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Elements inter-diffusion in the turning of wear-resistance aluminum bronze

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Abstract: Inter-diffusion of elements between the tool and the workpiece during the turning of aluminum bronze using high-speed steel and cemented carbide tools have been studied. The tool wear samples were prepared by using M2 high-speed steel and YW1 cemented carbide tools to turn a novel high strength, wear-resistance aluminum bronze without coolant and lubricant. Adhesion of workpiece materials was found on all tools' surface. The diffusion couples made of tool materials and aluminum bronze were prepared to simulate the inter-diffusion during the machining. The results obtained from tool wear samples were compared with those obtained from diffusion couples. Strong inter-diffusion between the tool materials and the aluminum bronze was observed in all samples. It is concluded that diffusion plays a significant role in the tool wear mechanism.

Key words: machining; wear-resisting aluminum bronze; inter-diffusion

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1 Introduction

Aluminum bronze is an important engineering material due to its excellent physical, mechanical, anticorrosion and wear-resistance properties. Our research group developed a special type of high strength, wear-resistance aluminum bronze (KK), which is exceptionally good for wear resistance engineering parts that work under high stress [1-4]. However, problem was encountered when machining this novel bronze. Unlike common Cu alloys the high strength, wear resisting aluminum bronze used in this study possess high shear yield stress. It can induce a high cutting temperature during the turning process and thus shorten the service life of the tools. Therefore, a series of experiments were carried out to find out the tool wear mechanism in the turning of the wear-resistance KK aluminum bronze.

During machining process the cutting force creates an intimate contact between the tool and the workpiece. The sliding speed induced a tremendous frictional force on the contacting surfaces and dissipates a considerable amount of heat. The high temperature created will encourage the inter-diffusion of elements between the contacting surfaces. For workpiece, the contacting time involving the tool and the workpiece is instantaneous. Freshly cut workpiece materials flow through the tool surface in milliseconds, it is not easy to develop significant diffusion effect on the constantly changing workpiece (the chip). However, it is possible for the diffusion effects to show in the tool since the contacting tool surface is relatively stationary.

It is well known that diffusion plays an important role in tool wear especially when the cutting temperature is high. In hope to clarify how the diffusion took place between the workpieces and tools, diffusion couples made of tool materials and KK aluminum bronze were prepared and studied in our previous paper [5] to simulate the inter-diffusion in the machining process. In order to get a comparable results between the diffusion couple samples and the actual machining tool wear samples, thermodynamically their preparation conditions should be as close as possible. In diffusion couple experiment it is not possible to provide a continuous supply of fresh workpiece material to the tool surface as what had happen in the actual machining process. Neither it is easy to reproduce the high contacting pressure nor friction that were experienced by the tool and the workpiece. However, it is possible to estimate the temperature at the contact surfaces during machining. Typical machining temperature in

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turning is in a range of 600 to 1100℃ [6] depending on conditions and what kind of tools and workpiece materials are involved. The temperature of 1200℃ may be reached if cemented carbide tools were used [7, 8]. Wright *et al.* show that using high-speed steel tool to cut mild steel at a speed of 183 m/min the hottest spot can reach up to 950℃ [9]. Consider the slow cutting speed as recommended in the turning of aluminum bronze [10], thus the diffusion couple experiments were conducted at 900℃. The previous results on diffusion couple experiment indicate that inter-diffusion of elements plays a significant role in the tool wear during the machining of aluminum bronze [5]. In this paper, experimental results on the inter-diffusion of elements in the turning process were compared with the results obtained from the diffusion couple experiments.

2 Experimental

Commonly used M2 high-speed steel (HSS) and YW1 cemented carbide tools were chosen for the experiment. The workpiece was the high strength, wear-resisting aluminum bronze (KK). **Table 1** is a list of nominal chemical compositions of the materials involved in this study.

