Orthogonal Cutting of Ti-48at% Al Lamellar Structure Alloy

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Abstract:
The machinability, especially generation of surface defects, of Ti-47.7at%Al fully lamellar structure was examined by orthogonal cutting. Although surface defects were observed in every cutting condition, the machined surface tended to be significantly smoother as the depth of cut decreased 100µm to 20µm, and the rake angle of the tool was changed +5° to -5°. The surface defects were categorized into 2 groups depending on whether it is caused by lamellar layer, or lamellar colony boundary. It is discovered that the former is generated preferentially onto certain lamellar angle, and the latter showed no relation to the lamellar angle.

Keywords: Processing of advanced materials, Intermetallic compounds, Orthogonal cutting, Ti-Al, Machinability

1. Introduction
TiAl based intermetallic compound has excellent heat resistance, corrosion resistance, and specific strength. Thus this material is expected to be applied to turbine blades and many other heat resistant structural material for next generation. Especially, the range of 46-48at%Al which contains TiAl-Ti₃Al lamellar structure is considered as most close to practical use due to its strength-toughness-balance compared to single phase intermetallic compound.

On the other hand, TiAl based intermetallic compound is known for its brittleness which leads to difficulty of machining process like many other intermetallic compounds[1]. Although there is an attempt of shaping process by precision casting, finish cutting is still necessary for high accuracy. Furusawa et al. reported that when lamellar structure had been cut, surface defects observed, which oriented perpendicular to the cutting direction on machined surface[2]. It was also pointed out that these defects weaken bending strength remarkably.

In this study, Ti-Al intermetallic compound is tested with orthogonal cutting, and the relationship between the direction of lamellar structure and cutting condition will be reported.

2. Experimental procedure
2.1 Specimen
Ti-47.7at%Al alloy ingot which made from vacuum arc melting was used for test piece. After the casting, the ingot was annealed at 1000°C for 240 hours to homogenize, then vacuum-annealed at 1400°C for 1min to obtain fully lamellar structure. Fig.1 shows optical micrograph of lamellar structure obtained. The colony size was 0.5mm to 1.0mm in average. From this, specimen was cut out into 30mm × 20mm × 1mm by diamond wheel.

Figure 1: Optical micrograph of lamellar structure in Ti-47.7at%Al.

2.2 Orthogonal cutting
Cutting test was performed by orthogonal cutting as shown schematically in Fig. 2. Cutting condition was as follows. Depth of cut, a = 100µm, 80µm, 50µm, 20µm, cutting speed, v = 1mm/sec, rake angle, θ = +5°, -5°, and tool was cemented carbide WC-5%Co alloy (K10).

Figure 2: Schematic representation of orthogonal cutting.
After cutting test, the machined surfaces were observed by SEM microscope. After SEM observation, every specimen was mechanically polished both its machined surface and cross sectional surface, etched by 3% hydrofluoric acid, and observed its lamellar orientation by optical microscope. Additionally, the cross sectional surface was mechanically polished until half way through the thickness of the specimen, in order to avoid the effect of burr and chipping on the edge.

For the discussion hereafter, the depth of surface defects, and lamellar angle are defined as in Fig. 3. Depth of surface defects, d, is defined as the perpendicular distance between the bottom point of the defect and the machined surface. Lamellar angle is defined from following two angles, $\alpha$ and $\beta$. $\alpha$ is an angle between cutting direction and the lamellar angle on the cross sectional surface. $\beta$ is an angle between cutting direction and the lamellar angle on the machined surface. Furthermore, at the boundary of two different lamellar colonies, there is a lamellar colony boundary formed with lamellar grain boundaries from each colony. We define this boundary as not grain boundary, but lamellar colony boundary.

Figure 3: Definition of $\alpha$, $\beta$, and d in orthogonal cutting.

3. Results and discussion
3.1 Observation of machined surface

Figure 4 and 5 shows the SEM micrographs of machined surface when depth of cut was 100 $\mu$m, and 20 $\mu$m. There were surface defects, such as cracks and peelings, observed in each cutting conditions. Although Furusawa et al.[2] only reported the cracks which are generated perpendicular to the cutting direction, there are also cracks generated in other directions as well. In Fig. 4(a), there are cracks which oriented at slant angles to the cutting direction. These cracks forecast the effect of lamellar angle to the surface defects. As the depth of cut decreases to 20 $\mu$m from 100 $\mu$m, the number of surface defects decreases. For other cutting conditions, as the depth of cut decreases, the number and depth of defects decreased as well. In addition, rake angle of -5° showed lesser surface defects compared to +5° in any depth of cut (Fig. 5).

