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DYNAMIC RECRYSTALLIZATION AS A POTENTIAL CAUSE FOR ADIABATIC SHEAR FAILURE

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Dynamic recrystallization (DRX) is almost universally observed in the microstructure of adiabatic shear bands. It is usually admitted that DRX *results* from the large temperatures that develop in the band along with very high local strains. This paper reports the observation of dynamically recrystallized nano-grains in Ti6Al4V alloy specimens that were impact loaded to only half the failure strain at which the adiabatic shear band develops. This observation shows that DRX not only *precedes* adiabatic shear failure but it is also likely to be a dominant micromechanical factor in the very generation of the band. This result means that adiabatic shear failure is not only a mechanical instability but also the outcome of strong microstructural evolutions leading to localized material softening prior to any thermal softening.

Adiabatic shear failure is a dynamic failure mechanism that develops in the vast majority of ductile materials subjected to impact loading. The characteristic of this mechanism is the development of a narrow band (adiabatic shear band, subsequently referred to as ASB) in which very large local strains and high temperatures develop, resulting in uncontrolled failure [1]. The failure process is therefore treated as a mechanical instability for which an extensive mathematical framework has been developed, based on perturbation analysis of an imperfection, either geometrical or thermal in nature [2, 3]. The basic model for the prediction of the onset of ASB formation relies on the competition between strain-rate hardening and thermal softening [4]. When the latter, resulting from thermo-mechanical coupling, overcomes strain-rate hardening, the material (structure) looses its hardening capacity and fails in a localized mode. The phenomenon has been extensively investigated, since the early work of Tresca [5], with emphasis being put on its microstructural aspects [6]. Abundant literature is available on the subject with the recurring observation, irrespective of the investigated material, of dynamic recrystallization (DRX) taking place in the adiabatic shear band [7], as evidenced from very small (a few tens on nanometers) grains with a very low dislocation density, indicating a soft undeformed material. DRX is therefore intimately associated with adiabatic shear failure with its characteristic large strains and temperatures, even if the phenomenon has been shown to be athermal, occurring even at cryogenic temperatures (see e.g. [8]). The interested reader will find a detailed discussion of DRX in the recent review of Xu et al. [9], emphasizing the above-mentioned points. Dynamic recrystallization was recently modeled numerically in a dynamic failure simulation involving ASB, as an attempt to include microstructural evolution in the failure zone [10]. At the same time, Rittel et al. [11], relying on experimental evidence, identified the dynamic stored energy of cold work as the driving force for ASB formation, as an alternative failure criterion. The stored energy of cold work is the fraction of the mechanical energy that remains stored in the microstructure, e.g. through dislocation re-arrangements [12], while the remaining energy gets dissipated as heat [13, 14]. This concept ties naturally the microstructure of the material, the driving force for its evolution, and the observed mechanical instability. What remains to be identified (missing link) is the exact (or one of the) micromechanisms that leads to local de-stabilization. Here, one would naturally suspect that the universally observed DRX is precisely this micromechanism that results in local material softening [15]. However, as mentioned in the introduction, DRX is considered to result and follow the ASB formation. The purpose of this paper is to show experimentally that *DRX precedes and triggers ASB failure instead of being its consequence.*

A commercial titanium alloy (Ti6Al4V), in the annealed condition, was selected as the material of this study for its marked propensity to fail by ASB formation [1, 6, 16, 17]. Dynamic tests were carried out at a typical strain rate of $\dot{\varepsilon} = 3000\,s^{-1}$ using a Kolsky apparatus [18] and shear compression specimens (SCS) with a 1.5 mm gauge height. The SCS is a specimen in which the kinematics of the deformation enforce a shear dominant situation in the gauge section, with homogeneous strain and stress fields [19-21]. The specimen shown in Figure 1 consists of a cylinder with a pair of diametrically opposed grooves, making an angle of 45º with respect to the longitudinal axis, which delineate the deforming gauge section of the specimen. As with any non-smooth specimen, a mild state of stress concentration develops in the root of the 2 pairs of fillets that define the gauge section [19], so that adiabatic shear bands *always* initiate in this region of the gauge. The dynamic tests consisted of either impacting a specimen until its failure (fracture) by ASB formation, or bringing it to a controlled level of strain using hardened steel stop-rings, followed by elastic unloading. The stop ring ensures that the specimen is impacted only once, as opposed to being repeatedly pounded by the stress waves trapped in the bars. For this specimen, the normalized strain (with respect to a fractured specimen), was 0.45. An additional experiment was carried out quasi-statically, in which the specimen was deformed to a normalized strain of the approximate same magnitude, and unloaded without failure. Typical stress strain curves are shown in Figure 2. One should note that apart from one specimen that failed by ASB formation (noted 'failed'), none of the remaining specimens failed whatsoever. Transmission electron microscope (TEM) specimens were prepared from each type of specimen (interrupted static, interrupted dynamic and dynamically failed) to allow for a comparative characterization of the microstructure. For the failed specimen, the observation area was set to include the fracture plane (fillet area), while the same area was selected for the non-fractured remaining specimens (Figure 1).