Table 1 Nominal chemical compositions of materials involved (mass fraction in %)

Materials	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	1	—	—	—	—
YW1	—	—	—	—	—	—	—	—	—	—	6	84	6	4

For diffusion couple samples, commercially available M2 high-speed steel and YW1 cemented carbide tools were cut into 6 mm × 6 mm × 4 mm pieces. After being ground and polished to obtain mirror surfaces they were cleaned by alcohol. With the help of a pair of ceramic rods, each of these pieces was then fixed upright at the center of a cylindrical metal mould with a dimension of ϕ 30 mm × 60 mm. KK was then cast into these molds. As soon as these casts solidified, they were quickly dropped into cold water and machined into cylinders with a size of ϕ15 mm × 20 mm. These cast cylinders were then annealed at (900 ± 2) ℃ in vacuum for 6 h. Started from one end of these cylinders; they were ground until the tool materials were exposed. These samples were then polished, cleaned and ready for metallography, scanning electron microscope (SEM) analysis and electron probe microanalysis (EPMA).

Tool wear samples were prepared by turning cylindrical workpiece made of KK aluminum bronze using M2 high speed steel and YW1 cemented carbide tools without using coolant and lubricant. Turning conditions were: back orthogonal clearance = 6°, feed per revolution = 0.15 mm/r, tool cutting edge angle = 90°, tool minor cutting edge angle = 15°, back engagement = 2 mm and other turning conditions are listed in **table 2**. Wire cutting technique was used to cut out the cutting edge together with rake and flank. The surface morphology and chemical composition on the surface of the tools were studied. The cross sectional plane which perpendicular to the cutting edge and the rake was polished for EPMA and SEM analysis.

Table 2 Turning conditions for the tool wear samples

Sample number	Tool materials	Turning speed / (m·min^{-1})	Turning time / min	Orthogonal rake / (°)
1	HSS	54.25	7.5	15
2	HSS	35.00	30.0	10
3	HSS	17.27	55.0	10
4	YW1	54.25	7.5	15

3 Results and discussion

The EPMA results at and near the contact interfaces show that inter-diffusion of the major elements such as Fe, C, Cu and Al was detected in the HSS/KK diffusion couple and the HSS tool wear samples. And inter-diffusion of the major elements such as Co, C, Cu and Al was detected in the YW1/KK diffusion couple and the YW1 tool wear samples. Diffusion couple samples clearly show the diffusion of C and Co away from the tool materials.

Table 3 shows the energy dispersive X-ray spectroscopy (EDX) composition measurement results at the vicinity of the tool-materials/KK interface of the diffusion couple samples.

Table 4 shows the EDX composition measurement results at the vicinity of the tool-materials/KK interface of the tool wear samples.

Table 3 EDX results at the vicinity of the tool/KK interface of the diffusion couple samples (mass fraction in %)

Sample	Distance from interface / μm	Al	Cu	Ni	Mn	Fe	Cr	W	Mo	V	Co	Ti
HSS/KK	5 (KK side)	8.81	84.64	1.20	1.28	3.31	0.07	0.45	0.08	0.17	—	—
	10 (KK side)	9.51	84.64	1.20	1.31	2.78	0.13	0.30	0.07	0.06	—	—
	15 (KK side)	10.19	84.61	1.07	1.37	2.41	0.04	0.31	0.00	0.00	—	—
	5 (HSS side)	0.36	4.83	0.45	0.28	84.91	2.08	1.50	5.33	0.27	—	—
	10 (HSS side)	0.51	3.63	0.44	0.25	82.56	3.15	3.17	4.96	1.33	—	—
	15 (HSS side)	0.03	3.13	0.39	0.16	87.54	1.97	1.36	5.25	0.18	—	—
YW1/KK	5 (KK side)	10.82	82.03	1.70	1.73	1.99	—	1.12	—	—	0.45	0.16
	10 (KK side)	8.51	85.80	0.92	1.38	2.08	—	0.89	—	—	0.25	0.15
	15 (KK side)	9.36	85.22	1.06	1.40	2.13	—	0.72	—	—	0.06	0.05

Table 4 EDX results at the vicinity of the tool/KK interface of the tool wear samples (mass fraction in %)

Sample No.	Location	Al	Cu	Ni	Mn	Fe	Cr	W	Mo	V	Co	Ta
1 (HSS)	Adhered KK at flank	9.27	78.24	1.08	1.47	8.92	0.69	0.22	0.10	0.00	—	—
2 (HSS)	Adhered KK at rake	7.24	82.14	0.85	2.30	5.27	0.00	1.03	1.18	0.00	—	—
	Tool's rake	1.18	0.17	0.00	0.36	80.44	3.61	8.63	4.40	1.21	—	—
3 (HSS)	Adhered KK at rake	15.66	77.88	1.77	0.92	3.71	0.06	0.00	0.00	0.00	—	—
4 (YW1)	Adhered KK at flank	4.41	90.39	1.35	1.58	1.46	—	0.00	—	—	0.03	0.78

