Proceedings of the Canadian Society for Mechanical Engineering International Congress 2020
CSME Congress 2020
June 21-24, 2020, Charlottetown, PE, Canada

Dynamic Deformation Mechanisms and In-situ Thermal Response of 7050 Aluminium Alloy at High Strain Rates

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Abstract— Under mechanical extremes and high rate of deformations, materials accommodate the excessive deformation through nucleation of defects, as well as activation of strain localizations (⇨adiabatic shear band-ASB) associated with crack nucleation and propagation. 7050 Aluminium (Al) alloys are widely utilized for high performance aircraft structures being considered for use in increasingly extreme conditions. In this work, the high strain rate deformation behaviour (evolution of ASB and consequent temperature rise) in T6 7050 Al was investigated using a direct impact Kolsky bar at compressive strain rates (800-3005) s^{-1}. A high-speed infrared thermal camera was employed simultaneously to observe the local temperature rise in-situ during the deformation process. During high strain rate deformation, 7050 Al alloy exhibits susceptibility to shear localization. However, strain localization is not realized at relatively lower high strain rates values, implying that critical strain(cs) may be required for ASB formation in 7050 Al. Multiple nucleation's of arc-shaped interconnecting ASBs of distinct boundaries uniquely characterized with distortions and seeming refinement compared to ASB surroundings and bulk specimen is observed. Nonetheless, shear deformation surroundings appear more distorted and refined compared to the bulk specimen. Additionally, dispersoid particles become elongated and flattened at ASB regions compared to those present at ASB surroundings and the bulk specimen microstructure. It is realized that the regions within ASB exhibit higher hardness characteristics than its surrounding matrix due to refinement and distortion of elongated grains and increased surface area of dispersoid particles. In-situ observation shows at most 24 ^{o}C of peak temperature rise which was not enough to cause softening effect. Multiple nucleation sites of heat rise are observed regardless of strain rate.

Keywords-7050 Aluminium alloy; Microstructure; High strain rate; strain localisation-Adiabatic Shear Band; Temperature rise; In-situ

I. INTRODUCTION

Aluminium (Al) and its alloys have widely been utilized as structural components in the aerospace and automobile industries due to it low density, high ductility and specific-strength. Among the many Aluminium alloys, the high strength age-hardened 7xxx series, (x: Zinc, Magnesium, Copper), are mainly used for aircraft structures where they are exposed to extreme loading conditions [1]. The 7050-group posse's excellent combination of strength, ductility, resistance to corrosion and stress corrosion cracking [1,2]. This makes it an ideal candidate during selection in the structural industries. In structural applications, important combination of physical and mechanical that ought to be considered includes damage tolerance and accumulation, strength and environment (corrosion).

However, even though the deformation behavior of most 7xxx series Al have been immensely been studied, with regards to 7050 Alloy, only the effect of processing parameters on the deformation behavior during forming process and at relatively extremely low strain rates are premeditated. At low strain rates, the deformation performance and microstructural evolution of Aluminium alloys are dictated by softening mechanisms which are influenced by thermo-mechanical parameters [2-4]. There are rare studies on the high strain rate deformation behavior of 7050 Al alloy.

At high strain rates, deformation behavior of materials is really, complex, that involves strain localization with associated competition between thermal softening and work hardening that may lead to plastic instability [5,6]. At extreme strain localizations, narrow bands are formed termed adiabatic shear bands which are characterized by extreme gain refinement and hardness which are generated due to insufficient time of heat dissipation of high temperature rise as a result during impact. The narrow bands act as preferential sites for crack initiation and propagation that have the tendency to thwart the mechanical integrity of the plastic behavior during high strain rate deformation [7]. Therefore, the goal of this work is to perform premier studies to simultaneously determine the high strain rate mechanical and in-situ thermal response of 7050 Al alloying during dynamic deformation in order to access the subsequent microstructural mechanism that leads to strain localization. The deformation behavior of a T6 tempered 7050 Aluminium and the associated temperature rise are characterized in-situ using high speed infrared thermal imaging camera coupled to direct impact Kolsky bar available at AMIBLab, York University.