The initial microstructure of the alloys consists of α and β phases. As deformation proceeds, the microstructure gets increasingly refined by forming dislocation cells with a small misorientation first, followed by subgrains with a higher misorientation. In some instances, stress-induced martensite (α' or α'') and twins are formed in the β phase. The various microstructural features are identified from their corresponding selected area diffraction patterns (SADP). Figure (3) shows the characteristic microstructure of the deformed quasi-static specimen, consisting essentially of dislocation cells and stress-induced martensite. The microstructure of the dynamically broken specimen is shown far away (Figure 4a) and within the ASB (Figure 4 b, c). Away from the ASB, the refined microstructure consists of dislocation cells with high misorientation angles, with a high density of stress-induced martensite transformed from the β phase. The morphology is different inside the ASB: a high dislocation density is noticeable, and the SADP shows incomplete rings, which indicate the presence of recrystallized nanograins. However, the individual grains can not be resolved as they are screened by the high dislocation density. The nanograins are the result of DRX. This observation is in total accord with previous reports of DRX grains inside adiabatic shear bands. Figure (5) shows the microstructure of the deformed material in the fillet area of specimen S6 that was not loaded to failure. Small DRX grains are clearly observed with a typical size of is 10-30 nm, which are essentially free of dislocations. The corresponding SADP shows a ring pattern, which is typical of nanograined polycrystalline materials and quite similar to that shown in Figure 4(b).

A surprising outcome of this work is that dynamically recrystallized grains are clearly observed in a specimen that was not loaded to failure, and barely reached half of its failure strain (Figure 5). This figure bears a strong resemblance to Figure 4(c), both having a diffraction pattern that confirms the presence of recrystallized nanograins.

The implication of these observations is that *DRX actually precedes ASB formation and is not the mere consequence of the high local temperatures and strains as commonly accepted*. Dynamic recrystallization has a clear mechanical meaning, in that these nanograins are virtually strain free, with a low density of dislocations which indicates their softness in the heavily deformed, thus hardened, surroundings. Such soft inclusions, as they multiply with the ongoing deformation process, are most likely to generate a weak enclave whose evolution (growth) into a localized adiabatic shear band is the final step before general failure (fracture). Here, the soft nanograins constitute a perturbation in terms of mechanical properties. DRX can therefore be considered as the missing microstructural link in the succession of events leading to ASB formation. We now postulate that our previous identification of the dynamic stored energy of cold work as the parameter for the onset of ASB [11], can be translated as the driving force for DRX. It should also be noted that DRX was observed at a stage at which homogeneous adiabatic heating effects in the specimen are very small, if not negligible, in accord with previous work [16].

To summarize. Dynamic recrystallization has always been observed in adiabatic shear bands and is considered *to result from the conditions in the band*. The latter is treated as a material/mechanical instability based on the perturbation of homogeneous temperature or deformation fields. The present results just point to the contrary, namely that *DRX precedes significanly ASB formation*, at a stage where homogeneous adiabatic heating effects are negligible. DRX results from the finite capacity of a material to store dynamic deformation energy [11]. Being a soft enclave in hardened surroundings, the soft recrystallized grains multiply as deformation proceeds and are believed to generate the commonly observed adiabatic shear band that leads to catastrophic failure.

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BIBLIOGRAPHY

[1] Y. Bai, and B. Dodd, *Shear Localization: Occurrence, Theories, and Applications* (Pergamon Press, Oxford, UK, 1992).

[2] T. Wright, The Physics and Mathematics of Adiabatic Shear Bands (Cambridge University Press, Cambridge, 2002).

