Machinability of Hypereutectic Silicon-Aluminum Alloys

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The machinability of high-silicon aluminum alloys made by a P/M process and by casting was compared. The cutting test was conducted by turning on lathes with the use of cemented carbide tools. The tool wear by machining the P/M alloy was far smaller than the tool wear by machining the cast alloy. The roughness of the machined surface of the P/M alloy is far better than that of the cast alloy, and the turning speed did not affect it greatly at higher speeds. The P/M alloy produced long chips, so the disposal can cause trouble. The size effect of silicon grains on the machinability is discussed.

Keywords high-silicon aluminum alloy, machinability, powder metallurgy

1. Introduction

Hypereutectic aluminum-silicon (Al-Si) alloys are low in specific gravity and coefficient of thermal expansion and have excellent wear resistance; hence they are used extensively in the manufacture of heat-resistant and wear-resistant parts, especially of parts where the alloy is a substitute for cast iron when the engineering advantage of light weight and wear resistance in service are considerations.

Machining is generally needed in producing structural parts. Hypereutectic Al-Si alloys are said to be the most difficult to machine among the various aluminum alloys. Tools wear very rapidly (Ref 1). For this reason attempts have been made to optimize selection of cemented carbide tools, cutting conditions (Ref 2, 3), and tool geometry (Ref 3) and to study the effect of the flank buildup (FBU) on the tool wear (Ref 4), the improvement of machinability by adding special elements (Ref 5, 6) and heating workpieces (Ref 7), and the effect of cutting fluids (Ref 8) on the machinability. However, a significant improvement in machinability has not been achieved. This is because the primary-phase silicon grains are much harder than any other phases in the microstructure and exert an abrasive influence on the tool. Although the refining of primary silicon is effective in improving the mechanical properties and machinability (Ref 9), it is difficult to obtain the optimum microstructure when the alloy is conventionally processed by ingot metallurgy (I/M) since the growth of proeutectic silicon cannot be prevented.

Conversely, powder metallurgy (P/M) technology using rapid solidification provides aluminum alloys with finely dispersed silicon grains. In addition, iron (Fe), manganese (Mn), and nickel (Ni) and their compounds can be successfully added in fine dispersive phases to produce novel aluminum alloys with excellent high-temperature properties and wear resistance (Ref 10). Few reports exist on the machinability of P/M processed Al-Si alloys in comparison with I/M processed alloys.

This report concerns the experimental analysis of machinability of P/M and I/M hypereutectic Al-Si alloys in terms of tool wear, surface roughness of machined surface, cutting force, and chip form.

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2. Experimental Procedure

Work materials of P/M and I/M hypereutectic Al-Si alloys, which are nearly equivalent to alloy AC9A (JIS H 5202), were prepared. The chemical composition and the hardness of the work materials are shown in Table 1. The I/M alloys were cast in sand molds without a grain refiner. The P/M alloys (Ref 10) were formed by compressing the atomized and classified hypereutectic Al-Si powder by cold isostatic pressing to produce the green compacts. The compacts were placed in 250 mm diameter aluminum cans and degassed. The degassed alloys in aluminum cans were hot pressed and hot extruded to a diameter of 90 mm, and the work material was categorized as a wrought alloy. The I/M workpiece had a flange form, which had a diameter of 110 mm and an effective length of 80 mm.

A tungsten carbide-cobalt (WC-Co) type cemented carbide tool of ISO-K10 (G10E, Sumitomo Electric Industries,

Table 1 Chemical composition and hardness of the samples

Sample	Composition, mass %				Hardness, HV100
	Cu	Si	Mg	Fe	
Al-20Si-2Cu-1 Mg, P/M	2.03	19.6	0.97	0.16	74
Al-20Si-2Cu-1 Mg, I/M	2.08	20.7	1.06	0.22	114
Al-20Si, I/M	<0.01	19.8	<0.01	0.15	59
Al-20Si-2Cu, I/M	2.07	20.9	<0.01	0.17	78

I/M: Cast in sand or metallic molds

Ltd.; Osaka, Japan) was used for the turning tests. The tool was a throwaway type (TPGN160308). The turning test on a lathe was done without a cutting fluid. The feed rate ranged from 0.05 to 0.2 mm/rev, and the depth of cut was in a range of 0.5 to 2.5 mm. The maximum width of flank wear land was determined by the use of a measuring microscope as a measure of the machinability.

