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# Chip formation and microstructure evolution in the adiabatic shear band when machining titanium metal matrix composites

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ABSTRACT

Titanium metal matrix composite (Ti-MMC) is a relatively new class of material, which has high potential applications in the aeronautical and biomedical sectors. Similar to titanium alloys, Ti-MMC produces segmented chips, which are characterized by adiabatic shear bands (ASB). Transmission Electron Microscopy (TEM) observations were performed and dislocations were observed on the atomic scale. Furthermore, the sheared surfaces, as well as the effects of the hard TiC particles on the ASB formation were investigated. It was shown that the grains located in the lightly strained areas within the chip segment are characterized by a high dislocation density. This is contrary to the highly strained areas inside the ASB, where the temperature was estimated to be close to the recrystallization temperature. Analysis of the results showed that no phase transformation took place inside the ASB. The strain and strain rate in the ASB were estimated to reach 7.5 and $4.5 \times 10^5\ s^{-1}$, respectively. Using TEM and Focused Ion Beam (FIB) for sample preparation, the microstructure inside the ASB was found to be composed of elongated and equiaxed nano-sized grains. The segmentation mechanism of chips was observed to start from a crack on the material free surface ahead of the tool, and not at the tool tip. Furthermore, the hard particles inside the matrix were found not to be hindering, or retarding the ASB formation. A microstructural evolution model, based on these observations, has also been proposed. To the authors' best knowledge, TEM studies of ASB for Ti-MMC were never done previously for machining applications.



## 1. Introduction

Titanium Metal Matrix Composite (Ti-MMC) is relatively a new type of metal composite. It has superior physical properties over titanium alloys, since the reinforcement with carbide (TiC) particles improves the material modulus of elasticity, elevated temperature strength, creep resistance, and wear resistance [1]. This material has recently been used in landing gears and aerospace engine components, as well as automotive parts [2,3]. Similar to titanium alloys, machining of Ti-MMC produces segmented chips that are characterized by *adiabatic shear bands* (ASB). The mechanism of deformation in a localized shear band is one in which the rate of thermal softening exceeds the rate of strain hardening. This is usually referred to as an "adiabatic shear process" [4]. This phenomenon has been the subject of intensive research for the last few decades, since the early work of Zener and Hollomon [5]. Meyers [6] calculated the onset of instability of ASB in relation to shear strain ($\gamma_{sh}$). Although strains up to 5 were found in impact test of Ti6Al4V alloy, a value of $\gamma_{sh}=1$ was determined for pure titanium. Culver [7] predicted the thermal instability shear strain to be 1.15 for the same material. In addition, high strain rates and stresses are required for ASB formation [8]. These conditions are met in machining and in high speed impact tests, where strain rates in the order of $10^6\ s^{-1}$ were found [9–11]. In comparison, titanium forming typically involves strain rates in the range of 3–5 $s^{-1}$[12] .

In ballistic experiments, ASB has been clearly identified as a precursor to fracture [13]. In experiments resulting in a fractured surface with a presence of an ASB and crack initiation, it is often uncertain whether the crack initiated the ASB, or if it resulted from the ASB phenomenon. In high speed impact tests of Ti-6Al-4V and other metals, it was observed that dynamic recrystallization precedes the ASB failure tests [14]. If the temperature rise in the ASB exceeds the material recrystallization temperature, a new grain size of less than 0.1 μm [9] is produced. It was suggested in [9,10,15] that 'rotational dynamic recrystallization' (RDX) is responsible for the micro grain formation in the ASB. There was,

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**Nomenclature**

| | |
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| $\gamma_{sh}$ | shear strain |
| $\sigma_y$ | yield strength |
| $\delta_s$ | thickness of the ASB |
| $\beta$ | thermal conversion factor |
| $\rho$ | density |
| $A_f$ | fractured surface |
| $a_p$ | depth of cut |
| $f$ | cutting feed |
| $v_c$ | cutting speed |
| $C$ | heat capacity of the material |
| $t_{ASB}$ | time during which the ASB is formed |
| $T_m$ | melting point of the matrix |
| $T_{cr}$ | recrystallization temperature |

however, no evidence of catastrophic release of dislocation pile-up that causes localized heating on the slip plane, as suggested by the "avalanche dislocation concept" [6]. Based on the grain size observations made by Meyers [15], migrational recrystallization is unlikely to be a dominant mechanism during the deformation and cooling periods. In these high speed impact tests, the link between ASB and phase transformation was also established for titanium alloys [9,10,16,17]. However, the phase transformation was not observed by others in the presence of ASB [6,18].

