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Effect of the superelastic properties of a NiTi alloy on its machinability

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Abstract

In this study, the machinability of a nickel–titanium (NiTi) alloy was investigated by orthogonal cutting and end face cutting. Room temperature austenite NiTi was used as the work material, which exhibited superelasticity phase transformation between austenite and stress-induced martensite. A special fine grain size of ~5 mm was observed in the common crystal grain of the work material. Common crystal grain boundaries and martensite surface reliefs were observed on the rough surface of the chips generated as a result of the orthogonal dry cutting under specific cutting conditions, and the special fine grain was severely compressed. However, an uneven machined surface and martensite surface relief on the machined surface were observed after end face cutting. These characteristic phenomena are considered to be caused by the superelasticity, special crystal structure and anisotropy of the NiTi alloy work material.

Keywords: shape memory alloy, superelastic alloy, turning, cutting mechanism

1. Introduction

NiTi alloy is a typical shape memory alloy because of its unique functional properties, including the shape memory effect and superelasticity. The shape memory effect and super elasticity behaviour contribute to the restoration of a large strain of up to 8% on account of a solid–solid phase transformation between martensite and austenite by unloading or heating [1]. Cutting is utilised to obtain the final shape for the purpose of satisfying the demands for the high accuracy manufacturing of NiTi products. However, previous studies have reported on the several difficulties that were encountered during the cutting of a NiTi alloy, including rapid tool wear, particularly notch and flank wear, high cutting force and poor chip breakability [2].

Several studies have reported on the effects of drilling parameters on the subsurface of work materials, the poor machinability [3-4] and surface characteristics of machined NiTi alloys [5-7]. However, few studies have focused on the effect of superelasticity on the cutting of NiTi alloys. In this study, the effects of superelasticity, special crystal structure and anisotropy of the machined surface and chips were investigated.

2. Work material

A Ni_{51}–Ti_{49} (at%) alloy was used as the workpiece. The phase transformation temperatures were determined from differential scanning calorimetry measurements, with martensite start (Ms), martensite finish (Mf), austenite start (As) and austenite finish (Af) temperatures of −23.6°C, −41.2°C, −17.9°C and −2.5°C, respectively. Thus, the workpiece is in the austenite state at room temperature and exhibits superelasticity. To observe the crystal structure of the workpiece, electrolytic polishing using an alcoholic electrolyte solution was performed.

3. Turning experiments

Two experiments were conducted to investigate the effect of the superelastic effect on the chip generation mechanism and finished surface. The face turning experiment was performed to observe the finished surface, and the orthogonal cutting experiment was performed to observe chip generation.

Table 1 summarises the cutting conditions in the face turning experiment, while Table 2 summarises the cutting conditions for the orthogonal cutting experiment. A disc-shaped workpiece was turned in the radial direction with a pre-determined feed.

Table 1 Cutting conditions for the face turning experiment

Revolution	500	[rpm]
Work size	ϕ60, t = 10	[mm]
Depth of cut	0.05	[mm]
Feed	0.0125	[mm/rev]
Cutting tool	K10 TNGG16040 HTi10 (MITSUBISHI)	

Table 2 Cutting conditions for the orthogonal cutting experiment

Cutting speed	25	[m/min]
Work size	ϕ80, t = 2	[mm]
Feed	0.0125,0.025,0.05,0.1	[mm/rev]
Cutting tool	K10 TPGN160304 HTi10 (MITSUBISHI)	

4. Results and discussion

4.1. Microstructure of the work material

Figure 1 shows the optical micrograph of the mechanically polished surface and the SEM micrograph of the electropolished surface. Fine particles of ~5 µm (Figure 1-b) were observed in a 100–200 µm crystal (Figure 1-a), which has been conventionally reported [5-8]. Regarding the microstructure in these crystals of NiTi alloys, Yanqiu Zhang et al. reported on miniaturization of crystals due to the influence of SPD [8]. The workpiece in this experiment was a rod material when extruded from an ingot. The influence of these processes was the cause of such a structure.

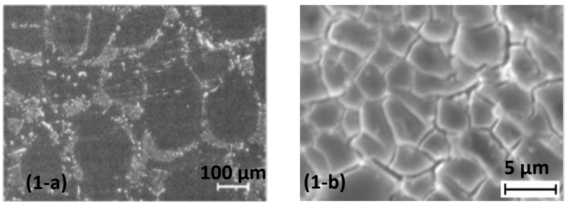

Figure 1. Optical micrograph of a mechanically polished surface (a) and SEM micrograph of a chemically polished surface (b)