The cutting force and thrust force were measured, and surface roughness of R_z (JIS B 0601-1994) was measured by using a stylus instrument. The measuring length was 2.5 mm.

3. Experimental Results

3.1 Tool Wear

Figure 1 shows the effect of depth of cut and feed rate on the maximum flank-wear width of the carbide tool when hypereutectic Al-20%Si-2%Cu-1%Mg alloys were turned. When the cast alloy was machined, the flank-wear width increased with increases in the depth of cut and the feed rate. The effect of the depth of cut was greater than that of feed rate. Their effects were much smaller in turning the P/M alloy than the I/M alloy.

Figure 2 illustrates the progress of the flank-wear width. It shows that the wear for the I/M alloys increases gradually until the maximum flank-wear width, VB_Bmax, becomes about 0.2 mm, but with increased cutting times, VB_Bmax grows rapidly beyond that value. The wear rate for P/M alloys is much smaller than that for I/M alloys. The tool-life curves for both alloys were plotted on a log-log graph paper as in Fig. 3. The cutting speed versus tool-life diagram produced the following equations. For I/M alloys:

VB_Bmax = 0.1 mm as the tool life criterion

$$VT^{0.63} = 63$$

where V is velocity and T is tool life.

VB_Bmax = 0.2 mm as the tool-life criterion

$$VT^{0.73} = 118$$

For P/M alloys:

VB_Bmax = 0.1 mm as the tool-life criterion

$$VT^{0.61} = 1644$$

The slopes of the tool-life curves for the alloys are not much different from each other, but the tool life for the P/M alloy is much longer than that for the I/M alloy (e.g. the tool life for the P/M alloy was about 200 times that for the I/M alloy for a cutting speed of 600 m/min).

The addition of copper (Cu) and magnesium (Mg) to hypereutectic Al-Si alloys deteriorates the wear resistance of carbide tools in dry cutting, but the tool wear for the P/M alloy

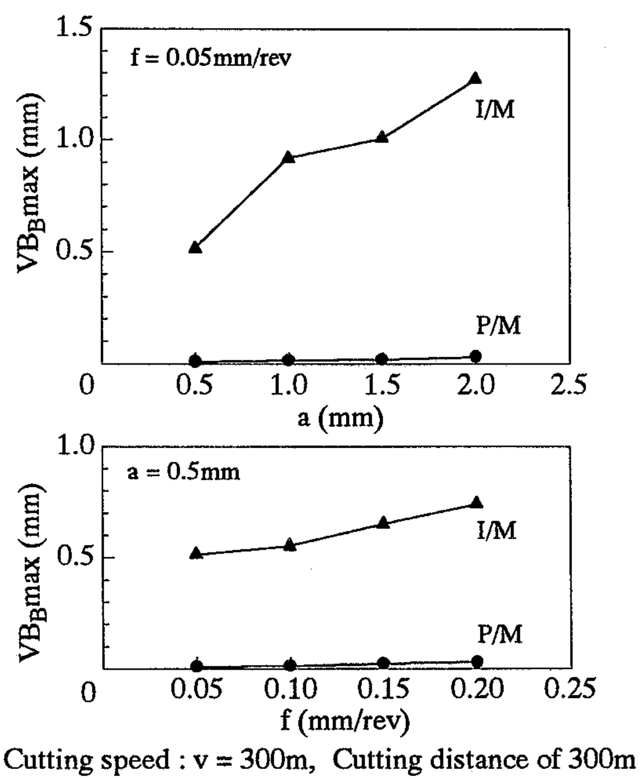

Fig. 1 Effects of depth of cut, *a*, and feed, *f*, on the width of flank wear land, VB_Bmax, for K10-tool in turning Al-20%Si-2%Cu-1%Mg alloys