II. Materials and Methods

The material used for this work was 7050 Al alloy produced by rolling and annealed. The top part after rolling was sectioned into 10.5 x 9.5 mm (thickness and diameter) and subsequently heat treated to the T6 Temper. Room temperature dynamic compression impact testing were performed on the T6 Tempered condition materials at strain rates of (831-3005) s^{-1} using a direct impact Kolsky bar available at York university (AMIBLab) with the incident (projectile) and the transmitter bars made of 4140 stainless steel. A projectile bar of mass, diameter and length of 1.02 Kg, 38 and 112.3 mm respectively was used. The stress strain waves were recorded in a LabVIEW and the corresponding stress-strain values were analyzed using a series of wave data theories. The direct impact Kolsky bar setup was simultaneously coupled to a high-speed infrared camera for in-situ thermal imaging during the test as illustrated in Fig. 1. A thermal camera with a maximum frame rate of 1064 fps was used. However, an adjustable frame rate of 843 fps was used. After the test, both an un-impacted and the impacted specimens were taken for metallographical studies. The specimens were cold mounted (with the impacted surface outwards), grinded and polished using aqueous Alumina suspension (1-0.05µm), and etched using Keller's reagent (10ml HNO3, 10ml HCl, 5ml HF 5ml HF and balance ethanol) for 20 secs. The microstructure was observed using Zeiss microscope for both the prepared pre-impacted and impacted specimens. Hardness measurement was conducted using a micro-Vickers hardness tester with a 300gf load (2.94 kN) at a dwell time of 15secs. Atleast 10 indentations were made.

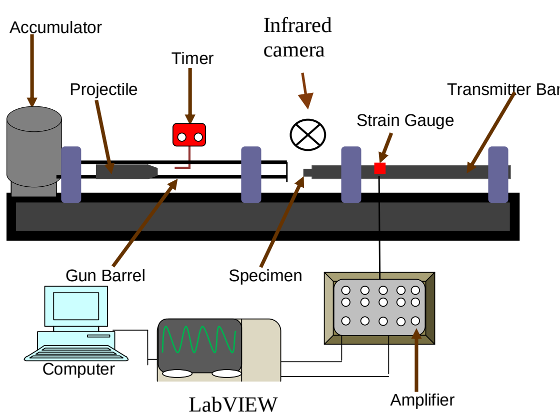

Fig. 1. Direct Impact Kolsky bar [11]

III. Results

A. Microstructure before Impact

Fig. 2 shows the microstructure of the specimen after T6 condition before impact. This serves as a baseline of comparism to the impacted specimens. Generally, three main features were observed. The microstructure comprised mainly of elongated grains due to the rolling process, sub-grains due to static recrystallized from heat treatment and globular shaped dispersoid particles. Higher percentages of the dispersoid particles were mostly aligned on grain boundaries (GBs) whereas few were lightly found on the elongated grains.

B. Microstructure after Impact

The microstructure after impact are displayed in Fig. 3. After impact at a strain rate of 831 s^{-1}, adiabatic shear band (ASB) was not observed within the microstructure of the specimen impacted at this strain rate until the strain rate was raised. However, the elongated grains appeared deformed and finer than the bulk specimen. Dispersoid particles are aligned along the elongated grains boundaries GBs as shown in Fig. 3a. When the strain rate was raised to 3005 s^{-1}, the impacted specimen surface microstructure experienced intense strain localization with evolution of arced shaped shear band (Fig. 3b). Multiple nucleation's of interconnecting bands of distinct boundaries were observed at the shear band region as shown in Fig 3(b&c). The ASB region was distorted and appeared refined compared to the shear band surroundings and the bulk material. Nonetheless, the shear deformation surrounding grains was also intensely distorted compared to the bulk specimen as shown in Fig.3d. Additionally, the dispersoid particles became elongated and flat at ASBs and still present on GBs at ASB surroundings.

