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Tool wear mechanism in turning of novel wear-resisting aluminum bronze ①

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[Abstract] Tool wear and wear mechanism during the turning of a wear-resisting aluminum bronze have been studied. Tool wear samples were prepared by using M2 high-speed steel and YW1 cemented carbide tools to turn a novel high strength, wear resisting aluminum bronze without coolant and lubricant. Adhesion of workpiece materials was found on tool's surface. Under the turning condition used in this study major wear mechanisms for turning aluminum bronze using M2 high-speed steel tool are diffusion wear, adhesive wear and plastic deformation and shear on the crater. Partial melting of high-speed steel on the rake plays a role in the tool wear also. Major wear mechanisms for turning aluminum bronze using YW1 cemented carbide tool are diffusion wear, attrition wear and sliding wear. To control the machining temperature is essential to reduce tool wear.

[Key words] tool wear mechanism; machining; wear-resisting aluminum bronze

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1 INTRODUCTION

Aluminum bronze is an important engineering material due to its excellent physical, mechanical, anti-corrosion and wear resisting properties. Our research group developed a special type of high strength, wear-resisting aluminum bronze (KK), which is exceptionally good for wear resisting 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 (KK) 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 tools' wear mechanism in the turning of the wear-resisting KK aluminum bronze. Among Cu alloys, relatively speaking, bronze is difficult to machine and aluminum bronze is one of the worst. Its machinability is about 20% of that of brass[5]. Both high-speed steel and cemented carbide tools can be used to machine aluminum bronze[6]. The recommended turning condition for C63000 nickel aluminum bronze, which has a chemical composition close to that of the KK aluminum bronze used in this study, are: feed per revolution = 0.3 mm/r, cutting speed = 76 m/min for high-speed steel tool and cutting speed = 53 m/min for cemented carbide tools[6]. Coolant and lubricant must be used during the turning. The hottest point at the rake during machining is very close to the main cutting edge[7]. At the main cutting edge the stress caused by the cutting force is very large therefore cemented carbide tools, with a maximum Co contents less than 10% and WC particle size of approximately 0.8 μm, are the better choice[7]. In contrasts to its vast applications, tools wear and tool wear mechanisms during the machining of aluminum bronze are rarely available in general literature. In order to make the machining process of the wear resisting aluminum bronze parts more efficient, our group carried out a series of study on the wear of the turning tools.

Our previous results on diffusion couple experiments and tool wear experiments indicate that significant inter-diffusion of elements between the tool and the workpiece can be observed in the machining of KK aluminum bronze[8, 9] and diffusion plays an important role in the tool wear mechanism. In this paper, tool wears and tool wear mechanism were studied.

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). Detail concerning the casting of KK can be found in references [1] and [2]. Table 1 is a list of nominal chemical compositions of the materials involved in this study.

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

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	1	–	–	–	–
YW1	–	–	–	–	–	–	–	–	–	–	6	84	6	4

Tool wear samples were prepared by turning cylindrical workpiece made of KK aluminum bronze against M2 high speed steel and YW1 cemented carbide tools without using coolant or 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. Surface morphology and chemical composition on the surface of the tools were studied. Cross sectional plane perpendicular to the cutting edge and the rake was polished for electron probe microanalysis (EPMA) and scanning electron microscope(SEM) analysis.

Table 2 Turning conditions for tool wear samples

Sample number	Tool materials	Turning speed / ($m\cdot min^{-1}$)	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

Fig. 1 and Fig. 2 show the rake and flank morphologies of high-speed steel tool after turning at speeds of 54. 25 m/min and 17. 27 m/min, respectively. Crater and KK adhesion were observed in all HSS tool wear samples. From Fig. 1(b) we can see that the average width of the flank wearland is 0. 13 mm for the tool that operates at a speed of 54. 25 m/min for 7. 5 min. From Fig. 2(b) we can see that the average width of the flank wearland is 0. 10 mm for the tool that operates at a speed of 17. 27 m/min for 55 min. In just 7. 5 min the flank wear of the tool that operates at a higher speed exceeds the flank wear of the tool that operates at a slower speed for 55 min. It can be seen that the flank wear at a higher operating speed, which means a higher machining temperature, is much faster than those operate at slower speed. The relatively smooth surface on the flank wearland, as shown in Fig. 1 (b) is a typical morphology characteristic of diffusion wear[10]. Since adhesive wear and diffusion wear are major wear mechanism at the flank the best way to reduce flank wear is to reduce the generated heat. By increasing the tool orthogonal clearance angle the average width of flank wearland can be reduced.