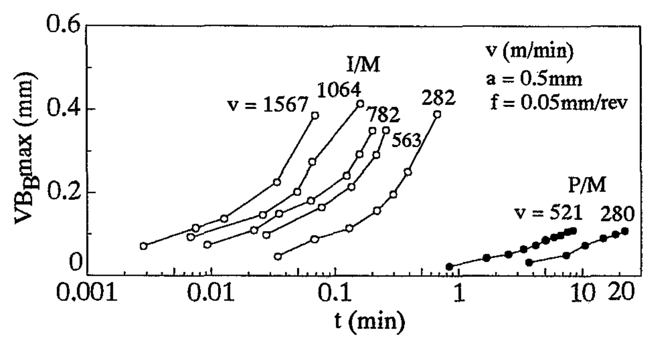

Fig. 2 Effect of cutting time, *t*, on the width of flank wear land, VB_Bmax, for K10-tool in turning Al-20%Si-2%Cu-1%Mg alloys

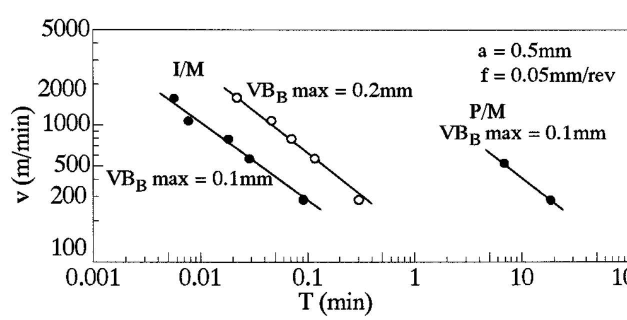

Fig. 3 Cutting speed, *v*, versus tool-life, *T*, curves for turning Al-20%Si-2%Cu-1%Mg alloys

with Cu and Mg addition was much smaller than that for the I/M alloy without Cu and Mg addition, as shown in Fig. 4.

3.2 Surface Roughness

The addition of Cu or Mg to hypereutectic Al-Si alloys of I/M production significantly improves the surface roughness in turning with the carbide tool, as can be seen in Fig. 5, which illustrates an example under the conditions of a speed of 300 m/min, a feed of 0.05 mm/rev, and a depth of cut of 0.5 mm. The surface roughness of the P/M alloy, however, was better than that of the I/M alloys with Cu and Mg addition.

Figure 6 shows the effects of the depth of cut and the feed on the roughness of the machined surface. The effect of the cutting depth was hardly recognized for both the I/M and the P/M alloys while the tools had a sharp cutting edge at the initial stage of cutting. However, the roughness of the I/M alloy increased with an increase in the depth of cut at a cutting length of 300 m. This is because the width of flank wear land increased rapidly with increasing depth of cut (as shown in Fig. 1), which caused the surface to become worse. On the other hand, the influence of the feed on the surface roughness was strong, as the ideal surface roughness calculated from the given tool shape and feed suggests. At a cutting length of 300 m, the surface roughness was nearly the same as that at the beginning of cutting, even though the feed increased. This was expected because the flank-wear width at a 300 m cutting length was nearly equal to that at the beginning of cutting as shown in Fig. 1.

Although flank buildup (FBU) was seen in turning at greater undeformed chip cross sections and at higher cutting speeds, the effect of the FBU on the surface roughness seemed slight under these cutting conditions.

Figure 7 shows the relationship between the cutting speed and the surface roughness of the Al-20%Si-2%Cu-1%Mg alloy. The average roughness value was measured at a cutting distance of up to 100 m. When turning the I/M alloy, large built-up edge was generated on the cutting edge so that the surface roughness was inferior to that for the P/M alloy. At higher cutting speeds the size of the built-up edge became smaller, and as a result the roughness improved remarkably as shown in Fig. 7. While the I/M alloy workpiece had a measured surface roughness of more than 20 times that of the calculated value of R_z, the P/M alloy had a surface roughness only several times that of the ideal value even at lower speeds, for example, 100 m/min, and the effect of the cutting speed was negligibly small.

