Comparison of Chip Breakability between Age-hardened Al-Cu and Al-Cu-Si Alloys

Masatsugu KAMIYA¹, Tomohiro SASAKI² and Takao YAKOU³

¹ Graduate student, Yokohama National University, Japan, d02sa301@ynu.ac.jp

² Department of Mechanical Engineering and Materials Science, Yokohama National University, Japan, tomodx@ynu.ac.jp

³ Department of Mechanical Engineering and Materials Science, Yokohama National University, Japan, tyakou@ynu.ac.jp

Abstract:

The chip breakability of age-hardened Al-4.0mass%Cu alloy and Al-5.6mass%Cu-4.0mass%Si alloy during turning with carbide inserts (K10) were examined. In dry cutting, overaged materials showed increased chip breakability compared to underaged and peakaged materials for both Al-Cu and Al-Cu-Si alloys. This was considered due to increased adhesion of workpieces to the surface of the tool. In contrast, in wet cutting, the chip breakability of Al-Cu-Si alloys increased largely. This increase of chip breakability in Al-Cu-Si alloys is due to the decreased strength of chips as a result of infiltration of cutting oil to the microcracks in chips.

Keywords: Processing of advanced materials, Al-Cu alloy, Al-Cu-Si alloy, Machining, Chip breakability

1. Introduction

In the machining of Al alloys, chip breakability, surface finish and tool life are major factors in machinability [1, 2]. However, to ensure reliable operation in automated machining of conventional Al alloys, chip breakability is highlighted as the most important feature [3]. Pb added free-cutting Al alloys once played an important role in industry. However, because of its adverse environmental impact, the addition of Pb has been restricted. As such, an alternative method has been required. Among Al alloys with Si, Ni, Fe, or Mn added, Si added Al alloys have exhibited the best performance in terms of chip breakability as demonstrated in drilling operations [4]. The chip breakability of a Si added Al-Cu alloy was shown to be improved from two to ten times compared to the Al-Cu alloy; however, the chip breakability of the Si added Al-Cu alloy was smaller than that of a Pb added free-cutting Al alloy [5].

Since Al-Cu system alloys are heat treatable, the machinability of the Al-Cu system alloys may be improved with aging treatment. In the present paper, we report on the comparison of the chip breakability between age-hardened Al-Cu and Al-Cu-Si alloys, and on variation of chip breakability with aging treatment.

2. Experimental procedure

The materials used in the experiments were Al-4.0mass%Cu alloy (Al-Cu alloy) and Al-5.6mass%Cu-4.0mass%Si alloy (Al-Cu-Si alloy). The chemical compositions of the materials are shown in Table 1. The materials were solution-treated for three hours at 550°C for the Al-Cu alloy and at 500°C for the Al-Cu-Si alloy. They were then quenched into cold water, and subsequently aged at 100°C, 200°C, 300°C or 450°C for one hour.

Cutting tests were performed on a lathe. The depth of cut and feed rate were 0.5 mm and 0.1 mm/rev

respectively, and the cutting speed was varied from 0.5 to 1.5 m/s. Carbide cutting inserts (K10) with a positive 5° rake angle were used in the turning tests. Polycrystalline diamond inserts which have the same shape as the carbide inserts were also used in turning tests. The turning tests were carried out under dry and wet cutting conditions, and compounded cutting oil was used as lubricant.

Table 1 Chemical composition of specimens (mass%)

	Cu	Si	Fe	Mn	Mg	Zn	Al
Al-Cu	3.98	-	-	-	-	-	bal.
Al-Cu-Si	5.60	4.00	0.20	0.50	0.40	0.25	bal.

3. Results

3.1 Microstructure and mechanical properties of Al-Cu alloys and Al-Cu-Si alloys

Figure 1 shows a SEM micrograph of workpieces aged at various temperatures. Examination of the surface of the workpieces by EDX analysis revealed the white particles to be CuAl₂ and the black particles to be Si. Particles of several micrometers were observed in both alloys, and there was no obvious change in size distribution of the particles in any of the stages of aging. However, in the overaged materials shown in Fig. 1 (e), the precipitation of CuAl₂ particles of about one micrometer was confirmed.

