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과공정 알루미늄 실리콘 합금의 초음파 진동 절삭에 관한 연구

이은상*

A Study on the Ultrasonic Vibration Cutting of Hypereutectic Aluminum-Silicon Alloy

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ABSTRACT

과공정 알루미늄 실리콘 합금 (Hypereutectic Al-Si Alloy, A390)은 내마멸성 및 우수한 강성에 의해서 자동차 부품에 많이 사용되고 있다. 본 연구에서는 초음파 진동 절삭에 의한 과공정 알루미늄 실리콘 합금의 가공성과 실리콘 석출의 실험적 연구를 수행 하였다. 최적 공구와 가공조건의 선정 실험을 통하여 보다 효과적인 초음파 진동 절삭을 수행하였으며, 과공정 알루미늄 실리콘 합금의 가공 표면거칠기와 실리콘 석출은 절삭속도와 절삭깊이와 밀접한 연관성을 갖고 있다.

Key Words : Hypereutectic Al-Si Alloy(과공정 Al-Si 합금), Ultrasonic Vibration Cutting (초음파 진동 절삭), Extraction of Silicon Particles (실리콘 입자 석출), Critical Cutting Speed (임계속도)

1. Introduction

In recent years, developments in the auto industry have brought a rapid increase in the use of hypereutectic Al-Si alloys for the manufacture of automotive components. Because of their low density, high wear resistance and high strength at elevated temperatures(1), such alloys are used for engine blocks, air compressor cylinders and VTR cylinder heads. The alloys generally contain 16 to 18% of silicon and have a wear resistance better by about 35% than that of eutectic Al-Si alloy containing 12% of silicon. In addition, the fluidity of the molten alloy is improved by 18 to 20%. However, the hard particles present in hypereutectic alloys accelerate the wear of cutting tools during machining(2). This restricts the use of hypereutectic Al-Si alloys. Miller(3) has observed tool wear phenomena during the machining of Al-Si alloys with tungsten-carbide tipped and polycrystalline diamond tools. Hanasaki(4) studied the mechanical scratching action of Si particles on the cutting edge of a tool, and observed micro-cutting under scanning electron microscope. Sugaho(5) investigated the surface roughness produced during mirror-like machining of an Al-Mg alloy with a single-crystal diamond tool. He found that surface roughness is affected by feed rate

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and tool tip radius, and concluded that proper tool selection is an essential element of the process of optimizing the machining conditions. As the result of the extraction of Si particles on the surface after cutting, the mechanical properties of the Al-Si alloy is improved. In the case of hypereutectic Al-Si alloy, conventional cutting is limited from the standpoint of improvement of the machined surface and the extraction of Si particles. Skelton[6] suggested that ultrasonic vibration could be used to reduce the mechanical strength of the workpiece material during the cutting process. Takeyama[7] showed experimentally that ultrasonic vibration cutting of CFRP is highly effective in terms of cutting force and surface quality.

In this study, the machinability of the hypereutectic Al-Si alloy and the extraction of Si particles at its surface by means of ultrasonic vibration cutting were experimentally investigated. By proper cutting tool selection and optimization of cutting conditions, effective ultrasonic vibration cutting of this alloy was achieved.

2. Theory of Vibration Cutting [8]

Fig. 1 shows the ultrasonic vibration cutting mechanism, where f is the frequency, a is the one-side amplitude of vibration, and T is the period of vibration. The displacement of the cutting tool starts from origin O and a cutting force curve of pulse type is applied. The displacement of the cutting tool y is :

$$y = a\sin\omega t \qquad (1)$$

where ω is the angular frequency of the cutting tool.