3.3 Cutting Force

The effect of the depth of cut and the feed on the cutting force is plotted in Fig. 8 and 9. While the cutting edge remained

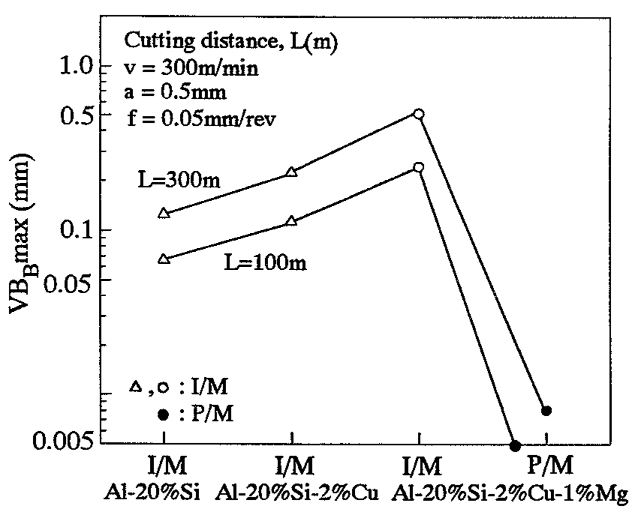

Fig. 4 Difference in width of flank wear land, VB_Bmax, for K10-tool in turning Al-20%Si, Al-20%Si-2%Cu, and Al-20%Si-2%Cu-1%Mg alloys

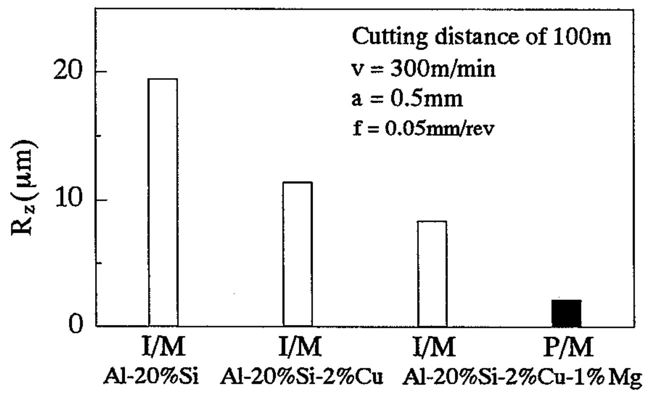

Fig. 5 Surface roughness, R_z, in turning aluminum alloys with different alloying elements and manufacturing methods

