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

Lei Dong, Judy Schneider
Department of Mechanical Engineering
Mississippi State University

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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Lei Dong, Judy Schneider

Department of Mechanical Engineering

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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 has 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

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

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

\[ \tan \phi = \frac{t}{1 - \frac{t}{t} \sin \alpha} \]
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: $0.22 \sim 0.57 \, m/s$
- Estimated shear strain rate: $1 \sim 2 \times 10^5 \, s^{-1}$
- Estimated shear strain: $\sim 5$

*Schematic of turning operation with chip morphology*
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 $\alpha$ to $\beta$ phase transformation.
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 × 10^5 s^-1
No change in grain size observed on cutting surface

- SEM images

Equiaxed \( a \) grain = 4.8 \( \sim \) 5.1 \( \mu \)m

\[ 1.1 \times 10^5 \text{ s}^{-1} \quad 1.9 \times 10^5 \text{ s}^{-1} \]
Evidence of nano-crystalline microstructure observed in TEM/SAD

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

$1.9 \times 10^5 \text{ s}^{-1}$

Cutting surface
TEM micrograph of heat treated metal-cutting chips

Heat treated at 730 °C

5 min

30 min

90 min

TMS 2009

February 15-19, 2009, San Francisco, CA
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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Microstructure observation shows an evolution from initial bi-modal 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 $730^\circ C$. 
Acknowledgements

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