The velocity of the cutting tool y' is:

$$y' = a\omega\ \cos\omega t \qquad (2)$$

The velocity of the tool is the same as the velocity of the workpiece at points A and D. If the time at point A is t_1, then at point D it is $(t_1 + T)$. The velocity is:

$$-V = a\omega\ \cos\omega t \qquad (3)$$

The critical cutting speed (which determines whether there is contact or separation between the rake face of the tool and the workpiece) is as follows:

$$Vc = a\omega = 2\pi af \qquad (4)$$

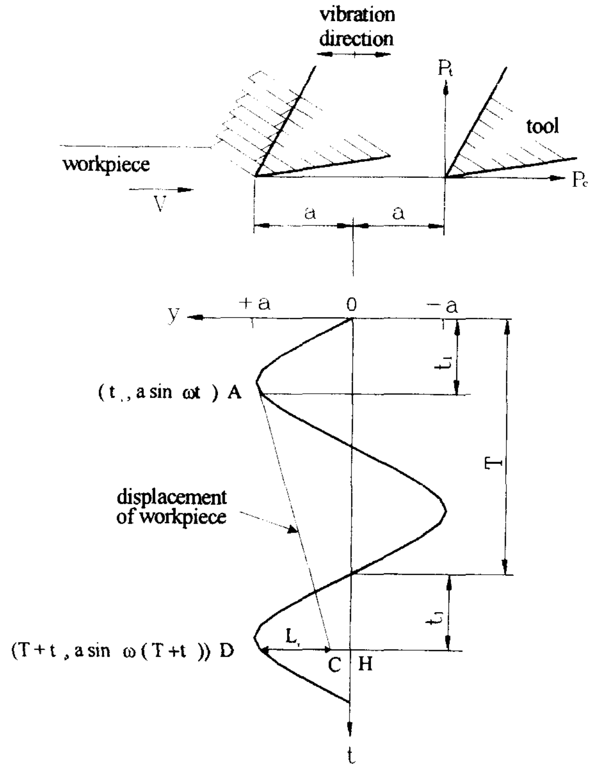


Fig. 1 Mechanism of the ultrasonic vibration cutting

The time from point A to point D is a period of vibration cutting and a moving distance CD is the cutting length for one period. The displacement of the workpiece after point A is as follows:

$$y = a\sin\omega t_1 - V(t - t_1) \qquad (5)$$

The time at point D is $T+t_1$ and the time after point A is $(T+t_1) - t_1$

$$CH = a\sin\omega t - VT \qquad (6)$$

$$CD = L_T = DH - CH = VT = V/f \qquad (7)$$

Thus, the cutting length L_T in the cutting direction during a vibration period of the cutting tool is:

$$L_T = V\ /\ f \qquad (8)$$

3. Experimental procedure

The material used in this investigation was the hypereutectic alloy A390, whose chemical composition (ASTM STD E176) and mechanical properties are shown in table 1. Fig. 2 shows the experimental system of ultrasonic-vibration cutting using a lathe. In order to measure the cutting force, a tool dynamometer is installed below the ultrasonic vibration cutting unit, its cutting-force signal being measured by a pick up and passed to a computer after A/D conversion. The ultrasonic vibration system used in the experiments has 19.5 kHz frequency and 15μm amplitude.

Table 1 Chemical composition of hypereutectic Al-Si alloy (A390 ; ASTM STD. E716)

Contents	Compositions (%)
Silicon	16.0 - 18.0
Copper	4.0 - 5.0
Magnesium	0.45 - 0.65
Manganese	0.1 Max
Iron	0.5 Max
Zinc	0.1 Max
Titanium	0.2 Max
Others	0.2 Max
Aluminum	Remainder

Mechanical properties of A390

Young's Modulus	8.2 x 10^7 (KPa)
Thermal Conductivity	126.4 (W/m.K)
Thermal Expansion	1.8 x 10^{-5}(per°C)
Hardness (500Kg)	125 (HB)
Density	0.28 (Kg/m^3)

Fig. 3 shows a schematic diagram of ultrasonic vibration cutting of hypereutectic Al-Si alloy. The cylinder surface is machined by vibration cutting.