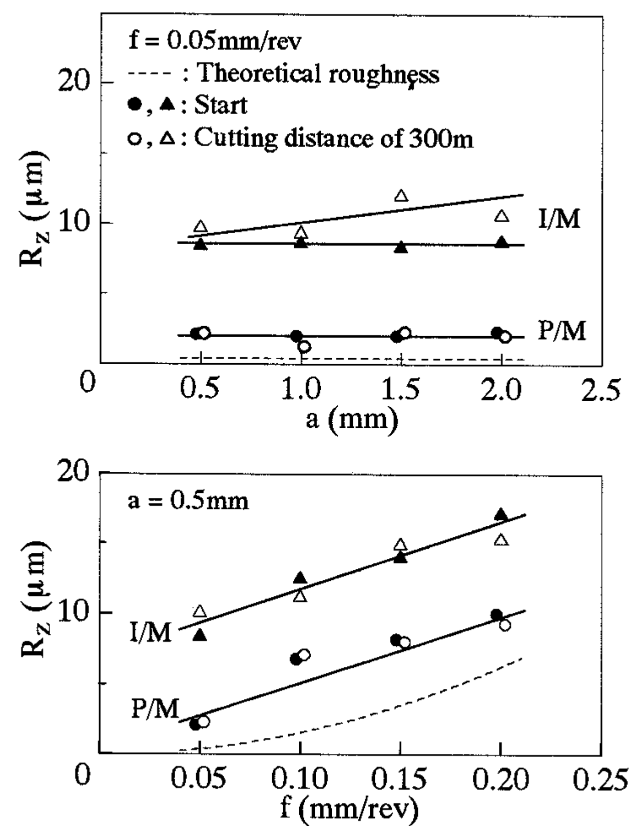

Fig. 6 Effects of depth of cut, *a*, and feed, *f*, on surface roughness, R_z, of Al-20%Si-2%Cu-1%Mg alloys for a cutting speed of 300 m/min

relatively sharp at the beginning of cutting, the cutting forces increased gradually for both the I/M and P/M alloys with increasing depth of cut or feed. As the cutting proceeded, the cutting forces considerably increased by raising the depth of cut.

Regarding the increase of the cutting forces, it is possible that the FBU is involved in the situation. In Fig. 8 the closed triangle and the open triangle symbols represent the values at the beginning of cutting with a sharp cutting edge and those at a cutting distance of 300 m, respectively. The half-closed triangles indicate the values at cutting after the FBU on the tool engaged in cutting for a 300 m distance was removed by etching. Figure 8 shows that the difference between the tools with and without the FBU is not appreciable; for this reason the increase in the cutting forces is mainly due to the increase in the flank-wear width.

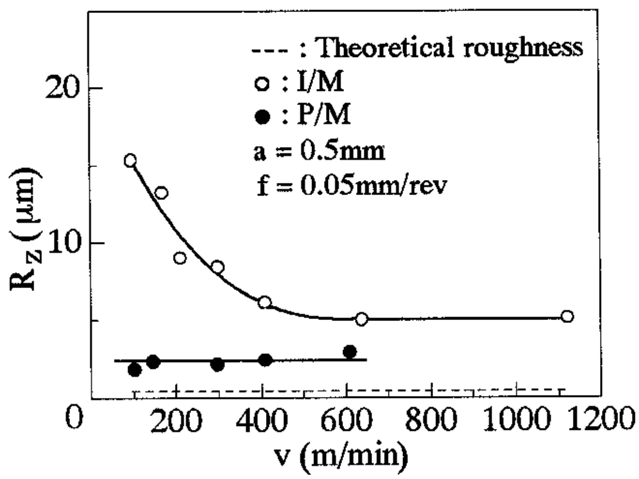

Fig. 7 Relationship between cutting speed, *v*, and surface roughness, R_Z, of Al-20%Si-2%Cu-1%Mg alloys

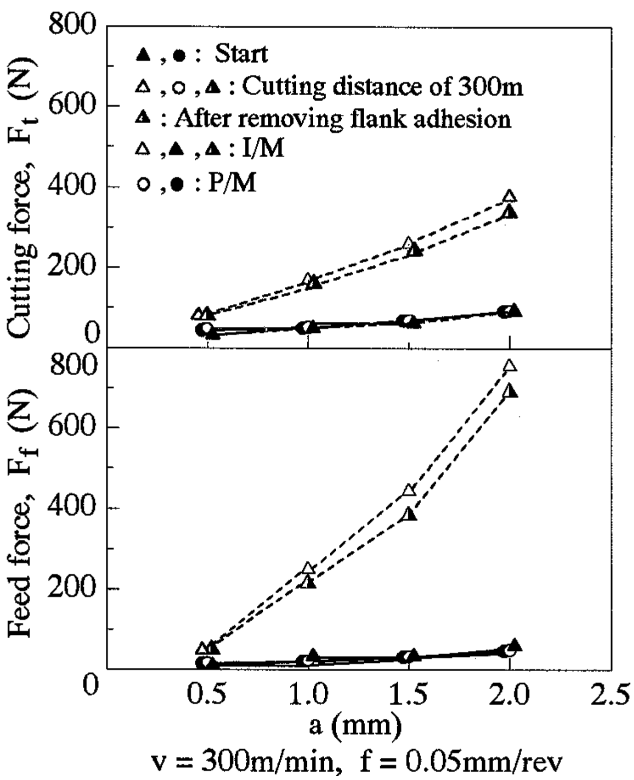

Fig. 8 Effect of depth of cut, *a*, on the cutting forces in turning Al-20%Si-2%Cu-1%Mg alloys