Figure 2 shows stress-strain curves of the workpieces. The yield strength and tensile strength of the Al-Cu alloys and Al-Cu-Si alloys increase as aging temperature rises up to 200°C, above which they decrease. In contrast, the fracture strains of these alloys decrease as aging temperature rises to 200°C, above which they increase. The yield strength and tensile strength of Al-Cu-Si alloys are about twice as high as for Al-Cu alloys for all aging conditions. The fracture strain of the Al-Cu-Si alloys,

Figure 1: SEM micrographs of workpieces.

Figure 3: Chip shapes after machining of Al-Cu alloy and Al-Cu-Si alloy at a cutting speed of 0.5 m/s in dry cutting.

Figure 2: Stress-Strain curves of Al-Cu alloy and Al-Cu-Si alloy.

however, is about 30% lower than that of the Al-Cu alloys for all aging conditions.

3.2 Chip breakability in dry cutting

Figure 3 shows photographs of chips formed during turning in dry cutting at a cutting speed of 0.5 m/s. The size of the chips tends to be smaller in the overaged alloys of (d) and (e) for both the Al-Cu and Al-Cu-Si alloys. The size of Al-Cu-Si alloy chips tend to be slightly smaller than those of the Al-Cu alloys.

To quantify the information contained in these photographs, we defined the chip breaking factor N as a parameter of chip breakability, measuring the numbers of chips contained in a 100 g sample of chips. According to Asano et al. [6], the chip breakability is optimum in the range of $10^4 < N < 10^5$.

Figure 4 shows the variation in the chip breaking factor N with aging temperature for various cutting speeds in dry cutting. The chip breaking factor of the Al-Cu alloys and the Al-Cu-Si alloys hardly changes as aging temperature

risers to 200°C; above this temperature, the factor increases rapidly. Al-Cu-Si alloys have a greater chip breaking factor than Al-Cu alloys for all aging conditions and cutting speeds. For both alloys, the chip breaking factor decreases with increasing cutting speed.

The hatched area in the graph shows the optimum range of chip breaking factor for Pb added free-cutting Al alloys [5]. The Pb added free-cutting Al alloys have good chip breakability in the range of $1.5 \times 10^4 < N < 5 \times 10^4$.

For most aging and cutting conditions, the chip breaking factor of the Al-Cu alloys and Al-Cu-Si alloys is lower than that of the Pb added free-cutting Al alloys. However, when the overaged Al-Cu alloys and Al-Cu-Si alloys are cut at a low cutting speed of 0.5 m/s, the chip breaking factor obtained is equivalent to that of the Pb added free-cutting Al alloys.

Figure 5 shows the variation in the surface roughness Ra with aging temperature for various cutting speeds in dry cutting. From the comparison of Fig. 4 and Fig. 5, Ra shows large value when large N is obtained. On the other

Figure 4: Chip breaking factor of Al-Cu alloy and Al-Cu-Si alloy plotted against aging temperature in dry cutting. The hatched area indicates the range of chip breaking factor for the Pb added free-cutting Al alloy (Al-Cu-Pb,Bi alloy).

hand, Ra shows small value as the decrease of N . From this fact, it can be said that N of Al-Cu alloys and Al-Cu-Si alloys never reach the N of the Pb added free-cutting Al alloys as long as good machined surface is required.

Figure 5: Surface roughness after machining of Al-Cu alloy and Al-Cu-Si alloy with aging temperature in dry cutting.