Fig. 4 shows the geometries of the tools used. Three types of tools (R 0.5, straight and R 1000) were used. At first, the experiments were carried out on the basis of the effect of machining on the alloy,

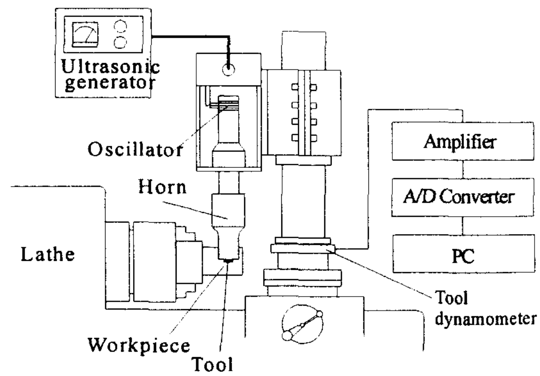


Fig. 2 Experimental apparatus of the ultrasonic vibration cutting

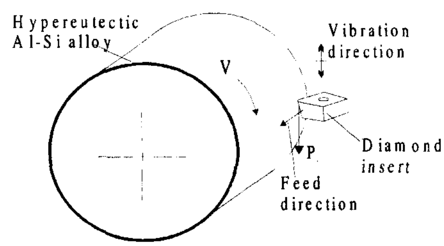


Fig. 3 Ultrasonic vibration cutting of hypereutectic Al-Si alloy

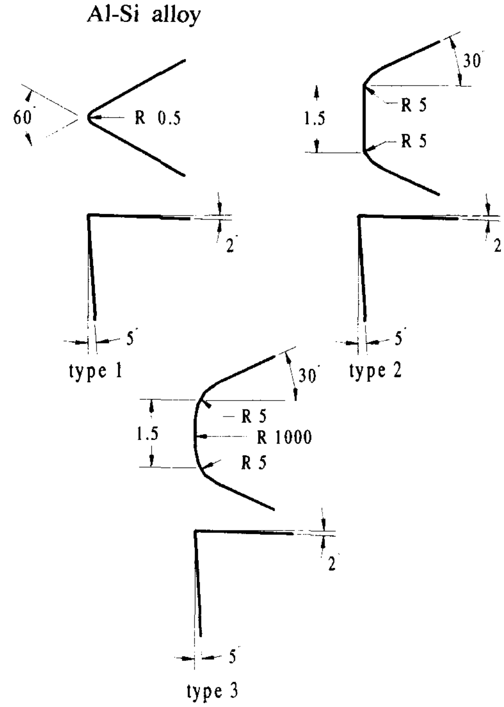


Fig. 4 Geometry of tools

and the adaptability of ultrasonic vibration cutting and hypereutectic Al-Si alloy machining under various cutting conditions was investigated. Table 2 shows the cutting conditions for the ultrasonic vibration cutting. In addition, the machined surface and the extraction of silicon were observed and analyzed by means of a surface roughness tester and Scanning Electron Microscope (SEM).

Table 2 Experimental cutting conditions

Tool (material)	Poly crystal diamond Single crystal diamond
Workpiece	Hypereutectic Al-Si alloy
Cutting speed	0.7 - 130 m/min
feed rate	0.07 - 0.4 mm/rev
Depth of cut	0.01 - 0.3 mm
Ultrasonic frequency Amplitude	 19.5 kHz 15 μm
Tool Dynamometer	Strain Gauge type Sambo Elec. Co.
Surface Roughness Tester	Mitutoyo Surftest - 420 λc /L = 0.8

4. Experimental Results and Discussion

4.1 Effect of ultrasonic vibration cutting

Fig. 5 shows the surface roughness of hypereutectic Al-Si alloy machined by poly crystal diamond (type3) and single crystal diamond tool (type3), comparing the results of conventional and ultrasonic vibration cutting for various cutting speeds, with a fixed feed rate 0.07 mm/rev and depth of cut 0.04mm. For a cutting speed from 0.7 m/min to 88 m/min, the surface roughness by ultrasonic vibration cutting is better than by conventional cutting, thus representing a good effect of hypereutectic Al-Si alloy machining. The reason for this seems to be that the ultrasonic vibration unit produces a sinusoidal vibration during hypereutectic Al-Si alloy machining, this operation