Fig. 3 shows 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. A small depression on the rake, as shown on the upper portion of Fig. 3, is the crater. Plastic deformation can be seen at the right hand side of this crater. It is surprised that the hard high-speed steel (HV= ~ 880) can be deformed by the relatively much softer KK aluminum bronze which has a hardness of HB= 169. Similar result reported by Wright et al[11] shows that, using high-speed steel tool to cut mild steel at a speed of 183 m/min, the hottest spot can reach up to 900 ℃. To their surprise the relatively soft mild steel can shear the high-speed steel and particles of carbides are carried away from the crater. The hot hardness of HSS drops rapidly when the temperature reaches 500 ℃ (HV= ~ 590 at 550 ℃)[12]. At a temperature

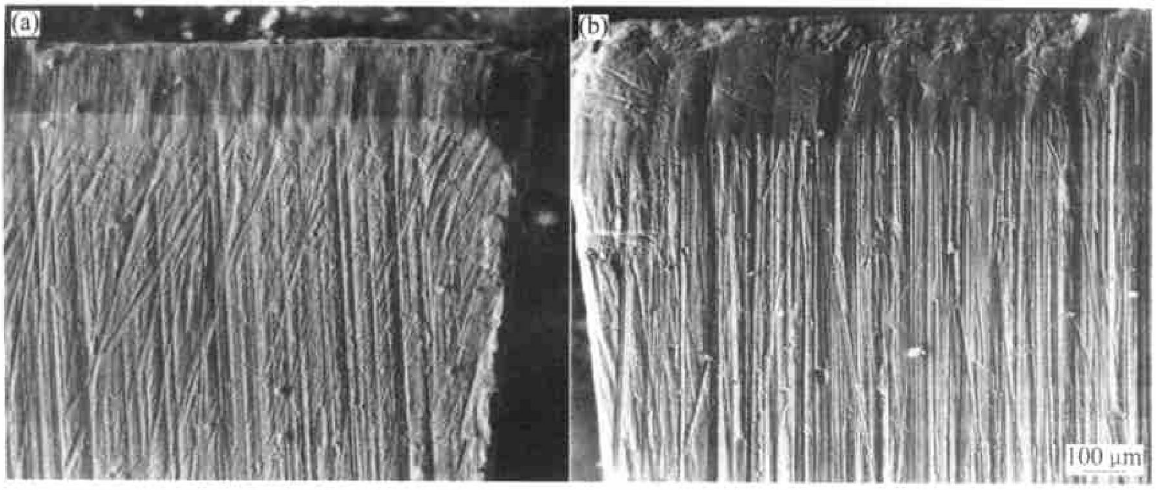

Fig. 1 Rake(a) and flank surface(b) morphologies of HSS tool after turning at a speed of 54. 25 m/min for 7. 5 min

