



Rapid communication

## High-cycle fatigue behavior of Zn–22% Al alloy processed by high-pressure torsion

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### ABSTRACT

A Zn–22% Al eutectoid alloy was processed by high-pressure torsion (HPT) and its high-cycle fatigue behavior was explored using novel small-scale bending fatigue experiments. Testing of the finest grain region in each HPT disk showed that the fatigue life decreases continuously with increasing numbers of torsional revolutions. The results are discussed in terms of the HPT-induced hardness change and the underlying fatigue failure mechanism.

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### 1. Introduction

The Zn–22 wt% Al eutectoid alloy is widely used for damping/energy-absorbing components [1,2] and is well known to exhibit excellent superplastic properties under optimum combinations of temperature and strain rate [3–5]. Recently, there have been efforts to enhance the superplastic properties of the Zn–Al alloy by refining the grains using severe plastic deformation (SPD) techniques [6,7] including equal-channel angular pressing (ECAP) [8] and high-pressure torsion (HPT) [9]. Among the available SPD techniques, HPT processing may be more attractive than ECAP since it is a simpler technique, it can impose higher plastic strains and hence it provides a capability of producing smaller grain sizes [10]. During HPT, the equivalent von Mises strain,  $\epsilon_{eq}$ , imposed on the disk is given by [11,12]:

$$\epsilon_{eq} = \frac{2\pi Nr}{h\sqrt{3}} \quad (1)$$

where  $r$  and  $h$  are the radius and thickness of the disk and  $N$  is the number of torsional revolutions. Thus, the strain varies locally across the disk and is a maximum near the edge.

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Recently, extensive research was conducted to investigate the evolution of microstructure and quasi-static mechanical properties (such as hardness and strain-rate sensitivity) of the Zn–22Al alloy during HPT processing [13–16]. However, there was no attempt to monitor the change in the dynamic mechanical properties under cyclic loading of the alloy after HPT processing although such properties are indispensable for practical engineering applications [1,2]. In fact, only limited attention has been given to the fatigue behavior of ultrafine-grained and nanocrystalline metals. In the small number of publications on this topic (see a recent review by Padilla and Boyce [17]), it was reported that the fatigue resistance of metals having a submicrometer grain size can be largely enhanced, which was explained within the framework of a Hall–Petch grain size dependent behavior. In the case of the Zn–22Al alloy, only low-cyclic fatigue testing was reported for the alloy processed by ECAP where the measurements used round-bar specimens under uniaxial loading conditions [1,2]. It should be noted that, while conventional fatigue testing methods are applicable to materials after ECAP having relatively large volumes with homogeneous microstructures, the disk samples produced by HPT are inappropriate for conventional measurements due to their small volumes as well as their inhomogeneous microstructures as suggested by Eq. (1). This difficulty may explain the absence of any attempts to examine the change in fatigue properties after HPT processing.

Accordingly, the present study was initiated as a first report to document the evolution of high-cycle fatigue (HCF) behavior in the Zn–Al alloy after HPT processing. In practice, a novel testing

system for small-scale bending fatigue was used for the investigation at the edges of the disks where the highest  $\epsilon_{eq}$  is imposed during the processing. This testing method, originally developed for thin film metals deposited on Si cantilever arrays [18], applies fully reversible compression-tension strain to the cantilever specimen (i.e., the fatigue strain ratio  $R = \epsilon_{min}/\epsilon_{max} = -1$ ) and thereby it is possible to measure HCF life and related damage in a small volume of the specimen.

## 2. Experimental

The experiments used a commercial Zn–22 wt% Al eutectoid alloy containing a binary microstructure of Al- and Zn-rich phases. Disk samples with a thickness  $h$  of  $\sim 1.5$  mm and radius  $r$  of  $\sim 5$  mm were carefully polished on both sides to give a final  $h$  of  $\sim 0.8$  mm and then annealed in air at 473 K for 1 h to give an average grain size of  $\sim 1.4$   $\mu\text{m}$ . The HPT processing was conducted under quasi-constrained conditions [19] at room temperature under a compressive pressure of 6.0 GPa and at a fixed rotational speed of 1 rpm. The disks were processed for totals of 1, 2 or 4 turns and measurements at the edges of the disks showed average grain sizes of  $\sim 400$ ,  $\sim 370$  and  $\sim 350$  nm, respectively. Details of the microstructural changes were demonstrated in recent reports [13–16]. The distribution of the Vickers hardness across the diameter of each disk was measured with HMV-2 equipment (Shimadzu, Tokyo, Japan) at a peak load of 100  $g_f$ . The initial condition before HPT processing showed a hardness of  $Hv \approx 68$ .

Fig. 1 shows a schematic of the sample preparation procedure and testing system of the novel fatigue technique. From each HPT disk, a cantilever specimen was machined into a rectangular shape with a width of 0.8 mm, length of 9.6 mm and thickness of 0.8 mm by using electrical discharge machining. Both sides of the cantilever were polished with SiC papers and diamond suspensions and then electropolished to a final thickness of  $\sim 100$   $\mu\text{m}$  for the removal of the damaged surface layers. The cantilever was fixed to a custom-made Al holder and masses, having total weight of  $\sim 850$  mg to produce the bending load, were attached on both surfaces of the cantilever.