C. Microhardness variation with shear deformation and its surroundings

It can be observed in Fig. 4 that shear deformation(ASB) region is much harder than its surrounding matrix. The micro-hardness measurement decreases gradually towards the center

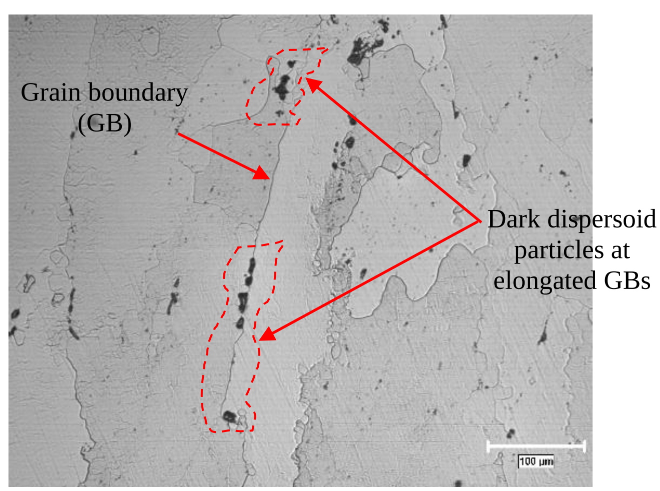

Fig. 2. Microstructure of un-impacted specimen showing elongated grains, globular shaped dispersoid particles at grain boundaries and sub grains