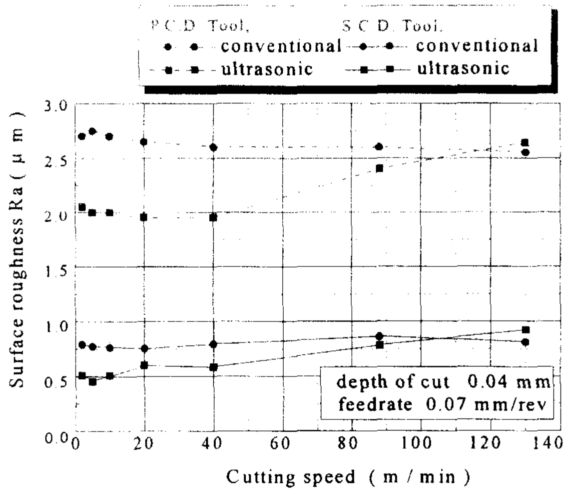


Fig. 5 Surface roughness according to cutting speed

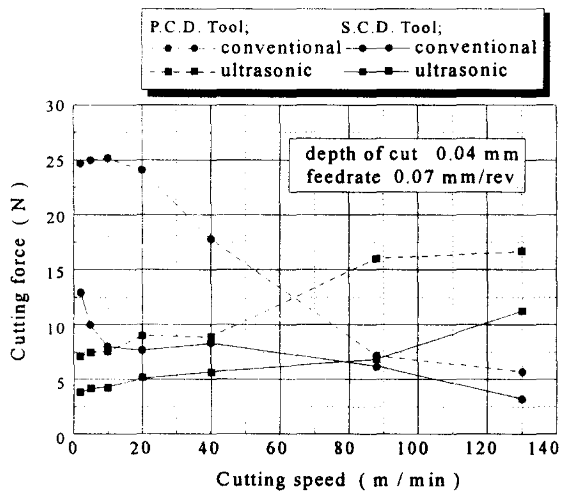


Fig. 6 Cutting force according to cutting speed

effecting a decrease of cutting force and cracks of hypereutectic Al-Si alloy during cutting because of the impact force arising from the motion of separation and re-contact between the tool and the workpiece. While the cutting speed increase, the cut length of cutting direction $L_T = V/F$ increases. Due to the shorter the cut length in the cutting direction per one period, there is no probability of removal of Si particles on the surface of Al-Si alloy. As a result, a low cutting speed and a high frequency of ultrasonic wave are effective. A low cutting speed is desired for good surface quality and the extraction of silicon on the surface, because the frequency of ultrasonic wave is fixed. And, the surface roughness by using single crystal diamond tool is better than that by using poly crystal diamond tool.

Fig. 6 shows the cutting force according to cutting speed using a poly crystal diamond and single crystal diamond tools. In the case of conventional cutting, the cutting force decreases as the cutting speed increases. However, with ultrasonic vibration cutting, the cutting force tends to increase with increasing cutting speed. If the cutting speed is greater than the critical cutting speed ($V_C=2\pi af$) of ultrasonic vibration, the effect of ultrasonic vibration cutting is cancelled because of an offset of the separation and re-contact motion between the cutting tool and the workpiece. In accordance with the specification (a=15μm, f=19.5KHz) of the ultrasonic vibration unit, the critical cutting speed is about 110 m/min. Considering the resistance to cutting, in ultrasonic vibration cutting the cutting force is a little below the critical speed. And, the cutting force with single crystal diamond tool is about half as much as with poly crystal diamond tool. Thus, below the critical cutting speed, the single crystal diamond tool is more effective for the machining of hypereutectic Al-Si alloy.