Figure 10 shows the cutting forces as a function of cutting speed. While the cutting edge was sharp at the beginning of cutting, the difference between the I/M and P/M alloys was slight irrespective of the cutting speed. The cutting forces of the I/M alloy increased, however, as the cutting proceeded and the tool wear grew.

3.4 Chip Forming

In cutting I/M alloy, broken chips were produced, which caused no problem, as shown in Fig. 11. However, continuous chips were produced in turning P/M alloy at higher speeds with reduced feeds, so controlling and breaking of chips might be needed in turning operations at the shop floor.

4. Discussion

The experimental results of the hypereutectic Al-Si alloys show that the tool wear for the P/M alloy was significantly smaller than that for the I/M alloy. In general tool wear is closely related to the hardness of the workpiece, the deformability of the matrix around the Si grains (Ref 12), and the size of proeutectic Si phases (Ref 9) in the work material. When the matrix of the work is hard and difficult to deform, the work material is difficult to deform in the shear zone in front of the cutting edge and on the tool surface so that the Si grains are secured firmly in their positions. As a result, the grains strongly abrade the tool cutting edge and flank. An increase in the hardness of the matrix results in greater width of flank wear (Ref 11, 12).

Figure 12 shows the results of the experiment together with the results of a previous report (Ref 11) on matrix hardness and tool wear. The difference in tool wear among the three types of Al alloy is very clear from the figure although the hardness of the alloys is distributed in different levels. The P/M alloy ex-

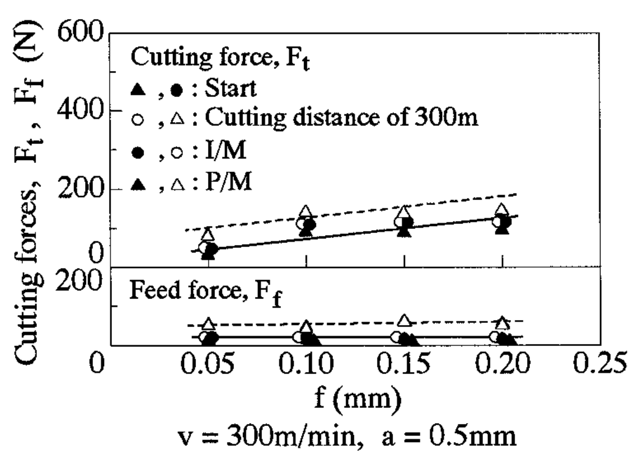

Fig. 9 Effect of feed, *f*, on the cutting forces in turning Al-20%Si-2%Cu-1%Mg alloys

hibited the best result for tool wear, and the tool wear for I/M alloy with sand molds is worse than that with metallic molds. Therefore, the hardness alone of the Al-Si alloys is not responsible for the tool wear development.

The eutectic composition of Al-Si alloys is about 12% Si, so about 8% in Al-20%Si alloys occurs as a primary phase. This primary-phase Si grain severely affects cutting tool wear when turning the alloys because the grain is much harder than any other phase in the microstructure. The flank-wear width $VB_B\max$ can be written as the following (Ref 9):