4.2. Effect of superelasticity on the finished surface

Figure 2 shows the optical micrograph of the finished surface. Crater-like texture corresponding to the crystal size on the finished surface was observed (Figure 2-a). Further, surface relief caused by the martensite transformation was observed in different directions as a result of cutting and feeding (Figure 2-b in a circle). Figure 3-a shows the laser microscopy contour image of the finished surface. The crater-like texture was actually uneven, and the surface relief was slightly convex. Micklich et al. have reported on the crystal anisotropy of a NiTi alloy [9]. Furthermore, our research group has reported that a superelastic NiTi alloy exhibits a greater elastic recovery compared with general metals on turning, which affects machinability [10]. The finished surface was uneven because of the crystal anisotropy and large elastic recovery. Figure 3-b schematically shows the difference in the elastic recovery as a result of crystal anisotropy. On account of anisotropy, the difference in the elastic recovery of each crystal led to surface irregularities. This unevenness (≥8 µm) was greater than the roughness in the feed direction (Ra = 0.4 µm, Rz = 2.5 µm), caused deterioration of accuracy of the finished surface. Therefore, the unevenness of finished surface can be thought as a problem in precision machining which high accuracy finished surface is needed.

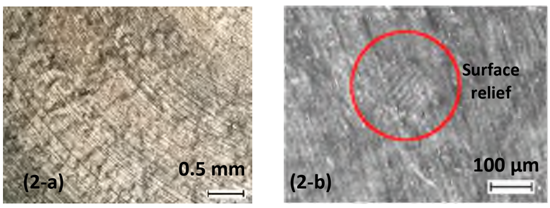

Figure 2. Optical micrograph of the finished surface after face turning (a) and enlarged image of the surface relief (b)

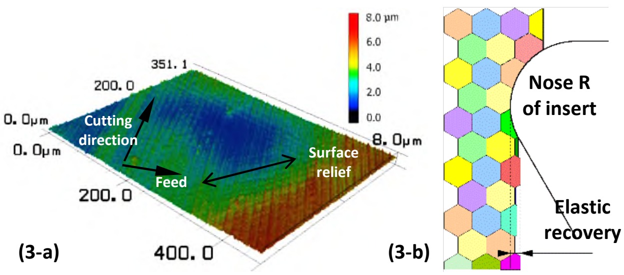

Figure 3. Laser microscopy contour image of the finished surface (a) and a schematic showing the effect of crystal anisotropy after face turning (b)

4.3. Effect of the microstructure on chip generation

Figure 4 shows the optical micrograph of the free chip surface and enlarged SEM image. Fine particles underwent shear deformation in a layered manner at a feed rate of less than or equal to 0.05 [mm/rev]. Different lamination pitches were observed for the fine layer depending on the crystal grain because of the same direction of the fine particles in the crystal, and the anisotropy of each crystal led to the difference in deformation. Figure 5 shows an enlarged view of the chip in which thin plates superposed with the shear deformation of fine particles overlapped in layers (Figure 5-a). Surface relief as a result of the martensite transformation was observed on the free chip surface (Figure 5-b). Benafan et al. [11] have reported a temperature Md at which the martensite phase disappears. Protrusions were not observed at a high cutting temperature. Therefore, when the cutting temperature was less than Md, surface relief was generated on the free chip surface.

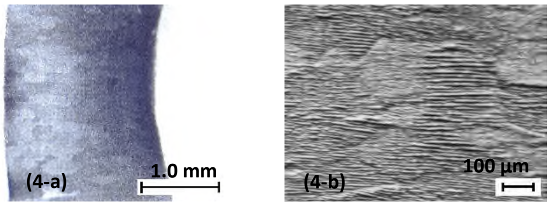

Figure 4. Optical micrograph of the free chip surface (a) and enlarged SEM micrograph (b)

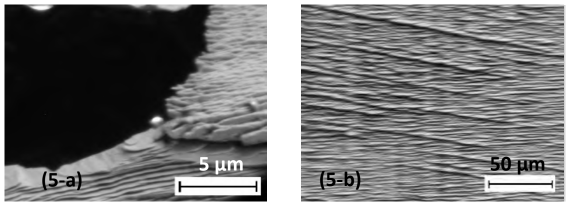

Figure 5. SEM micrograph of the chip edge (a) and surface relief caused by stress-induced martensite on the free chip surface (b)

5. Conclusion

The machinability of a Ni_{51}–Ti_{49} (at%) superelastic alloy was investigated with respect to the finished surface and chip generation after turning. The following conclusions can be drawn from this study:

- The extruded NiTi alloy exhibited fine crystal particles with the same orientation.
- The crystal anisotropy and large elastic recovery led to the unevenness resulting from the crystal grain size of the finished surface.
- Under specific cutting conditions, surface relief was observed on the finished and free chip surfaces. This phenomenon was significantly related to Md, which is specific to each material.

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