Although C was detected on both sides of the tool-materials/KK interfaces of all the samples, no C concentration is listed in tables 3 and 4 because EDX can only qualitatively identify the presence of C but not for quantitative measurement. Due to the high carbon concentration in YW1 and the inaccuracy of EDX on carbon, there was no attempt to report the chemical compositions on the YW1 side of the KK/YW1 contact interface, but it is no doubt that elements from KK such as Cu, Al, Fe, Mn and Ni were found on the YW1 side of the KK/YW1 interface. Since KK contains no C, the relatively high concentration of C on the KK side of the tool-materials/KK interface indicated that carbon-containing phase or phases have been formed. It is not surprise to find Al_4C_3 formed at the interfaces [5]. Thermodynamically, other than Al and Fe, major elements in KK cannot form carbide readily. Except for Cr, compared with carbides of the major elements in the tool materials, such as W, Mo and Fe, the free energy of the formation of Al_4C_3 is much lower than that of the others (−204 kJ/mol at room temperature and −153 kJ/mol at 1500 K for Al_4C_3 compared with approximately −37 kJ/mol for WC at both room temperature and at 1500 K) [11, 12]. Therefore at the contacting surface, in the presence of Al, some of the carbides in the tool materials become unstable at 900°C and forming carbide of Al instead, although it may not be the final equilibrium product.

Figure 1 is the optical micrographs showing the interface of HSS/KK and YW1/KK diffusion couples annealed at 900°C for 6 h, respectively. The microstructure of KK composes of α Cu (white phase), solid solution of $AlCu_3$ (β, dark phase) and intermetallics of Cu, Fe, Ni and Al (κ, small particles). The HSS used in this study composed of martensite (the matrix), carbides (bright spots) and some residual austenite. It can be seen from figure 1 that the contact interfaces are clean and tight. The carbide contents adjacent to the HSS/KK interface are obviously less than those in the rest of the HSS body. But there is no such carbide deficient zone can be seen at the YW1/KK interface.

Figure 2 is the cross sectional optical micrograph of the rake of HSS tool wear sample after turning at a speed of 35 m/min for 30 min. The white area on the top is the adhered KK and the bottom part is the HSS tool. The fine white spots are carbides and the rest on the bottom part are the matrix of HSS. At the KK/HSS contact interface, the amount of carbides on the HSS side right next to the interface is obviously less than those in the HSS body. This carbide deficient zone is similar to the carbide deficient zone observed in figure 1(a). The presence of this zone in both of the tool wear samples and the diffusion couple sample supports the argument that under this experimental condition some of the carbide particles in HSS have been decomposed in the presence of aluminum bronze. Due to the high carbide concentration in YW1 no such carbide deficient zone can be observed on the YW1 side of the YW1/KK diffusion couple interface.

No matter what kinds of diffusion products have been formed, from the diffusion couple experiment results, we can notice that it is the elements such as C and Co in the tools diffused away from the tool surface. The diffusion of C and Co away from the tools will degrade the surface strength of the tools. Even there is influx of Cu, Al, Ni and Fe (Fe for carbide tools only) from the workpiece, these elements cannot strengthen the tools since neither of them is strengthening elements for either the HSS or YW1 tools.