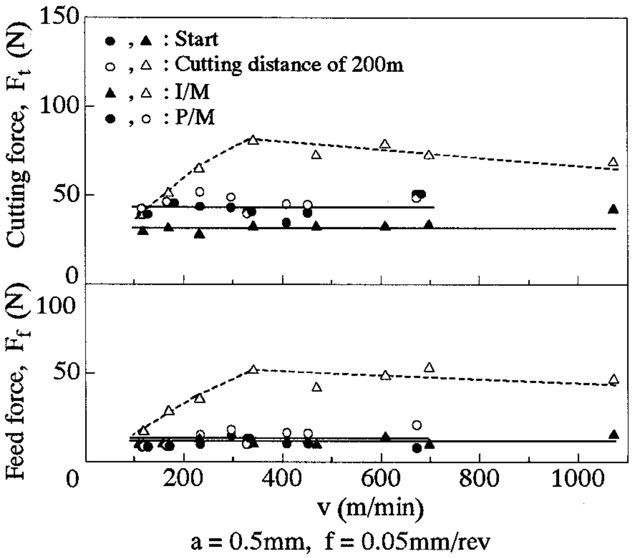

Fig. 10 Relationship between cutting speed, *v*, and cutting forces in turning Al-20%Si-2%Cu-1%Mg alloys

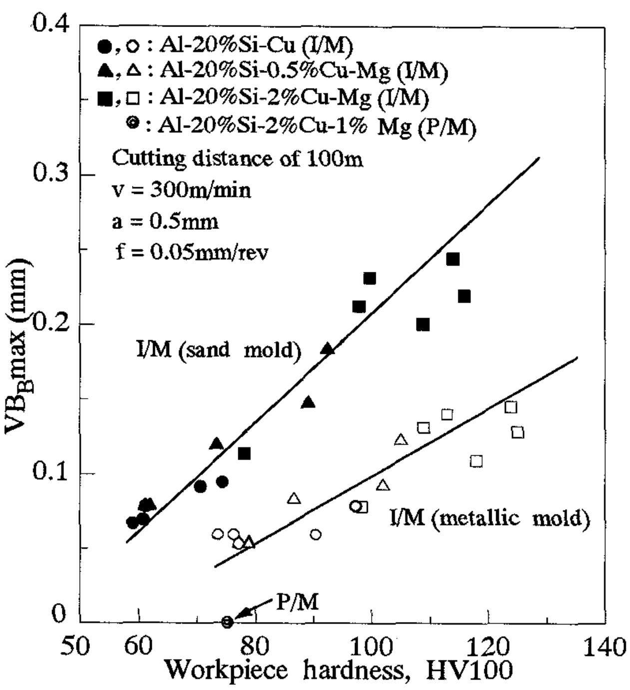

Fig. 12 Relationship between the width of flank wear land, VB_Bmax, and workpiece hardness of hypereutectic Al-Si alloys

$$VB_B\max = kd^{2.5}n$$

where k is constant, d = diameter of primary Si grains, and n is the number of primary Si grains.

This means that the effect of the grain diameter is greater than that of the number.

The effect of Si grain size on tool wear was investigated using Al-20%Si-2%Cu-1%Mg alloys with different grain sizes as follows: (a) P/M alloy with grains of an average diameter of 5. 6 μm, (b) I/M alloys with grains of an average diameter of 164 and 136 μm, sand mold casting, (c) I/M alloys treated by a grain refiner with grains of an average diameter of 87 μm, sand mold casting, (d) I/M alloys with grains of an average diameter of 114 μm and 93 μm, metallic mold casting, and (e) I/M alloys treated by a grain refiner with grains of an average diameter of 52 μm, metallic mold casting. The results obtained are shown in Fig. 13. As seen from Fig. 13, the refinement of Si grains is very effective in improving the machinability irrespective of the production method of the alloys.