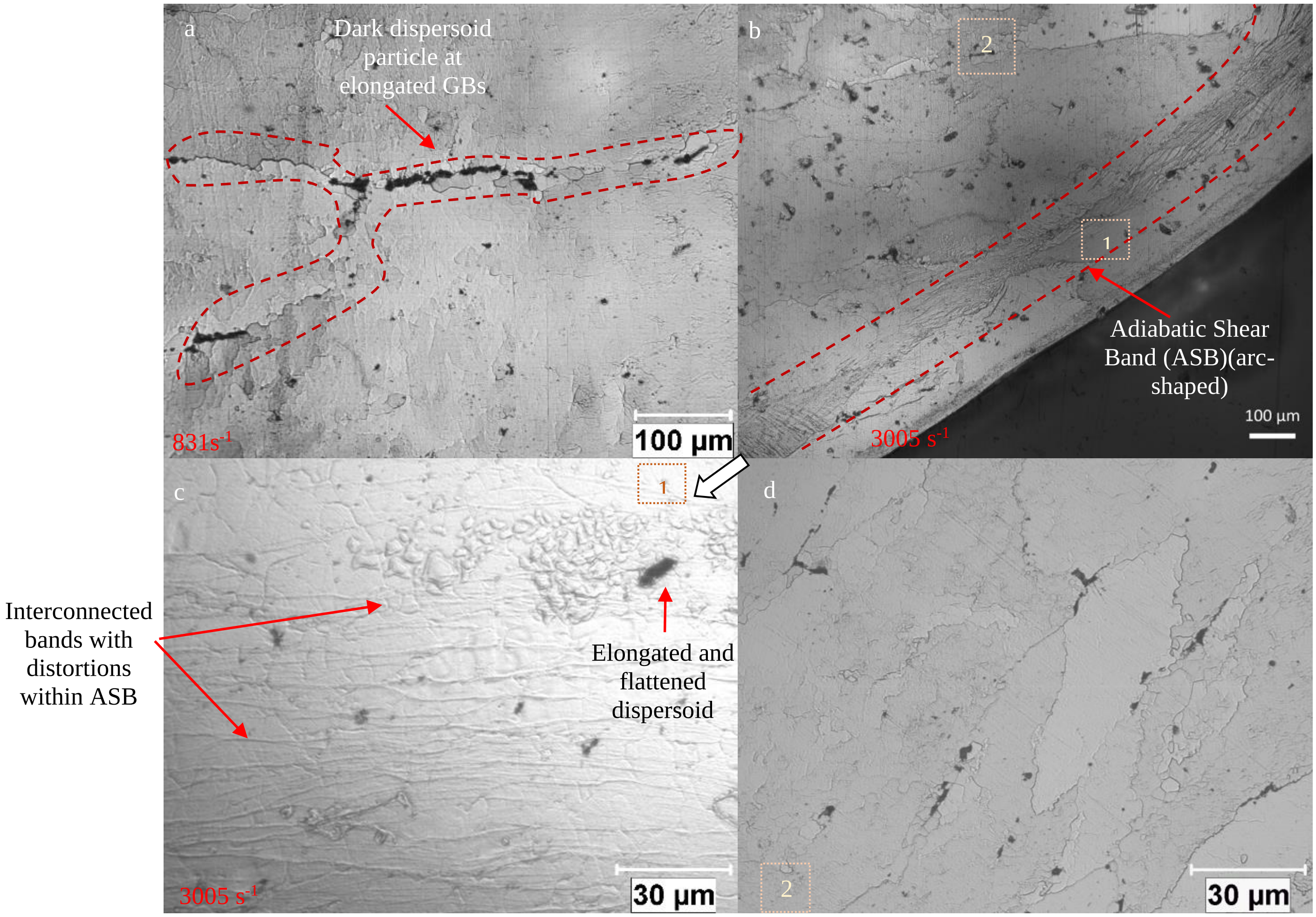

Figure 3: Microstructure after deformation showing aligned dispersoid particles at GBs at 831 s^{-1}, b) ASB zone with refined grains at 3005 s^{-1}c) dispersoids dynamic recrystallized grains within ASB region and d) deformed structure at ASB surroundings at 3005 s^{-1}

of the matrix away from the ASB regions.

D. *Stress strain Behaviour*

The yield and peak stresses observed are higher at high strain rates and impact momentums. Fig.5 displays the increasing trend of the flow stresses after impact. The flow stresses show variation with strain rates.

E. *Effect of Strain Rate on Temperature Rise*

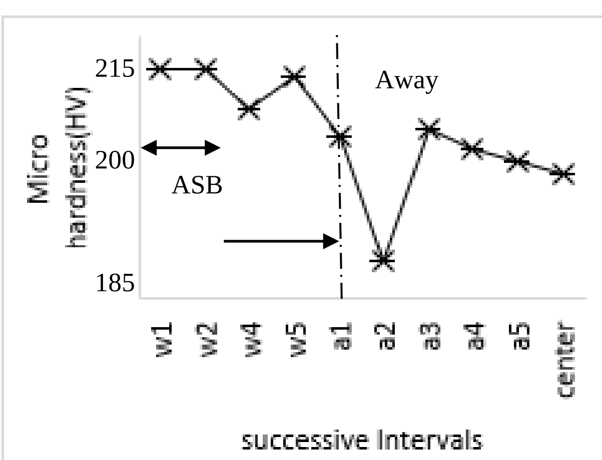

Figure 4. Microhardness variation within(w) ASB and away(a) from ASB region (w1) to center of matrix

The temperature rises were 5 and 23.7 °C respectively at 831 s^{-1} (Fig. 6a1) and 3005 s^{-1} (Fig. 6b1) strain rates. Fig. 6(a2 and b2) illustrate the respective temperature profiles of multiple nucleation sites of heat rise captured in-situ during impact.

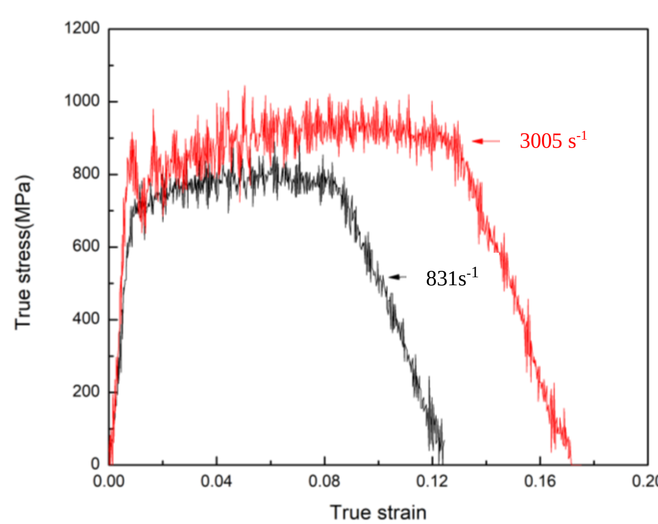

Figure 5. True stress-strain behavior of specimen impacted at 831 and 3005 s^{-1} strain rates

IV. Discussion

The behavior of materials at high strain rates is different compared to quasi-static strain rates. During high strain rate deformation, 7050 Al alloy exhibits susceptibility to shear localization. At increasing strain rates to 3005 s^{-1}, intense strain localization leads to the evolution of arced-shaped adiabatic shear band. The ASB region is made up of multiple nucleation of interconnecting bands of distinct boundaries. However, strain localization is not realized at slow high strain rates. This implies that strain localization requires critical strains for shear band formation mostly with respect to different materials. It is reported that strain localization intensely formed in AZ31B Mg alloy impacted at the same impact momentum of 35kgm/s with the same setup shown in Fig. [1][7]. The ASB regions are uniquely characterized with distorted and marginally refined regions compared to its surroundings and the bulk specimen. Nonetheless, shear deformation surroundings at high strain rates are also highly distorted compared to the bulk specimen.

