Microstructural evolution of Ti-6Al-4V during high strain rate conditions of metal cutting

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Abstract
The microstructural evolution following metal cutting was investigated within the metal chips of Ti-6Al-4V. Metal cutting was used to impose a high strain rate on the order of $\sim 10^5 \text{ s}^{-1}$ within the primary shear zone as the metal was removed from the workpiece. The initial microstructure of the parent material (PM) was composed of a bi-modal microstructure with coarse prior $\beta$ grains and equiaxed primary $\alpha$ located at the boundaries. After metal cutting, the microstructure of the metal chips showed coarsening of the equiaxed primary $\alpha$ grains and $\beta$ lamellar. These metallographic findings suggest that the metal chips experienced high temperatures which remained below the $\beta$ transus temperature.

Keyword: metal cutting, Ti-6Al-4V, grain refinement
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Outline

☐ Introduction
☐ Experimental Method
☐ Results
☐ Summary
☐ Future Works
Objective

- Utilized metal-cutting to subject material to strain rates in the range of $10^3$ to $10^5$ s$^{-1}$
- Evaluated the microstructure response of Ti-6Al-4V to high strain rate conditions above $10^3$ s$^{-1}$
- Investigated the response of the deformed microstructure to subsequent heat treatments
Ti-6Al-4V

- Titanium and its alloys have been widely applied in the aerospace, chemical, biomedical industry.
- Ti-6Al-4V is one of the most used titanium alloys.
- Young’s Modulus: 114 GPa; Ultimate Tensile Strength: 1170 MPa; Specific Heat Capacity: 0.5263 J/g-°C
- It is a two phase microstructure (α Ti + β Ti)
  - α Ti: hexagonal close-packed (hcp) structure
  - β Ti: body-centered cubic (bcc) structure
- Beta transus temperature: ~ 995°C
During metal-cutting, the metal removed experiences a localized high shear strain rate.

\[
\gamma = \frac{\cos \alpha}{\sin \phi \cdot \cos(\phi - \alpha)}
\]

\[
\dot{\gamma} = \frac{\cos \alpha}{\cos(\phi - \alpha)} \cdot \frac{V}{\Delta y}
\]

\[
\tan \phi = \frac{\frac{t}{\cos \alpha} - \frac{t}{1 - \frac{t}{\sin \alpha}}}{\frac{t}{t_c}}
\]
A turning process can be used to approximate orthogonal cutting conditions.

Cutting parameters:
- Rake angle: $+5^\circ$
- Depth of cut: $360\mu m$
- Travel velocity: $0.22 \sim 0.57 \text{ m/s}$
- Estimated shear strain rate: $1 \sim 2 \times 10^5 \text{ s}^{-1}$
- Estimated shear strain: $\sim 5$

Schematic of turning operation with chip morphology

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February 15-19, 2009, San Francisco, CA
Heat Treatment Schedule

- Heat treat as-cut metal chips at 260°C and 730°C for 5, 15, 30 and 90 minutes, respectively.
- 260°C was selected to study the low temperature microstructural response.
- 730°C was selected as the beginning temperature range of the α to β phase transformation.
Metallurgical Study

- Cut metal chips were characterized using variety of characterization techniques.

- Scanning Electron Microscopy (SEM)
  - Phase content and morphology

- Transmission Electron Microscopy (TEM)
  - Submicron microstructure

- X-ray Diffraction (XRD)
  - Phase content and Texture
As-received parent material shows a bi-modal microstructure

Width of α laths: 1.0 μm

Equiaxed primary α: 5.2 μm

Prior β: 50 μm

Volume fraction of β phase: 12 ~ 13%
Evidence of non-homogenous shear bands observed in side view

- SEM images

$1.9 \times 10^5 \text{ s}^{-1}$
No change in grain size observed on cutting surface

- SEM images

1.1 \times 10^5 \text{s}^{-1} \quad \text{Equiaxed } \alpha \text{ grain } = 4.8 \sim 5.1 \mu\text{m}

1.9 \times 10^5 \text{s}^{-1}
Evidence of nano-crystalline microstructure observed in TEM/SAD

Cutting surface

PM

$1.1 \times 10^5 \text{ s}^{-1}$

$1.9 \times 10^5 \text{ s}^{-1}$
TEM micrograph of heat treated metal-cutting chips

Heat treated at 730 °C

5 min

30 min

90 min
Grain growth rate of $\alpha$ phase

Heat treated at 730 °C
A change in rolling texture of the $\alpha$ phase is observed after the metal cutting process.
XRD Summary shows minor peak broadening

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Summary

- Microstructure observation shows an evolution from initial bimodal microstructure to equiaxed $\alpha$ grains with intergranular $\beta$ grains.
- The resulting microstructure suggests that the $\beta$ transus was not exceeded during the metal cutting.
- Microstructural analysis indicates a non-homogenous grain refinement has occurred within the shear band region.
- The heat treatment experiment indicated the formation of nano-crystalline and refined grains have good thermo-stability up to 730°C.
Acknowledgements

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