In any cutting condition mentioned above, there are surface defects such as cracks or peelings are observed. We categorized these defects to 2 groups as follows.
(a) A defect is possibly caused by a crack generated along the lamellar layer
(b) A defect is possibly caused by a crack generated along the lamellar colony boundary.

Figure 6 shows the typical example of each.

Figure 4: Machined surface of specimen with depth of cut, $a = 100 \mu$m

Figure 5: Machined surface of specimen with depth of cut, $a = 20 \mu$m.
3.2 Effect of depth of cut and rake angle

Figure 7 shows the relationship between depth of defects and depth of cut for each rake angle. Solid circles represent the defects caused by lamellar layer, and open circles in the figure represent the defects caused by colony boundary. In each case, the quadratic decrease of both depth and the frequency of defects along the decrease of depth of cut can be seen. In each figure, broken line represents the transition of open circles, and solid line represents the transition of solid circles. These two lines tell that the defects caused by colony boundary decrease with higher rate than it of the defects caused by lamellar layer depending on the decrease of depth of cut. As the rake angle been changed positive to negative, defects became smaller and fewer in any depth of cut. From these facts, it can be concluded that negative rake angle and smaller depth of cut is preferable.

Focusing on the difference in cause of defects, open circles tends to be larger than black dots. This tendency is seen especially in rake angle, \( \theta = +5^\circ \). As the depth of cut decreases, and as the rake angle turns out to be negative from positive, the defects caused by colony boundary decreases. Finally, those defects disappear in 20\( \mu \)m of \( \theta = -5^\circ \). This fact shows that the defects caused by lamellar layer is generated with lower stress, when defects caused by colony boundary are generated with relatively higher stress. Moreover, defects caused by lamellar layer are critical in micro cutting.

3.3 Effect of lamellar angle

Figure 8-9 shows the relationship between lamellar angle and depth of defects, d for each depth of cut, a, and rake angle. Focusing on \( \alpha \) in Fig.8, 2 peaks, which follows the curve drawn in figure, can be seen in every case. These peaks are at \( \alpha = 45^\circ \), and \( \alpha = 135^\circ \). Considering the fact that lamellar structure shows most weak tensile strength in shearing direction to the lamellar layer[3], this result seems proper. In addition, similar pattern is reported in the cutting of FRP. It is known that the generation of the surface defects has its peak when the fiber angle is 45\(^\circ\) misaligned to the cutting direction[4]. However, there is no peak around \( \alpha = 135^\circ \) in the case of FRP. For this reason, the effect of
Figure 8: Relationship between lamellar angle $\alpha$ and depth of defects
Figure 9: Relationship between lamellar angle $\beta$ and depth of defects
colony boundary can be considered.

In Fig. 8(a), circles seem out of this pattern on first glance. However, these circles are open circles, and solid circulars basically follows the pattern. This means that the defects caused by lamellar layer actually depends on the lamellar angle, but defects caused by colony boundary has no relation to the lamellar angle.

Focusing on lamellar angle $\beta$, in Fig. 9, rake angle $\theta$ of +5° and -5° shows different pattern. In $\theta = +5^\circ$, a peak seems to be around $\beta = 45^\circ$. And, in $\theta = -5^\circ$, as $\beta$ approaches closer to $90^\circ$, defects seem to be larger. In $a = 20\mu m$, both $\theta = +5^\circ$ and $\theta = -5^\circ$ seem to have the peak around $90^\circ$ exceptionally. For this cause, the effect of chamfer angle to the minute depth of cut can be considered. Even though the pattern of $\beta$ shown in -5° fits the report of Furusawa et al.[2] mentioned above, the difference between two patterns in $\beta$ remains unknown. Overall, $\alpha$ showed more obvious pattern compared to $\beta$.

4. Conclusion

The relationship between cutting condition, depth of cut and rake angle, and the surface defects of Ti-47.7 at% Al fully lamellar structure was examined by orthogonal cutting. The main results are as follows.

(1) Negative rake angle diminishes the generation of surface defects than positive rake angle. Also, the surface defects became smaller and fewer as the depth of cut decreases.

(2) Surface defects can be categorized into 2 groups by whether it is caused by lamellar layer, or colony boundary. The former is generated on certain lamellar angles preferentially, but the latter depends on colony boundary.

(3) The lamellar angles which are likely to originate the defects, are $\alpha = 45^\circ$, and $135^\circ$. $\beta$ also had slight pattern; defects are likely to be generated when $\beta$ is around $45^\circ$ with rake angle of $+5^\circ$, and when $\beta$ is around $90^\circ$ with rake angle of $-5^\circ$. However, the effect of $\alpha$ is more crucial.

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References


