must be taken during the spark machining to preserve the interface between the KK and the tool materials, and make sure that the KK layer has a thickness of approximately 600 ~ 700 μm, as shown in Fig.1. Alcohol was used to clean the ground surface and couple drops of KK etching agent were used to release the residual stress caused by grinding. X-ray diffractometer was employed to analyze the sample at the KK surface parallel to the contact interface. After the first X-ray analysis, the samples were then ground to remove some of the KK materials so as to reduce the KK thickness to less than 600 μm. The thickness of this KK layer was then measured by a micro-meter and now the sample is ready for X-ray analysis again. Repeated this procedure for 5 times until the last X-ray analysis reached the vicinity of the contact interface.

Table 1 Chemical compositions of diffusion couple materials (%)

Material	Al	Cu	Ni	Mn	Fe	Mo	Cr	V	W	C	Co	WC	TiC	TaC
KK	~10	~82	~2	~2	~4	-	-	-	-	-	-	-	-	-
HSS	-	-	-	-	~82	~5	~4	~2	~6	~0.8	-	-	-	-
YW1	-	-	-	-	-	-	-	-	-	-	6	84	6	4

3.2 Microprobe analysis

Fig.3 shows the line scanning of Al, Cu, Fe, W and C elements near the interface of HSS + KK diffusion couple. Relatively high C concentration is observed at the interface. The C concentration at the boundary is even higher than that in the core of HSS. It is quite obvious that carbide or carbides have been formed at the boundary. Since Cu is not likely to form carbide, thus most probably it is aluminum carbide. This is supported by the presence of Al and Cu at the interface, as shown in Fig.3.

Fig.4 shows the line scanning of Al, Cu, Co, W and C elements near the interface of YW1 + KK diffusion couple. In the vicinity of the boundary, relatively high C and Co concentrations are observed at the KK side of the interface. The concentration of C and Co at the boundary is as high as that in the core of the YW1 tool materials. It is quite obvious that carbide or carbides have been formed at the boundary. Since Co and Cu are not likely to form carbide, most probably it is aluminum carbide. This is supported by the presence of Al and Cu at the interface, as shown in Fig.4.

Microprobe analysis (WDS surface scan of 10 μm × 10 μm) in the vicinity of the interface shows inter-diffusion between the two contact surfaces of HSS + KK and YW1 + KK diffusion couples. Table 3 shows the typical chemical compositions of the tool materials and KK near the interface. It can be seen from this table that major elements of both tool materials and KK diffuse into their counterparts. From Figs.3 and 4 we can see that the diffusion of carbon is quite active at the interface. The reason for this is

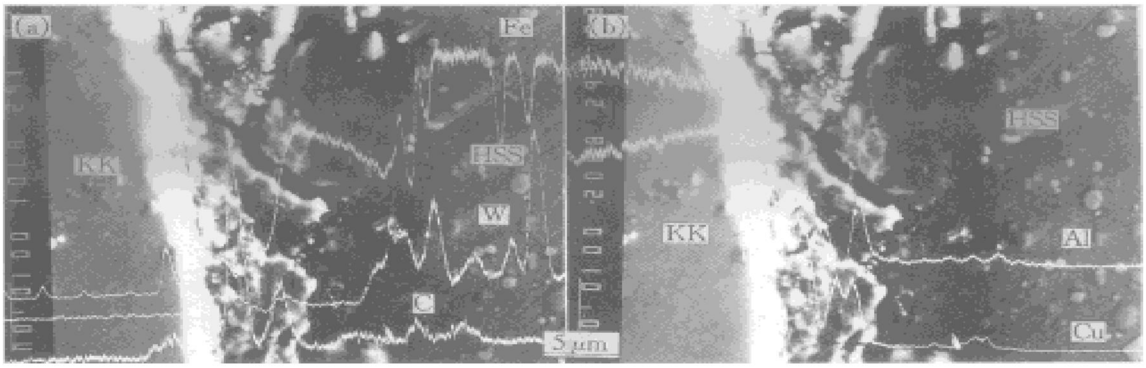

Fig.3 Line scanning of Fe, W, C (a) and Al, Cu (b) elements near interface of HSS + KK diffusion couple

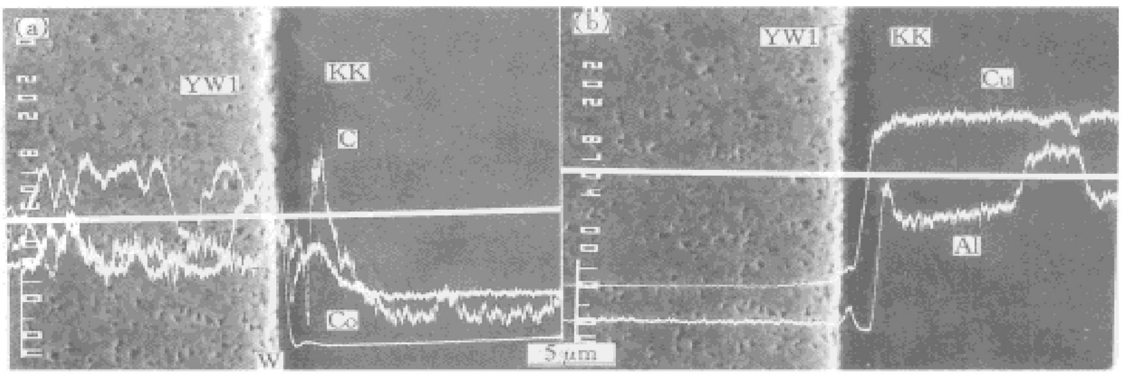

Fig.4 Line scanning of Co, W, C (a) and Al, Cu (b) elements near the interface of YW1 + KK diffusion couple