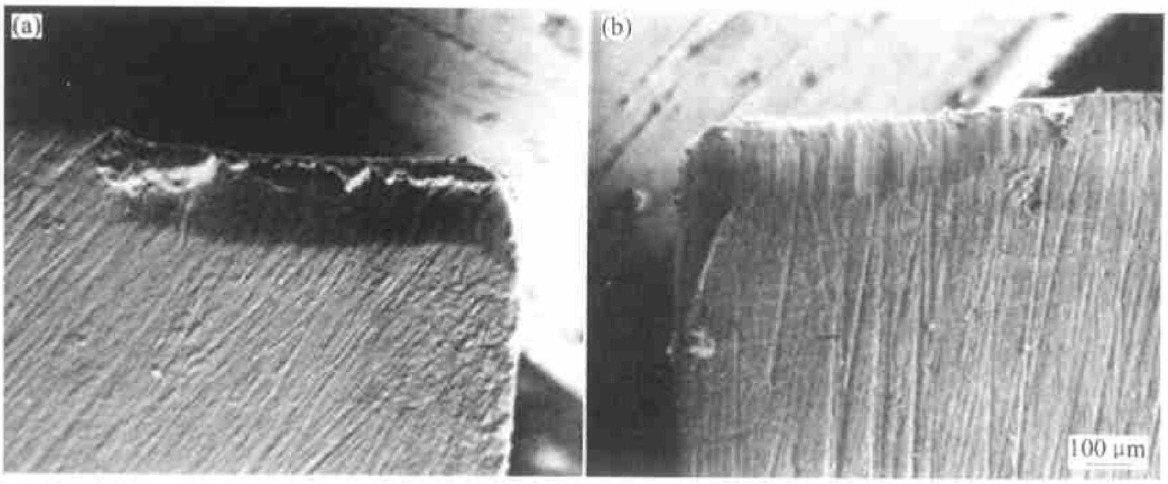

Fig. 2 Rake(a) and flank (b) surface morphologies of HSS tool after turning at a speed of 17.27 m/min for 55 min

of 650 ℃ the grain size of the precipitated carbides grows very fast and loss the ability to pin down the matrix (martensite). Diffusion of C away from HSS[8, 9] will weaken the tool also since the carbon content in the HSS matrix is essential to the stability of the martensite. As we know, martensite and the sub-micron size carbides precipitated during tempering stage of the tool manufacturing process are the backbone to provide the harness, especially the hot hardness, for the high-speed steel. Unlike the flowing chip, the rake and flank surfaces sustain a constant inflow of heat without an effective heat drain. Temperature build up is enormous compared to the workpiece (chip). This is the reason why plastic deformation is possible at the crater where the temperature is the highest. Compared to diffusion wear, plastic deformation and shear away of tool materials is a much faster wear mechanism. The dominant wear mechanism at the crater was plastic deformation and shear. The necessary condition for the plastic deformation to happen is the high enough temperature. For cutting high strength materials this phenomenon can be observed at a much lower cutting speed. Taking Ni alloy as an example, the high temperature generated during the cutting can cause the deformation at the cutting edge[13]. Crater wear is commonly found in the HSS tool. It may even cause the fracture of the tool. Therefore the cutting speed and the feed per revolution must be optimized.

At the cutting edge the temperature is not so high as that at the crater, deformation and shear is not likely to happen. From Figs. 1 and 2 chipping can be observed at the cutting edges. Micron sized debris of HSS tool material (composition verified by EPMA results) are found trapped between the rake and the KK adhesion near the cutting edge, as shown in Fig. 4. This carbide containing

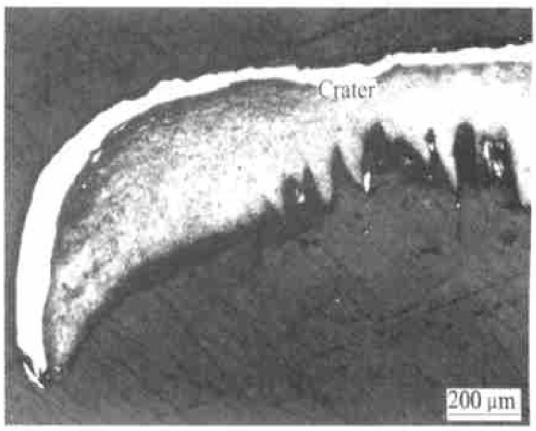

Fig. 3 Optical micrograph of HSS tool wear sample after turning at a speed of 35 m/min for 30 min