The surface roughness of a machined workpiece improves (Ref 13) with an increase in the hardness of Al-Si alloys. The hardness of the matrix and the surface roughness are plotted together with the results of a previous report (Ref 11) in Fig. 14. Up to a certain level, the hardness increase is effective in improving the surface roughness (Ref 13). The surface roughness of the P/M alloys is far better than that of the other alloys. The

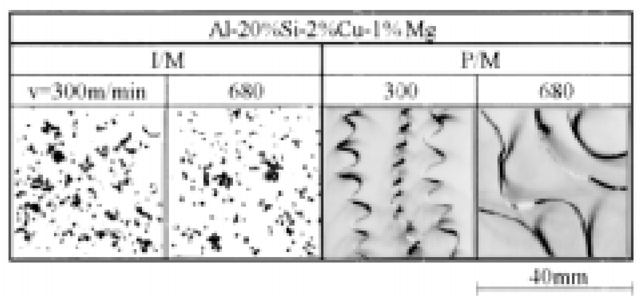

Fig. 11 Comparison of chips for I/M and P/M Al-20%Si-2%Cu-1%Mg alloys (tool without a chip-breaker, a = 0.5 mm, f = 0.05 mm/rev)

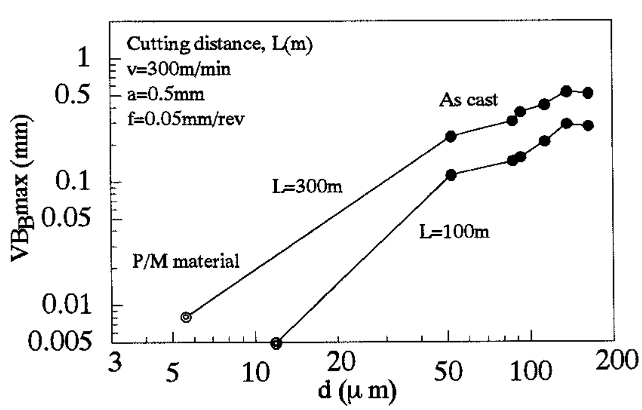

Fig. 13 Effect of average grain size of primary Si grains, *d*, on the width of flank wear land, VB_Bmax, for K10-tool in turning Al-20%Si-2%Cu-1%Mg alloys

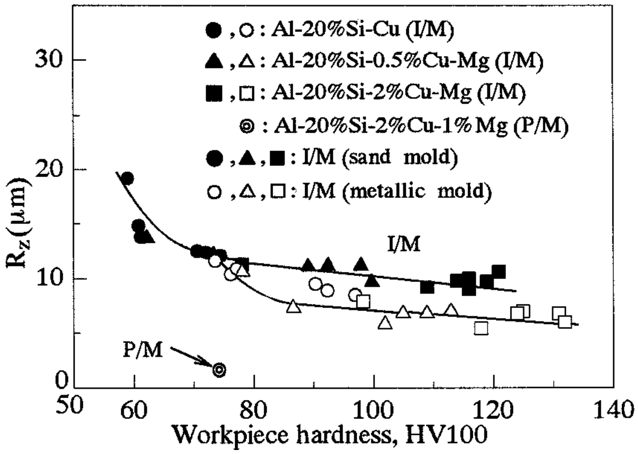

Fig. 14 Relationship between surface roughness, R_Z, and hardness of hypereutectic Al-Si alloys for a cutting distance of 100 m, v = 300 m/min, a = 0.5 mm, and f = 0.05 mm/rev

refinement of the Si grains in the P/M alloy might result in the smaller wear width and the finer minor cutting edge than that for coarse primary Si grains in the I/M alloys.

5. Conclusions

- The maximum flank-wear width for the P/M alloy was much smaller than that for the I/M alloy, and the effect of the depth of cut on the wear was slight for the P/M alloy while the effect for I/M alloy was significant.
- While the surface roughness of the machined workpiece for the I/M alloys at low cutting speeds was more than ten times the ideal roughness, the surface roughness for the P/M alloy was considerably better than that for I/M alloy and was almost unaffected by cutting speed.
- While the cutting forces for the I/M alloy increased with an increase in cutting distance due to the growth of tool wear and the effect of the depth of cut and the feed was great, the effect of these factors was small for the P/M alloy.
- When turning the I/M alloy, broken chips were produced. Chips from the P/M alloy tended to be long ribbons at small feeds.

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