Additionally, dispersoid particles becomes elongated and flat with increased surface area at ASB regions whiles others are mostll found at GBs at ASB surroundings as compared to the globular shaped dispersoid particles observed within bulk specimen microstructure. The refinement and distortion of the as received microstructure comprising of elongated grains and elongation of dispersoid particles indicates that the shear strain is much higher at ASB regions than its surrounding matrix and also at higher strain rates than lower strain rates due to severe plastic deformation. The shear deformation regions exhibit higher hardness characteristics than its surroundings. The higher hardness characteristics within the shear deformation region is due to the refinement of the elongated grains, distortion of the elongated grains to yield deformed grains and recrystallized grains and increased in surface area of the dispersoid particles. These have the potential to increase strain energy absorption by inhibiting dislocation motions, creating dislocation pileups at GBs at ASB regions. Dispersoid particles have the tendency to pin dislocation and inhibit dislocation slips to create dislocation dispersoid particles interactions [8,9]. Grain boundaries are sources of dislocations.

The temperature effect is negligible as the flow stress gradually increased with strain rates and did not play major role in softening. Increasing strain rates leads to gradual increasing flow and peak stresses. This is attributed to grain distortion and refinement, dispersoid particles refinement, dislocation multiplications and dispersoid particles dislocation pinning that occur at high strain rate loadings. This implies that the 7050 Al treated at T6-Temper condition exhibit significant sensitivity to strain rates at dynamic loadings [10].

The elongation to failure is high at higher strain rate. This suggest that Al becomes highly ductility at high strain rates. Thus, dislocation slip motions and easy slip glides activation become highly favored during deformation of 7050 Al at dynamic conditions. As dislocation density and slip increase, strength of the material increases, and toughness are simultaneously enhanced during deformation at high impact. Dislocations continues to multiply, grain refinements and dispersoid particles refinement are favored until dislocation saturation point is realized. Also, Al metals have appreciable number of slip system (12) that enables it to accommodate for more plastic deformation during forming. According to the Von Miss's criteria, materials are able to accommodate successive amount of plastic deformation with atleast 5 slip systems. This place Al in a reputable position during material selection for forming and manufacturing process.