Fig. 4 Micron sized debris of HSS tool material trapped between rake and KK near cutting edge(Sample number 2)

debris would cause abrasive wear on the HSS tool. Figs. 1 and 2 show some characteristic of abrasive wear but in this case they are not significant compared to adhesive wear and diffusion wear. Fig. 5 shows an unusual phenomenon on the rake. Groups of droplet like particles are found on the rake surface and on the KK layer that adheres to the rake of HSS tool wear samples. These "droplets" have chemical compositions close to those of HSS, but most of them have higher Mo and W concentration. Elements from KK such as Cu and Mn can also be detected in these "droplets". The smooth spherical shape indicates that they are products of partial melting of the HSS.

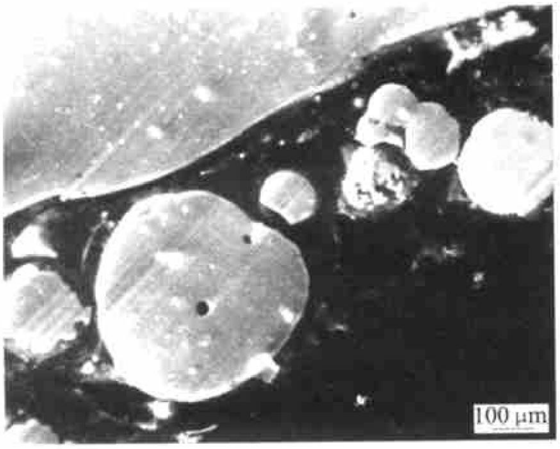

Fig. 5 "Droplets" on rake of HSS tool wear sample after turning at a speed of 35 m/min for 30 min

Considering the conclusion we have drawn in our previous papers[8, 9] that diffusion plays a significant role in the tool wear, the major wear mechanisms for turning KK aluminum bronze using M2 HSS tool under the turning condition of this study are diffusion wear, adhesive wear and plastic deformation and shear wear on the crater. The partial melting of HSS on the rake plays a role in tool wear also.

Fig. 6 shows the rake and flank morphologies of YW1 cemented carbide tool after turning at a speed of 54.25 m/min for 7.5 min. No crater is formed. KK adhesion is observed on both rake and flank, but compared to those of HSS the degree of adhesion is less. Fig. 6(b) shows that no obvious flank wearland is formed. The smooth surface at this location is characteristics of diffusion wear[10]. Fig. 6(a) shows a flake on the cutting edge. Under the influence of normal pressure and the tensile stress, voids in the tool's sub-surface may induce micro-cracks; the growth and interconnection of these cracks will lead to the formation of flakes. The origin of this flake is due to the weakening of the tool surface and sub-surfaces dimples and the tearing edges on the fracture surfaces of the composites are obviously observed from Fig. 6. It is concluded that the composite displays the feature of ductile rupture. In addition, it caused by the diffusion of C and Co away from the tool. The diffusion of C and Co into the workpiece[8, 9] reduces the strength of the tool materials on the tool surface. Eventually, the weakened tool surface will break away from the tool body. Fig. 6(a) shows a depression on the right hand corner near the tool edge. It is caused by the attrition wear. YW1 tool was carbides of W, Ti and Ta cemented together by Co. At this particular location, due to the high machining temperature, the "binder" Co diffuses away, carbide particles are then exposed and some of them plug out. Compared to the high-speed steel tools cemented carbide tools are much harder but less tough, it is more vulnerable to the attrition wear. When the chip flows through the rake its edge will slide on the tool surface. The high sliding speed of the chip edge and the unlimited supply of oxygen at this open surface will accelerate the oxidation of the cemented carbide tool material. The ditch found at the left-hand side of the cutting edge in Fig. 6(a) is characteristic of sliding wear. A longer turning time of 30 min shows that this kind of wear becomes more obvious. To limit the cutting temperature and the supply of oxygen is an effective way to reducing the adverse effect of sliding wear. The use of coolant can achieve this goal. Oxygen can be detected in all tool wear samples, both in HSS and YW1, but it is well known that reasonable amount of oxides formed during machining is beneficial to reduce the tool wear since it can act as solid lubricant and the adhesion wear[14]. Cemented carbide tools are more likely to be subjected to oxidation wear. Above 600 ℃ oxidation wear becomes a problem and above 900 ℃ oxidation wear becomes serious. Tool wear samples indicate that compared to other wear mechanisms, such as sliding wear, oxidation wear is not a major wear mechanism in this study.