3.3 Chip breakability in wet cutting

Figure 6 shows the appearance of chips machined by wet cutting at 0.5 m/s. The Al-Cu alloys chips show the same characteristics as those obtained by dry cutting (Fig. 3); the chips tend to be smaller for the overaged materials of (d) and (e). In contrast, the Al-Cu-Si alloys chips are smaller for the underaged and peakaged materials of (a), (b) and (c) than for the overaged materials. In general, the Al-Cu-Si alloys chips are much smaller those of the Al-Cu alloy.

Figure 7 shows the variation in chip breaking factor N with aging temperature for various cutting speeds in wet cutting. For Al-Cu alloys, the chip breaking factor shows a similar trend to that observed in dry cutting, i.e. the chip breaking factor is greater in the overaged materials. On the other hand, the chip breaking factor of the Al-Cu-Si

alloys is greater in the underaged and peakaged materials. For all aging conditions and cutting speeds, the chip breaking factor of the Al-Cu-Si alloys is comparable to that of free-cutting Al alloys. Moreover, at a cutting speed of 0.5 m/s, the chip breaking factor of the Al-Cu-Si alloys exceeds that of the free-cutting Al alloys.

In wet cutting, the surface roughness R_a was around $1.5\mu\text{m}$ for all machined surface.

Figure 6: Chip shapes after machining of Al-Cu alloy and Al-Cu-Si alloy at a cutting speed of 0.5 m/s in wet cutting.

4. Discussion

4.1 Chip breakability and adhesion of a cutting tool in dry cutting

As described above, the chip breaking factor was greater in overaged materials for both the Al-Cu and Al-Cu-Si alloys in dry cutting. We discuss the cause of this as follows. After machining, adhesion of the workpiece to the rake face of the cutting tool was observed for both Al-Cu and Al-Cu-Si alloys. The adhesion area on the rake face was measured from a photograph of the tool after machining. Fig. 8 shows the relationship between the adhesion area on the rake face and aging temperature. The adhesion area on the rake face varies in a similar way to the chip breaking factor with aging temperature: the adhesion area of overaged

Figure 7: Chip breaking factor of Al-Cu alloy and Al-Cu-Si alloy plotted against aging temperature in wet cutting. The hatched area indicates the range of chip breaking factor for the Pb added free-cutting Al alloy (Al-Cu-Pb,Bi alloy).

materials is larger than those of underaged and peakaged materials, and the adhesion area decreases with increasing cutting speed. Therefore, it would appear that the chip breaking factor in dry cutting is strongly related to the adhesion on the rake face.

Figure 9 shows the relationship between the chip breaking factor and the adhesion area on the rake face. The chip breaking factor is proportional to the adhesion area on rake face for both the Al-Cu and Al-Cu-Si alloys, although the slope of the line differs depending on the material composition. Therefore, the increase in chip breakability in the overaged materials leads to greater adhesion on the rake face.

As such, if adhesion does not occur in machining process, the chips should be larger at any aging condition. Fig. 10 shows the chip breaking factor of Al-Cu alloys and Al-Cu-Si alloys plotted against aging temperature at a cutting speed of 0.5 m/s using polycrystalline diamond cutting inserts. The chip breaking factor of the Al-Cu

alloys and the Al-Cu-Si alloys was around 1000 for all aging conditions; this is indeed consistent with the relationship between chip breaking factor and adhesion area on the rake face as shown in fig. 9.

Figure 8: Adhesion area on rake face of cutting tool after machining of Al-Cu alloy and Al-Cu-Si alloy with aging temperature in dry cutting.

4.2 Reason for increase of chip breakability in Al-Cu-Si alloys in wet cutting

Figure 11 shows the relationship between the chip breaking factor and the adhesion area A on the rake face in wet cutting. In Al-Cu alloys, the chip breaking factor is proportional to the adhesion area on the rake face as with dry cutting, although the adhesion area in wet cutting is much smaller than that in dry cutting. In contrast, the chip breaking factor of Al-Cu-Si alloys is inversely proportional to the adhesion area on the rake face; evidently, there are other factors in the increase in chip breakability in wet cutting of Al-Cu-Si alloys.