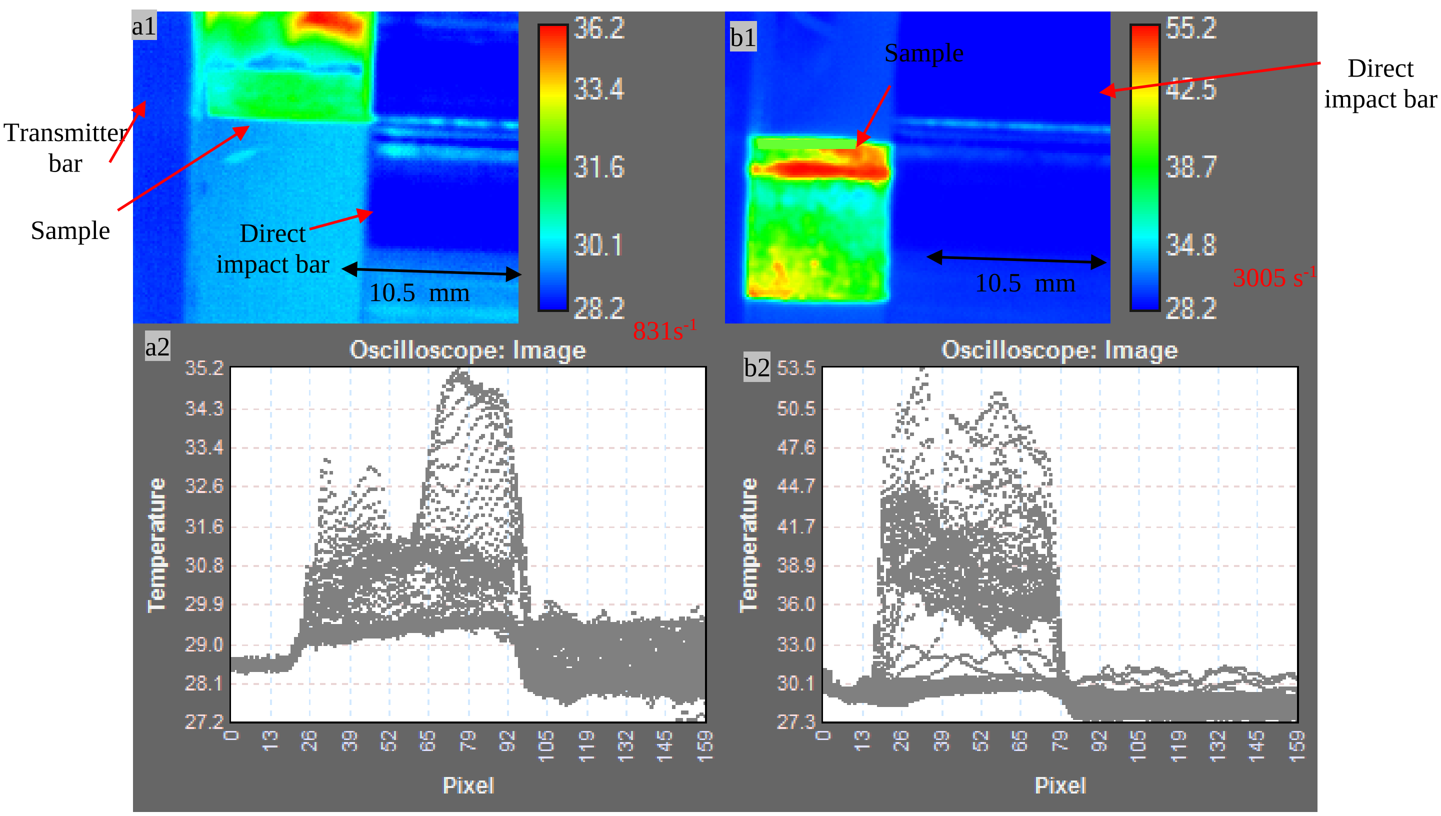

Figure 6. Effect of strain rates on temperature rise of specimen impacted at a) 831 s^{-1}, b) 3005 s^{-1}, a2 and b2 are the respective ive profiles showing multiple nucleation site of temperature

Processing and forming of Al is less difficulty compared to its counterpart Magnesium. Hence Al is almost available part in every appliance in addition to its lightweight merits.

V. Conclusion

High strain rate compressive tests were conducted to investigate the deformation behavior and the evolution of adiabatic shear band and consequent temperature rise in 7050 Al alloy using a direct Kolsky bar. A high-speed infrared camera was employed to observe the local temperature rise in-situ during the deformation process. It was found that:

- 7050 Al alloy exhibit susceptibility to shear localization at high strain rate impact. However, strain localization is not realized at slow high strain rates, implying that critical strain(cs) may be required for shear band formation in 7050 Al alloy. But the cs is unique to every material
- Multiple nucleation's of arc-shaped interconnecting ASBs of distinct boundaries uniquely characterized with distortions and seeming refinement compared to ASB surroundings and bulk specimen is observed. Nonetheless, shear deformation surroundings appear more distorted and refined compared to the bulk specimen.
- Additionally, dispersoid particles become elongated and flattened at ASB regions compared to those present at ASB surroundings and the bulk specimen microstructure.
- The shear band regions exhibit higher hardness characteristics than its surrounding matrix due to refinement and distortion of elongated grains and increased surface area of dispersoid particles. These have the potential to increase strain energy absorption by inhibiting dislocation motions and creating dislocation pileups at GBs at ASB regions
- In-situ observation shows at most 24 ^{o}C of peak temperature rise. Multiple nucleation sites of heat rise are occurs regardless of strain rate.
- Increasing strain rates leads to gradual increasing flow and peak stresses. Elongation to failure is also higher at higher impact momentum and strain rate.

Acknowledgment

The authors thank the National Science Engineering and Research Council (NSERC), Canada for the funds they provided towards this research.

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