As diffusion plays a significant role in the tool wear[8, 9], the major wear mechanisms for turning KK aluminum bronze using YW1 tool under the turning condition of this study are diffusion wear, attrition wear and sliding wear.

Comparing Fig. 6 with Fig. 1, which are different tools samples obtained under the same turning condition, we can see that the wear in the HSS is more severe than that in the YW1. It is not surprising since carbides are much harder and more stable than martensite. The diffusion of C away from the tool will degrade the surface strength of HSS due to the destabilization of martensite and carbides. Besides, the affinity of Al and Cu to Fe is much larger than the affinity of the Al and Cu to carbides, which composed approximately 94% of the YW1 carbide tool. Although the much better toughness of HSS tools makes it possess higher resistance to attrition wear, fatigue wear and impact wear, under the turning condition in this study, the toughness of the tool is not the predominant factor for the tool wear resistance.

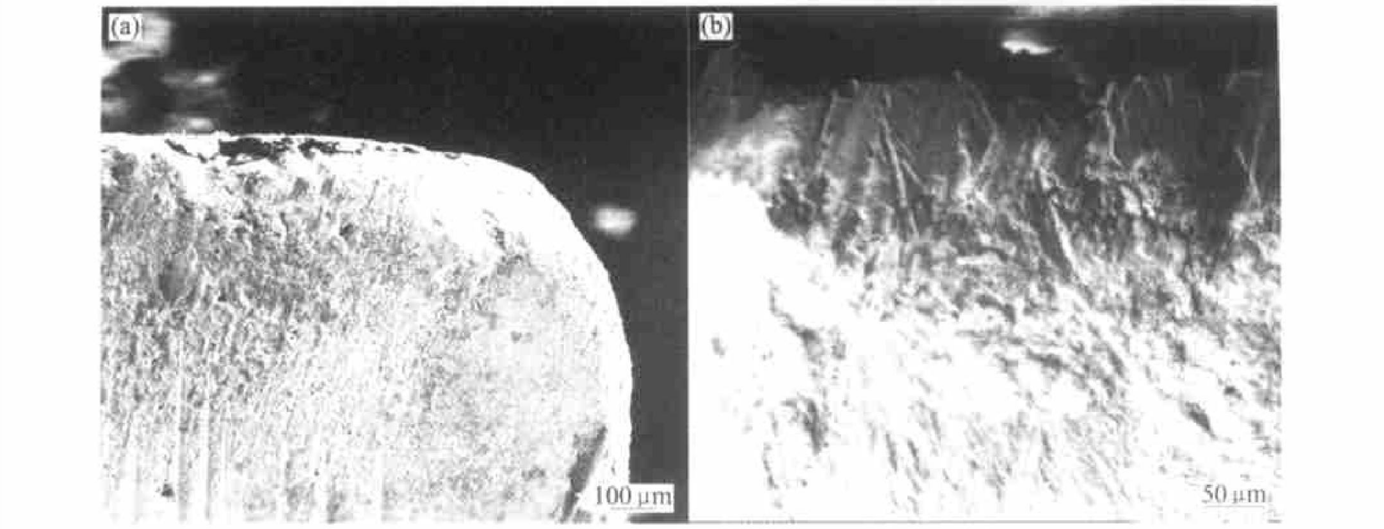

Fig. 6 Rake (a) and flank (b) surface morphologies of YW1 cemented carbide tool after turning at a speed of 54.25 m/min for 7.5 min

4 CONCLUSIONS

1) Major wear mechanisms for turning KK aluminum bronze using M2 HSS tool under the turning condition of this study are diffusion wear, adhesive wear and plastic deformation and shear wear at the crater. The partial melting of high-speed steel on the rake plays a role in tool wear also. Experimental results show that the flank wear of M2 HSS tool at a higher turning speed, which means a higher machining temperature, is much faster than those operated at slower speed.