[3] A. Molinari, and R. J. Clifton, J. Applied Mech. **54**, 806 (1987).

[4] C. Zener, and J. H. Hollomon, J. Applied Phys. **15**, 22 (1944).

[5] H. Tresca, Annales du Conservatoire des Arts et Métiers **4** (1879).

[6] M. A. Meyers, Dynamic Behavior of Materials (J. Wiley and Sons, New York, NY, 1994).

[7] M. A. Meyers *et al.*, J. Phys. IV France Colloq. C3 **PR9**, 51 (2000).

[8] J. A. Hines, and K. S. Vecchio, Acta Mater. **45**, 635 (1997).

[9] Y. Xu *et al.*, Metallurgical and Material Transactions A **39A**, 811 (2008).

[10] S. Medyanik, W. Liu, and S. Li, J.Mech. Phys. Solids **55**, 1439 (2007).

[11] D. Rittel, Z. G. Wang, and M. Merzer, Physical Review Letters 96, 075502 (2006).

[12] M. Bever, D. Holt, and A. Titchener, The Stored Energy of Cold Work (Pergamon Press, London, 1973), p. 191.

[13] W. S. Farren, and G. I. Taylor, Proc. R. Soc. **CVII**, 422 (1925).

[14] G. I. Taylor, and H. Quinney, Proc. Royal Soc. London **143**, 607 (1934).

[15] D. Rittel, Z. G. Wang, and A. Dorogoy, Int. J. Impact Engng. (2008).

[16] D. Rittel, and Z. G. Wang, Mechanics of Materials **40**, 629 (2008).

[17] Y. Me-Bar, and D. Shechtman, Matls. Sc. and Engng. **58**, 181 (1983).

[18] H. Kolsky, Proc. Phys. Soc. London **62-B**, 676 (1949).

[19] A. Dorogoy, and D. Rittel, Exp. Mech. **45**, 167 (2005).

[20] A. Dorogoy, and D. Rittel, Exp. Mech. **45**, 178 (2005).

[21] D. Rittel, S. Lee, and G. Ravichandran, Experimental Mechanics 42, 58 (2002).

FIGURE CAPTIONS

Figure 1: A typical shear compression specimen before (A) and after deformation (B). The block arrows show the applied load direction and the thin arrows point to the stress-concentration fillets (F) where ASB's form. Specimens for transmission electron microscopy were taken from this area. Note the shear dominant kinematics in (B).

Figure 2: True-stress strain curves. S1 was loaded quasi-statically up to $\varepsilon \approx 0.17$ and unloaded without failure. "Failed" indicates a specimen that was loaded dynamically until failure by ASB formation. The strain to failure was $\varepsilon \approx 0.24$, which is used to normalize the strain of S6. The latter was loaded dynamically up to a relative strain of 0.45, and did not fail.

Figure 3: Quasi-static specimen – TEM micrograph: (a) The typical microstructure consists of dislocation cells. (b) Area showing stress-induced (α") martensite (arrowed) transformed from the β phase, and its corresponding SADP.

Figure 4: Dynamically failed specimen - TEM-micrographs. (a) Far from the ASB: Dislocation cells and stress-induced martensite. The typical SADP mainly contains misoriented α phase cells. (b) Within the ASB: High dislocation density without any distinct morphology. The SADP shows incomplete rings indicating the presence of very fine recrystallized grains. (c) Higher magnification of (b): The high dislocation density screens the fine grains revealed by the SADP.

Figure 5: Interrupted dynamic tests - TEM-micrographs in the fillet area. Dynamically recrystallized grains formed in the highly dislocated area are indicated by arrows. The size of the grains ranges from 10-30 nm and they are free of dislocations. The corresponding SADP consists of ring patterns, typical of nanograined polycrystalline materials. Note the similarity of morphologies between Figures (5) and (4c), namely high dislocation density and the presence of very fine recrystallized grains.