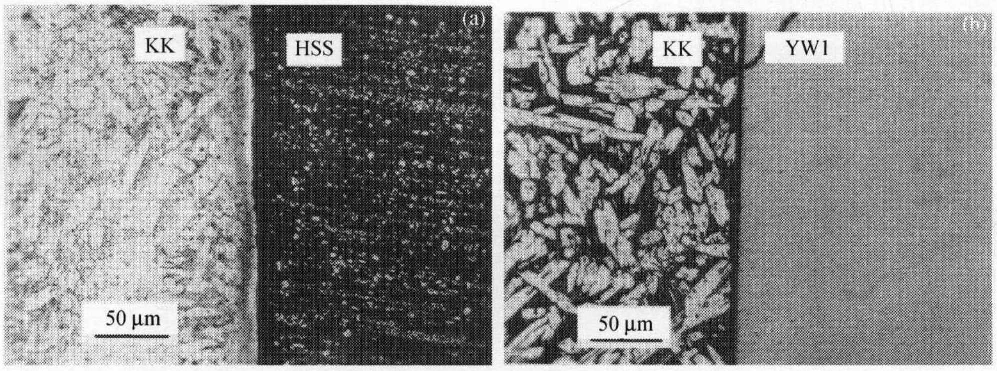

Figure 1 Optical micrographs showing the interface of (a) HSS/KK and (b) YW1/KK diffusion couples annealed at 900 °C for 6 h.

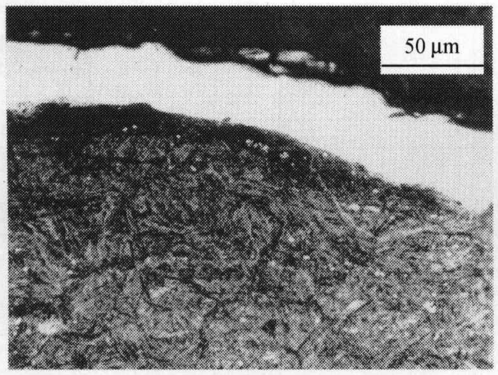

Figure 2 Cross-section of the rake of HSS tool wear sample after turning at 35 m/min for 30 min.

Hard particles of carbides such as WC (Hv = 1780), Fe_3W_3C (Hv=1150) and V_4C_3 (Hv=2000) in the matrix enhanced the hardness of high-speed steel. However, their contributions are limited since they occupied only 10% to 15% by volume. Martensite (Hv = ~750) and the sub-micron sized carbides precipitated during tempering are the backbone to provide the hardness for high-speed steel, especially the hot hardness. The tendency of carbide formation on the workpiece side enhanced the driving force for the diffusion of C. Nevertheless, the activation energy for C diffusion is relatively the lowest since C atoms occupy interstitial sites, while the diffusion of other metallic elements need to take up vacancies. The diffusion experiment and tool wear experiment results indicate that C diffuse into KK for a distance not less than 50 μm. The diffusion of C away from HSS will weaken the tool since the carbon content is essential for the stability of the martensite and carbides.

The diffusion of Co away from the tool will weaken the cemented carbide tool since the carbides on the tool surface are not tightly cemented together by Co anymore. The effect of losing Co from the cemented carbide tool surface is significant since the Co content is limited to 6% (mass fraction) and they take a vital role as "binder" in the tools. The carbides formed the framework of the cemented carbide tools, which composed of at least 80% by volume of carbides compared with 15% by volume of those in the high-speed steel. The lost of the "binder" will expose the framework and subject to impact wear and attrition wear. The influx of Cu, Al, Ni and Fe from the workpiece cannot strengthen the tools. Although Ni and Fe are potential alloying elements for the cemented carbide tools, their performances are not as good as that of Co. The lost of C due to diffusion will cause the undesired precipitation of the brittle M_6C or $M_{12}C$ phases (M = metallic elements), which were avoided during the production of the cemented carbide tools [8].

The adhesion of KK can be observed on the rake and flank of the tools. Other than the inter-diffusion of elements, no diffusion products can be detected in all tool wear samples. The results on tool wear samples, both HSS and YW1, clearly show that C and Co diffused away from the tool materials. It is no doubt that diffusion plays a significant role in the tool wear mechanism.

4 Conclusions

Diffusion couple experiments provided us some hints in the role of diffusion in the wear of M2 high-speed steel and YW1 cemented carbide. First of all it shows the inter-diffusion of elements across the workpiece/tool interface under the present experimental condition. Both metallography on diffusion couple sample and tool wear samples show a carbide deficient zone at the HSS side of the HSS/KK contact interface. This zone indicates that under this experimental condition some of the carbides have been decomposed in the presence of aluminum bronze. The diffusion of C and Co away from the tools can be found in all samples and this will eventually lead to the reduction in the surface strength of the tools. It is concluded that diffusion plays a significant role in the tool wear mechanism.

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