4.2 Effect of depth of cut and feed rate

Fig. 7 shows the surface roughness of hypereutectic Al-Si alloy machined with a single crystal diamond tool (type3), comparing the results of conventional and ultrasonic vibration cutting for various depth of cut, with a fixed feed rate 0.07 mm/rev and cutting speed 10 m/min. In the case of conventional cutting, the surface roughness increases largely according to increasing of depth of cut. However, the surface roughness in the ultrasonic vibration cutting is showed a tendency to increase small according to increasing of depth of cut. Thus, in spite of increasing depth of cut, the ultrasonic vibration cutting has a good effect on the surface roughness of Al-Si alloy.

Fig. 8 shows the cutting force when using single crystal diamond tool (type3), comparing the results of conventional and ultrasonic vibration cutting for various depth of cut, with a fixed feed rate 0.07 mm/rev and cutting speed 10 m/min. In the case of conventional cutting, increasing the depth of cut produced a higher cutting force, and this variation was more pronounced than with ultrasonic vibration cutting. The discontinuous cutting in the latter case thus has a favorable in that it reduces the cutting force.

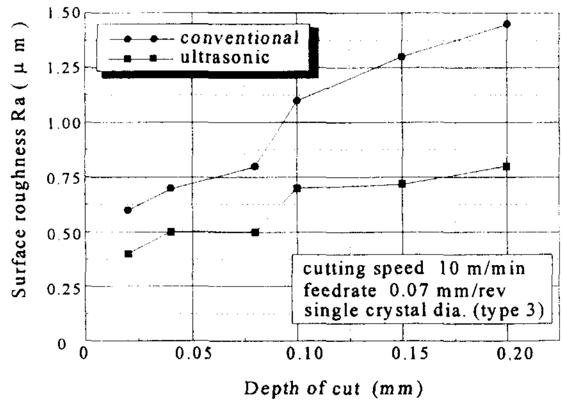


Fig. 7 Surface roughness according to depth of cut

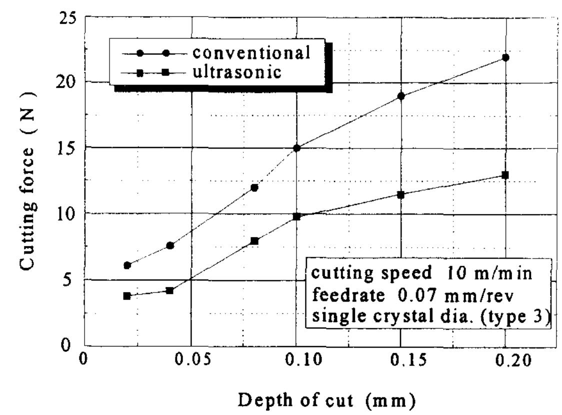


Fig. 8 Cutting force according to depth of cut

Fig. 9 shows the variation of the surface roughness of hypereutectic Al-Si alloy machined with single crystal diamond tool (type3) for various feed rates, with a fixed depth of cut 0.1 mm and cutting speed 10 m/min. The greater the feed rate, the worse was the surface roughness, but the surface roughness after