To investigate these factors, bending tests were carried out in air and cutting oil for the chips after machining. Fig. 12 shows the results of the bending tests. For the Al-Cu alloys, no differences were observed for samples bent in air and cutting oil. On the other hand, for the Al-Cu-Si

Figure 9: Relationship between chip breaking factor and adhesion area on rake face for Al-Cu alloy and Al-Cu-Si alloy in dry cutting.

Figure 10: Chip breaking factor of Al-Cu alloy and Al-Cu-Si alloy at a cutting speed of 0.5 m/s in dry cutting using a diamond tool.

Figure 11: Relationship between chip breaking factor and adhesion area on rake face for Al-Cu alloy and Al-Cu-Si alloy in wet cutting.

alloys, the fracture stress of chips bent in cutting oil was lower than for those bent in air.

Rehbinder et al. have reported that the strength of metals were reduced by the infiltration of liquid to the microcracks near the surface [7]. Addition of Si to Al-Cu alloys considered to be increasing the number of microcracks owing to flaking off of the Si particles and matrix during machining. The strength of the chip decreases due to permeation of the cutting oil to the microcracks and accordingly, increases the chip breakability of Al-Cu-Si alloys in wet cutting.

Figure 12: Relationship between fracture stress of chip and aging temperature for Al-Cu alloy and Al-Cu-Si alloy.

5. Conclusion

The chip breakability of age-hardened Al-Cu and Al-Cu-Si alloys, and the variation of the chip breakability of those alloys by aging treatment during turning with carbide inserts was investigated. The main results are as follows.

1. In dry cutting, chip breakability of Al-Cu alloys and Al-Cu-Si alloys were smaller than that of the Pb added free-cutting Al alloys. Only overaged materials show equivalent chip breakability compared to the Pb added free-cutting Al alloys. The increase of N in overaged materials is considered to be due to the increase in adhesion of the workpieces to the surface of the carbide tool.

2. In dry cutting of overaged materials, surface roughness was also largely increased while chip breakability increased. From a practical viewpoint, the dispersion of Si in Al-Cu alloys has little effect on the chip breakability in dry cutting.

3. In wet cutting, the chip breakability of Al-Cu-Si alloys increased largely. The chip breakability of the Al-Cu-Si alloys is comparable to that of Pb added free-cutting Al alloys with preservation of good machined surface. This increase of chip breakability in Al-Cu-Si alloys is due to the decreased strength of chips as a result of infiltration of cutting oil to the microcracks in chips.

References

- [1] ASM International, Metals handbook, ninth edition volume 16 Machining, Metals Park, 761-804.
- [2] E. M. Trent and P. K. Wright, Metal cutting, fourth edition, Butterworth Heinemann, (2000), 254-258.
- [3] X.D.Zhang, L.C. Lee, KHW Seah, Knowledge base for chip management system, J. Mater. Process. Tech. 48 (1995) 215-221.
- [4] S. Yoshihara, M. Hirano, T. Eto, Effect of Si Particles on chipping characteristics of Al-Mg-Si alloys during drilling operation, J. Jpn. Inst. Light Met. 51 (2001) 238-241, (in Japanese).
- [5] T. Yakou, S. Yoshida, T. Hasegawa, Machinability of age-hardened Al-Cu, Al-Cu-Pb, Bi and Al-Cu-Si alloys from a view point of chip breaking, Trans. Jpn. Soc. Mech. Eng. 66 (2000) 3772-3777, (in Japanese).
- [6] K. Asano, A. Fujiwara, Quantitative evaluation of free-machining properties of 2011 alloy, J. Jpn. Inst. Light Met. 21 (1971) 578-588, (in Japanese).
- [7] P. A. Rehbinder, E. D. Shchukin, Surface phenomena in solids during deformation and fracture processes, Prog. Surf. Sci. 3 (1972) 97-188.