In machining, two different theories on the mechanism of generation of segmented chips are found in the literature; namely, "crack initiation", and "thermo-plastic instability". The main difference between the two theories is the mechanism of catastrophic failure in the primary shear [19]. Shaw [20] postulated that shear bands form due to inside microfractures, and void propagation. However, due to heat and high normal stress the sheared band will weld again. Nakayama et al. [21,22], Shaw and Vyas [20], König [23], among others, suggested that the catastrophic failure is initiated first by a crack at the free surface ahead of the tool, which propagates toward the tool tip and forms a segment. The angle of the crack is in the direction of the highest shear stress, i.e., at 45° from this surface. Komanduri et al. [24] and Davies et al. [25] suggested, however, that a thermoplastic instability occurs within the primary shear zone. Komanduri [26] has identified two important stages in the formation of segmented chips. The first stage involves upsetting of a wedge-shaped volume of material immediately ahead of the tool. Once a critical shear strain is attained, thermo-plastic instability occurs and further shear strain is accommodated within the 'failed' shear zone. However, no full explanation of the thermo-plastic instability was included. In machining titanium alloys, Komanduri [26] noted a possible phase transformation from h.c.p. α-structure to b.c.c. $\beta$-structure due to the high temperature generated in the ASB.

The effect of cutting conditions on the formation of segmented chip during machining of TiMMC has been investigated by the authors in [27–30]. However, there is still a need for a fundamental understanding of the physical phenomena associated with chip segmentation, on the atomic and macro scales. This paper presents the first study of ASB of Ti-MMC using Transmission Electronic Microscopy (TEM), with Focused Ion Beam (FIB) specimen preparation, in machining applications. This research will provide in depth understanding of chip segmentation, tool-particle interaction and their effect on tool wear, as well as the generation of machining-induced residual stresses. These aspects are required for developing physics-based FEM simulations of the machining processes of this material, which is a terminal objective for process simulation, machinability improvement, and process optimization. From the material point of view, ASB results in the formation of nano-grains which have superior physical characteristics, as compared to the base material. Understanding the mechanism of formation of nano-grains in the ASB may lead to design improvement, and enhancement of the material development. A model describing the microstructure evolution at different stages of the ASB formation is also proposed.

## 2. Experimental setup and test matrix

Machining tests were conducted on a 6-axis Boehringer 200 CNC turning center. The turning experiments were carried out using 2.5 in. diameter cylindrical workpieces made of Ti-MMC. The material consists of a non-metallic phase TiC (10–12% by weight) distributed in a matrix of Ti-6Al-4V titanium alloy. A specially designed and developed quick stop device (QSD) was used to examine the chip formation process and the chip morphology [31]. With this QSD, the process of chip formation can be frozen and the site of crack initiation can be established.

Chips were collected for each experiment, mounted, polished and etched for further metallographic examinations. The chips microstructures were identified using an Olympus SZ-X12 microscope. A Scanning Electron Microscope (SEM) Jeol, JSM -840A was used for detailed studies of the chips morphology. For microhardness measurement, a Struer Duramin A300 was used. Because of the very small grains of the ASB microstructure, Transmission Electron Microscopy (TEM Jeol, JEM-2100F) was used to study the microstructure evolution. For sample preparation, the Focused Ion Beam method (FIB Hitachi FB-2000A) was used to extract the exact location of an ASB. Samples were extracted from different specific locations inside the chips to observe the microstructure inside the ASB and its proximity.

Since Ti-MMC is commonly produced in near net shape, the focus of this research is oblique finish cutting, at relatively high cutting speeds and low depths of cut. Basic orthogonal cutting tests and TEM investigation were also conducted for better understanding of the ASB phenomenon under plane strain conditions. In these set of tests, uncoated carbide tools with 0° rake angle were used. Based on the results of previous work by the authors [29] for defining the optimum cutting conditions that produce the lowest cutting force and surface roughness, the following machining parameters were used in oblique cutting for the cutting speeds of 60, 100, 180 and 230 m/min, and feed of 0.1 or 0.2 mm/rev with a constant depth of cut of 0.15 mm. These cutting speeds are much higher than the critical cutting speed for the occurrence of ASBs in machining Ti–6Al–4 V [32]. In these set of tests, the tool used was a Poly-Crystalline-Diamond (PCD), RNMN42 round insert with 12.7 mm diameter and 0° rake angle. Orthogonal cutting were also performed; for the cutting speed of 30, 50, 80, and 150 m/min, with a feed of 0.1 or 0.15 mm/rev.

## 3. Results and discussions

### 3.1. Chip morphology

Examination of the segmented chip morphology shows different characteristics at different cutting speeds (Fig. 1). At the cutting speed of 100 m/min, the grain microstructure of the chip is more elongated and deformed, indicating high plastic deformation as shown in Fig. 1(a). At much higher cutting speed of 230 m/min, however, the high plastic strain is limited to the ASB area. In the