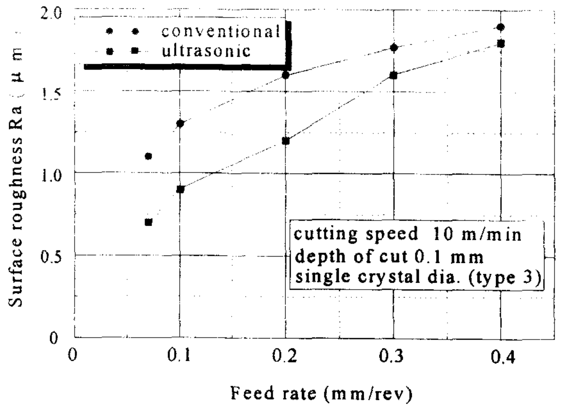


Fig. 9 Surface roughness according to feed rate

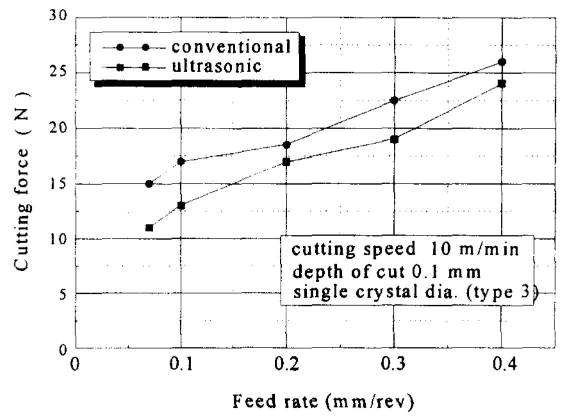
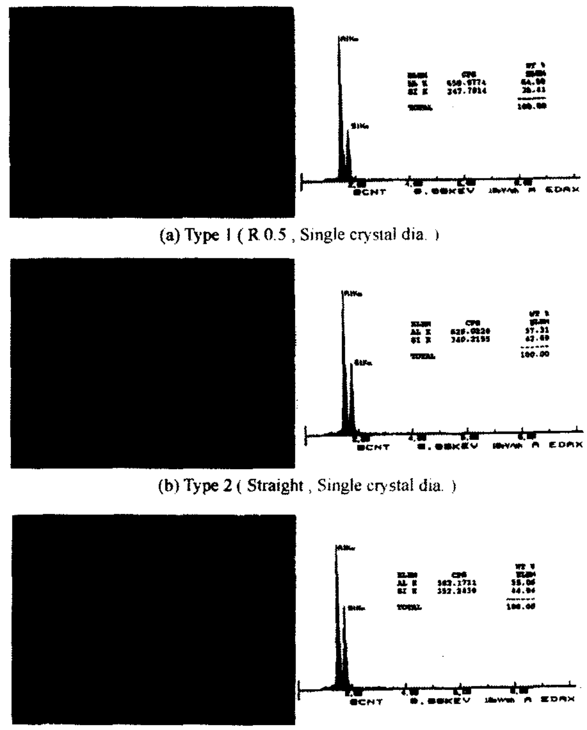


Fig. 10 Cutting force according to feed rate



(a) Type 1 (R 0.5 , Single crystal dia.)

(b) Type 2 (Straight , Single crystal dia.)

(c) Type 3 (R 1000 , Single crystal dia.)

cutting speed : 3 m / min feed rate : 0.1 mm / rev depth of cut : 0.05 mm
(A : silicon particles)

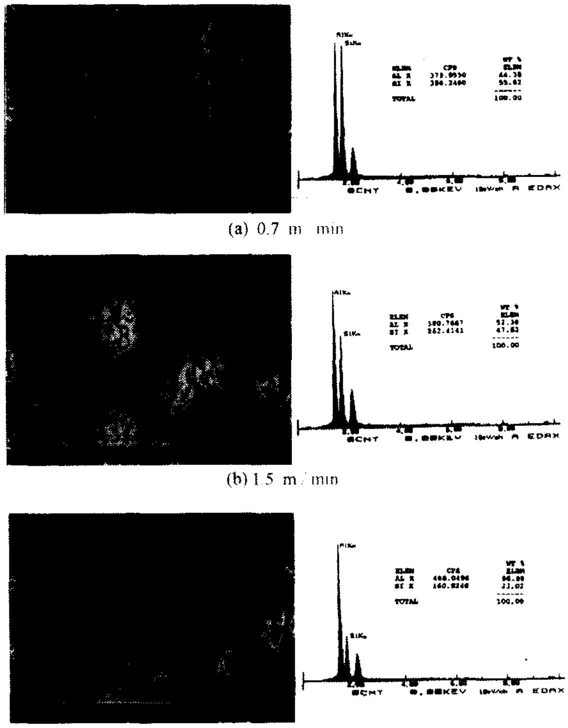
Fig. 11 SEM photograph and chemical composition of ultrasonic vibration cutting surface according to geometry of tools

ultrasonic vibration cutting was less than after conventional cutting. As the feed rate was increased, the surface roughness for conventional cutting and ultrasonic vibration cutting approached each other.