FIGURES

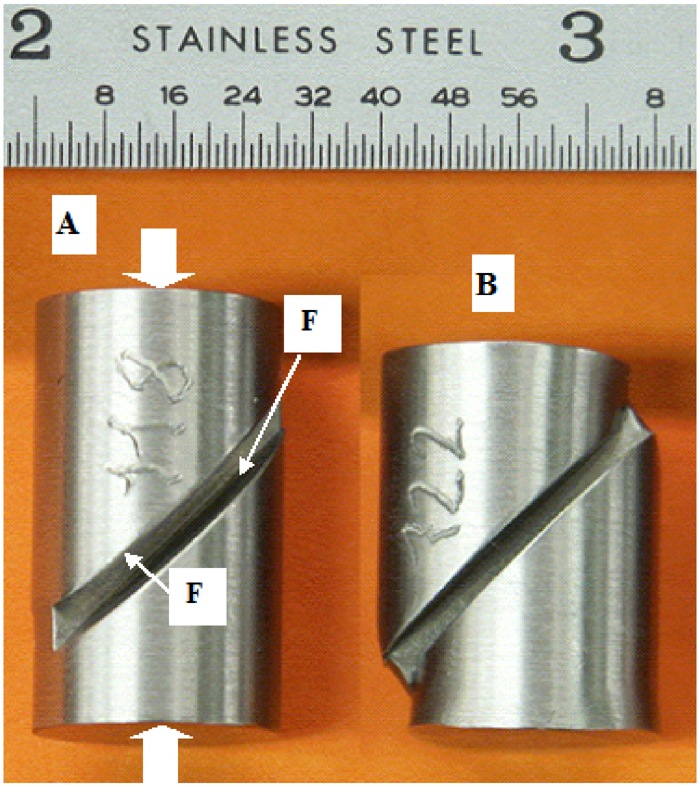

Figure 1

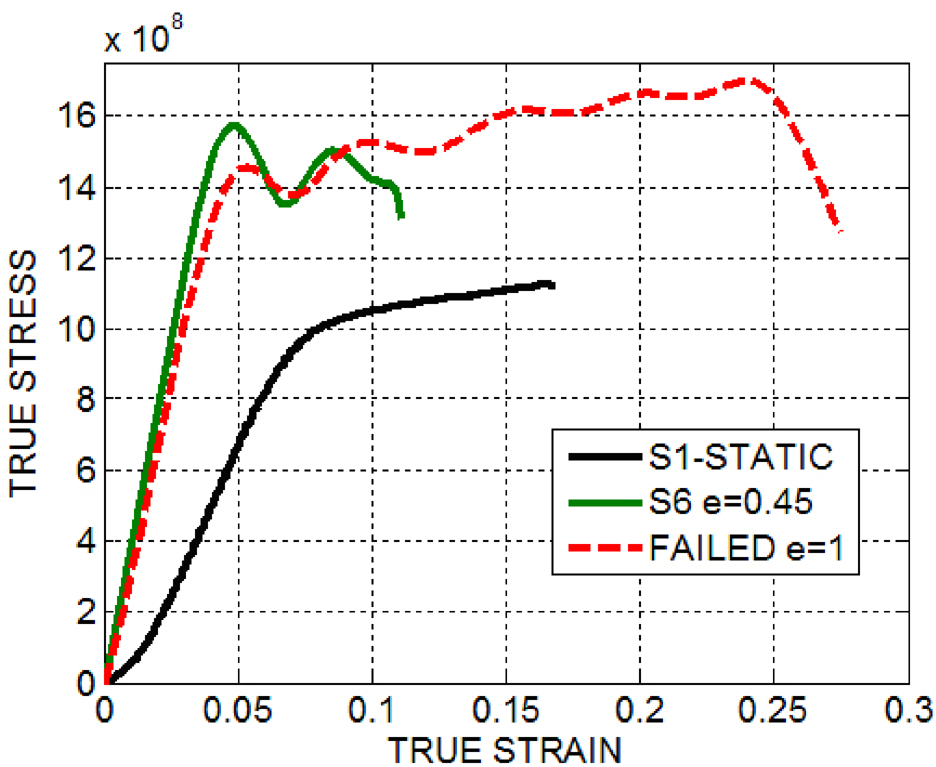

Figure 2

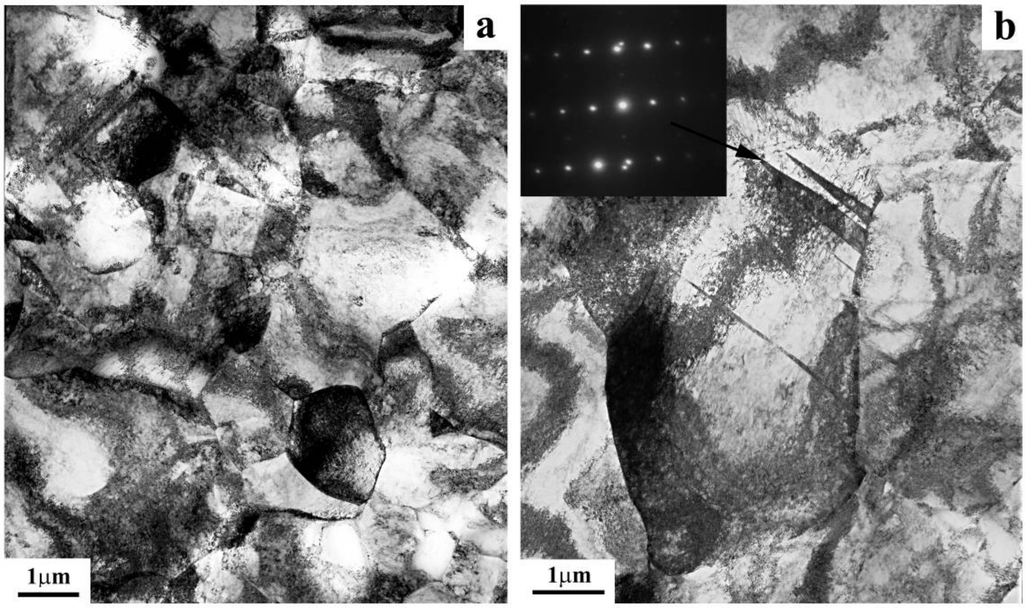