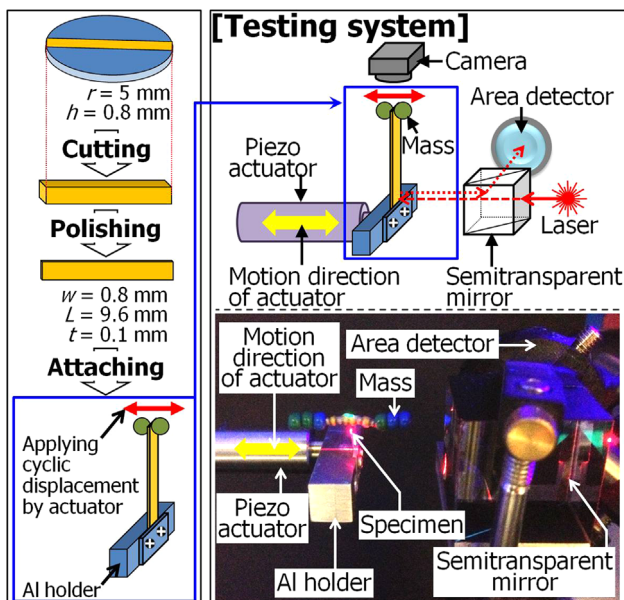


Fig. 1. Schematic illustrations of sample preparation procedure and bending fatigue testing set-up.

Fatigue testing was performed through a piezoelectric actuator (Physik Instrumente, Waldbronn, Germany) that applied a fully reversible strain by stimulating the beam to vibrate at its resonance frequency. To determine the proper resonance frequency for the cyclic loading, a laser was directed onto the sample and the reflected beam was observed using an area detector (see Fig. 1). Then, the change in the intensity of the reflected laser beam was monitored while the frequency increased, and finally the measured frequency at the maximum intensity was used for the fatigue testing. Other information on the testing system is provided elsewhere [18]. After fatigue testing, the surface damage of the cantilever was analyzed using an ultraviolet laser scanning microscope (UV LSM), VK-9700K (KEYENCE, Osaka, Japan) and the fracture surface morphology was observed with a field-emission scanning electron microscope (FE SEM), Quanta 250 (FEI Inc., Hillsboro, OR).

## 3. Results and discussion

Fig. 2 shows the variations in Vickers hardness  $Hv$  along the radial directions from the centers of the disks after HPT for 1, 2 and 4 turns where the upper dashed line denotes  $Hv$  for the unprocessed sample. The  $Hv$  values of all processed disks are highest at the centers and decrease with increasing distance from the centers to the peripheries. At the edges, the hardness is almost saturated at points beyond  $\sim 2$  mm from the centers of the disks. This is in a good agreement with earlier results reporting reasonably homogeneous distributions in hardness and microstructure near the edges of the Zn–22Al disks [13–16]. The results suggest that other mechanical properties may show reasonable consistency when measurements are taken in regions beyond  $\sim 2$  mm from the center, thereby confirming that the configuration for the fatigue testing shown in Fig. 1 is appropriate for evaluating the fatigue properties (of the edge region with the maximum  $\epsilon_{eq}$ ) without involving any inherent inhomogeneities of microstructure in the disks after HPT. In Fig. 2, the alloy shows exceptional weakening with increasing  $\epsilon_{eq}$  despite significant grain refinement after HPT [13–16] and this is due to a reduction in the rod-shaped Zn precipitates within the Al-rich grains during deformation by HPT [20]. This strain weakening after HPT is characteristic of alloys when processed at high homologous temperatures [21].

In this novel fatigue testing, the fatigue strain amplitude,  $\epsilon_a$ , varies along the location of the cantilever and is given as a function of distance from the fixed end,  $x$  [22]:

$$\epsilon_a(x) = \frac{3u_{max}t}{2L^3}(L-x) \quad (2)$$

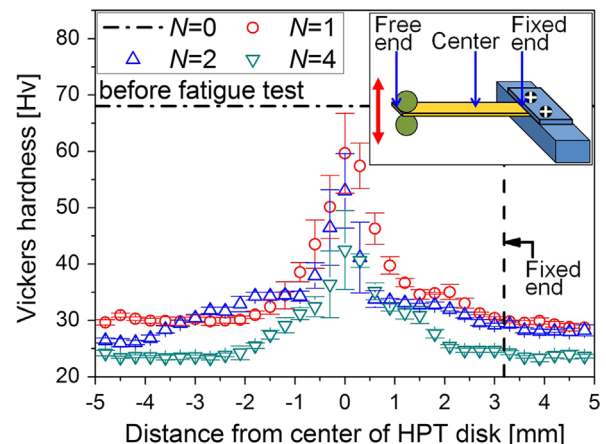


Fig. 2. Change in Vickers hardness with distance from the center of HPT disk.

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