Fig. 10 shows the cutting force with a single crystal diamond tool (type3), comparing the results of conventional and ultrasonic vibration cutting for various feed rates. Increasing feed rate resulted in a higher cutting force, displaying a similar trend to that of the surface roughness. In the ultrasonic vibration cutting, a smaller feed rate has a good effect on the decrease of cutting force and surface roughness.

4.3 Analysis of a surface quality

Fig. 11 shows the photograph and the results of chemical composition analysis by means of SEM on the machined surface of Al-Si alloy by ultrasonic vibration cutting according to tool geometry. Three types of tools are used (a) Type 1 (R0.5), (b) Type 2 (straight) and (c) and Type 3 (R1000). Silicon particles (A) are extracted on all surfaces, the surface by using R1000 tool is more silicon particles extraction than using other tools. The analysis of chemical composition is carried out within 0.2× 1.5mm measurement range. Assuming that the composition ratio of a surface is 100%, the weight composition of silicon on the machined surface by (a) type.1 is 35.41%, type.2 is 42.69% and (c) type.3 is 44.94%. Thus, as machining with single diamond tool of R1000, silicon particles on the machined surface are extracted the most plentiful. The geometry of tool (R1000) is the best for the machining of hypereutectic



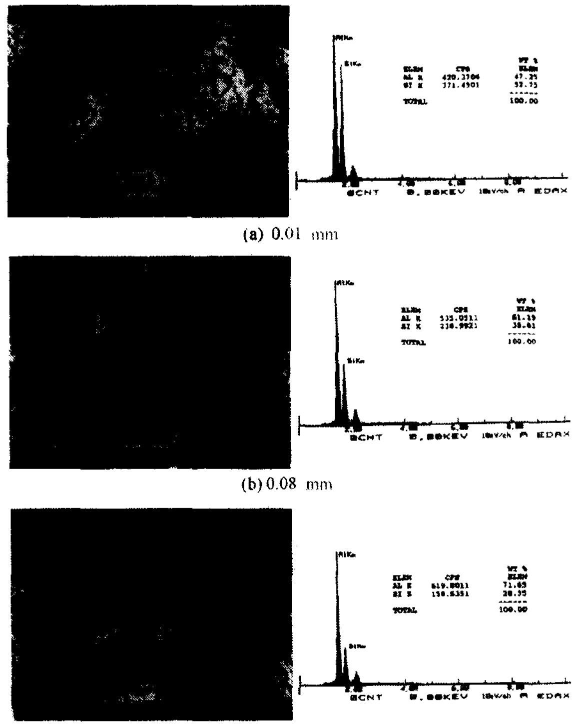
(a) 0.7 m/min

(b) 1.5 m/min

(c) 70 m/min

feed rate : 0.1 mm/rev depth of cut : 0.05 mm
(A : silicon particles)

Fig. 12 SEM photograph and chemical composition of ultrasonic vibration cutting surface according to cutting speed



(a) 0.01 mm

(b) 0.08 mm

(c) 0.1 mm

feed rate : 0.1 mm/rev cutting speed : 1 m/min
(A : silicon particles)