Figure 3

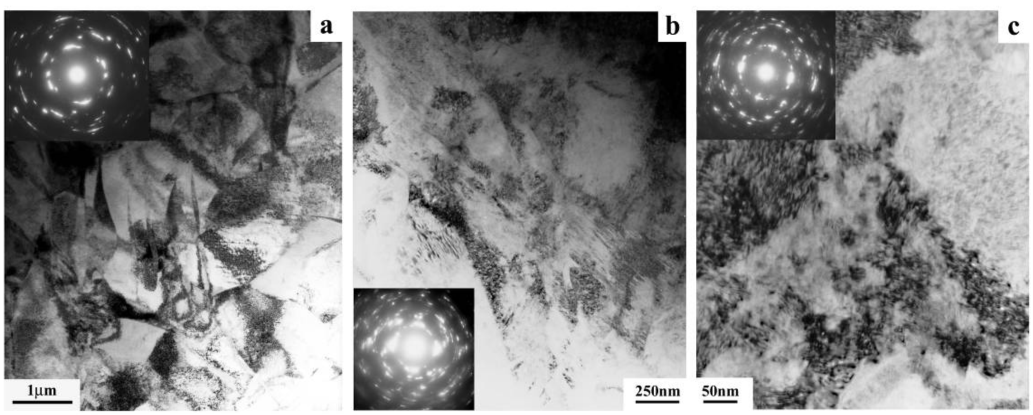

Figure 4

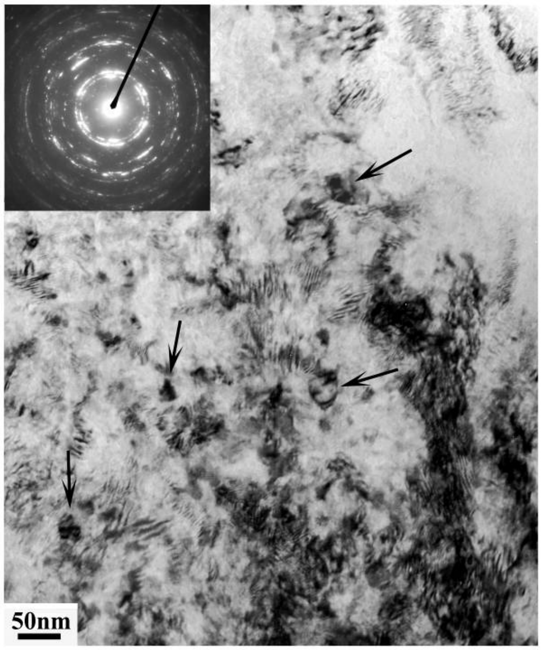

Figure 5