2) Major wear mechanisms for turning KK aluminum bronze using YW1 tool are diffusion wear, attrition wear and sliding wear.

3) To control the machining temperature is the key to reduce the tool wears not only because it can avoid the partial melting of tool materials but also it can limit the diffusion activity during the machining since diffusion coefficients of elements are strong functions of temperature. Under the same turning condition the wear in the M2 HSS tool is much more severe than that in the YW1 cemented carbide tool.

REFERENCES

[1] LI Yuan-yuan, NGAI Tungwai L, XIA Wei. Mechanical, friction, and wear behaviors of a novel high-strength wear-resisting aluminum bronze[J]. Wear, 1996, 197: 130 - 136.

[2] LI Yuan-yuan, NGAI Tungwai L. Grain refinement and microstructural effects on mechanical and tribological behaviors of Ti and B modified aluminum bronze[J]. J Mater Sci, 1996, 31: 5333 - 5338.

[3] LI Yuan-yuan, XIA Wei, ZHANG Wen, et al. Strong and wear-resistant aluminum bronze alloy and its tribological characteristics[J]. Chinese J Nonferrous Met, (in Chinese), 1996, 6(3): 76 - 80.

[4] LI Yuan-yuan, XIA Wei, WEN Li-ping, et al. The relation between the basic characteristics of aluminum bronze and its tribological behaviors[J]. Tribology, (in Chinese), 1996, 16(2): 130 - 136.

[5] ASM Metals Reference Book[M], 2nd edition, American Society for Metals, Metals Park, 1983. 1011.

[6] Metals Handbook[M], Vol. 2, 9th edition, ASM International Handbook Committee, Metals Park, 1989, 357 - 367.

[7] Metals Handbook[M], Vol. 16, 9th edition, ASM International Handbook Committee, Metals Park, 1989, 805 - 819.

[8] LI Yuan-yuan, NGAI Tungwai L, ZHANG Da-tong, et al. Diffusion couple between a high-strength wear-resisting aluminum bronze and machining tool materials[J]. Transc Nonferrous Met Soc China, 1999, 9(1): 6 - 10.

[9] LI Yuan-yuan, XIA Wei, NGAI Tungwai L. Diffusion wear study of tool materials on turning wear-resisting aluminum bronze[J]. J Mater Process Technol, (accepted).

[10] Trent E M. Metal Cutting[M]. Butterworths Press, London, UK, 1978. Chinese Translation by CHOU Qi-yuan, XU Hong-shan. Mechanical Industry Publication Co, Beijing, (in Chinese), 1980, 104 - 107.

[11] Trent E M. Metal Cutting[M]. Butterworths Press, London, UK, 1978. Chinese Translation by CHOU Qi-yuan, XU Hong-shan. Mechanical Industry Publication Co, Beijing, (in Chinese), 1980, 73 - 76.

[12] Trent E M. Metal Cutting[M]. Butterworths Press, London, UK, 1978. Chinese Translation by CHOU Qi-yuan, XU Hong-shan. Mechanical Industry Publication Co, Beijing, (in Chinese), 1980, 94.

[13] Trent E M. Metal Cutting[M]. Butterworths Press, London, UK, 1978. Chinese Translation by CHOU Qi-yuan, XU Hong-shan. Mechanical Industry Publication Co, Beijing, (in Chinese), 1980, 204 - 211.

[14] Trent E M. Metal Cutting[M]. Butterworths Press, London, UK, 1978. Chinese Translation by CHOU Qi-yuan, XU Hong-shan. Mechanical Industry Publication Co, Beijing, (in Chinese), 1980, 194 - 197.

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