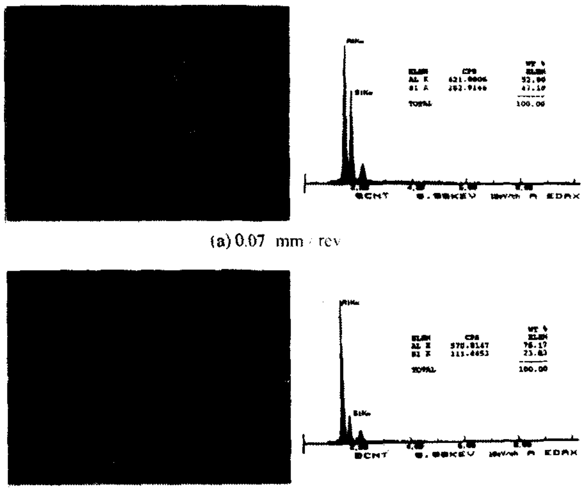
Fig. 13 SEM photograph and chemical composition of ultrasonic vibration cutting surface according to depth of cut

Al-Si alloy. The experiment was carried out afterward using the tool of R1000.

Fig. 12 shows the photograph and the result of chemical composition analysis by means of SEM on the machined surface of Al-Si alloy by ultrasonic vibration cutting according to cutting speed at fixed feed rate and depth of cut. The silicon particles of (a) 0.7 m/min are large and extracted good. In the case of (b) 1.5 m/min, it shows also good machined result which is silicon particles are spread over the whole surface. In the case of(c) 70 m/min, a few extraction of silicon particles is observed. In case of (a) 0.7m/min, the weight composition of silicon is 55.62%, (b) 1.5m/min is 47.62% and (c) 70m/min is 33.02%. Therefore, in the ultrasonic vibration cutting, the decreasing cutting speed has a good effect on the extraction of silicon particles.

Fig. 13 shows the photograph and the result of chemical composition on the machined surface of Al-Si alloy by ultrasonic vibration cutting according to depth of cut at fixed feed rate and cutting speed. In case the of 0.01 mm depth of cut, silicon particles (the weight composition of silicon : 52.75%) are extracted good. In the case of (b) 0.08mm and (c) 0.1mm, the extraction of silicon particles is very a few. If the depth of cut increases, the cutting force increases and the resistance of discontinuous cutting by ultrasonic vibration becomes large. Thus, the effect of ultrasonic vibration decreases and the silicon extraction on the machined surface is reduced.

Finally, fig. 14 shows the photograph and the results of chemical composition analysis by means of SEM of the machined surface of Al-Si alloy by



(a) 0.07 mm/rev

(b) 0.3 mm/rev

cutting speed : 1 m/min depth of cut : 0.04 mm
(A : silicon particles)

Fig. 14 SEM photograph and chemical composition of ultrasonic vibration cutting surface according to feed rate

ultrasonic vibration cutting according to feed rate at fixed depth of cut and cutting speed. The silicon extraction on the machined surface after machining with 0.07 mm/rev is more than after 0.3 mm/rev, the respective weight compositions of silicon on the machined surface being 47.1% and 23.83%. Thus, in the ultrasonic vibration cutting, decreasing feed rate has a good effect on the extraction of silicon particles.

5. Conclusions

From the experimental results in ultrasonic vibration cutting of hypereutectic Al-Si alloy A390, particular conclusions emerge, as follows :

1. Below a critical cutting speed, ultrasonic vibration cutting results in a better surface than does conventional cutting in the machining of hypereutectic Al-Si alloy. With ultrasonic vibration cutting, decreasing the cutting speed has a good effect on the extraction of silicon particles and the decrease of cutting force.

2. For the ultrasonic vibration cutting of hypereutectic Al-Si alloy, single crystal diamond is excellent as the tool material and the R1000 tool geometry is best for the extraction of silicon particles in the surface. Thus, the single crystal diamond tool of R 1000 geometry is the optimum tool for ultrasonic vibration cutting.

3. In the ultrasonic vibration machining of hypereutectic Al-Si alloy, depth of cut and feed rate are important factors that affect the surface quality and the silicon extraction.

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