Fatigue and Damping Behavior of PM Produced Aluminum Matrix Composites after Shot Peening

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Abstract

Two Aluminum (Al) materials were produced by hot extrusion of different powder mixtures at 350°C. For the first material only gas atomized powder of micro-scale 99.98 Al was consolidated. The second powder was mixed by ball milling of the same Al powder with 0.35 vol. % nano-scale hexagonal Boron Nitride (BN) before hot extrusion. Ball milling and subsequent hot extrusion resulted in a Metal Matrix Composite (MMC) strengthened by fine and homogenously dispersed BN particles. Due to this dispersion hardening the tensile strength of the produced the MMC increased by 65% compared to the PM material without BN dispersions with negligible loss of high ductility (18% plastic strain). Both materials have a high potential of hardness and fatigue strength increase by cold working or shot peening because they were dynamically recrystallized after hot extrusion. Fatigue strength of the dispersion hardened material could be increased using shot peening by about 20%. The Damping is increased for low and decreased at high strain amplitudes by the dispersions. Damping increases immediately after shot peening and ages afterwards whereas both the damping increase and the ageing strength are independent of the presence of dispersions. These measurements can be explained by the interaction of dislocations with point defects like vacancies and solid solutes. They can also be used to investigate crack nucleation and growth and to predict impending failure.

Keywords Powder metallurgy (PM), dispersion hardening, metal matrix composite (MMC), boron nitrite (BN), mechanical properties, fatigue, shot peening, aluminum, damping, internal friction, cracks

Introduction

The mechanical properties of metals can be improved by both hardening of the whole metal und hardening or compressive straining of the metals surface. In the present study both methods are applied to investigate how the according mechanisms superimpose. Dispersion hardening is a well-known method to strengthen metals in a broad temperature range [1,2]. For this, the intermediate free distance between the particles must be as small as possible. This can be achieved by homogeneously distribution of nanoscale particles even for small volume fractions in the order of 1 to 10%. For this publication the homogeneous distribution was attempted by ball milling of aluminum powder with nanoscale BN powder and subsequent hot extrusion. In many cases the degree of consolidation can not only be characterized by the porosity remaining in the consolidated material. Cracks or micro-cracks must be considered too. Therefore the mechanical properties of aluminum composites with nano-scale ceramic particles, produced by ball milling and hot extrusion were investigated with tensile tests at room temperature, hardness measurements, and strain amplitude depending damping measurements. The fatigue strength of metals is the lowest stress that can destroy them. For this alternating loading is necessary being accompanied by internal friction i.e. conversion of mechanical energy to heat. The movement of dislocations and cracks are reasons for internal friction. Therefore measuring impacts of internal friction like damping of free decaying vibrations can give some information about nucleation and growth of cracks decreasing the fatigue strength as well as training that increases fatigue strength. Fatigue strength of metals can be improved by both hardening mechanisms as well as suitable surface treatments like shot peening. While hardening affects both, yield as well as fatigue strength, surface treatments only affect fatigue. In the present investigation four powder metalurgically (PM) produced aluminum base materials have been investigated with and without dispersions of boron nitride (BN), and with and without shot peening to get some information how the effects of peening and dispersion hardening superimpose. The measurement of damping helps characterizing the materials and material treatments. This has already been shown for a commercial aluminum alloy in ref. [3].

Experimental Methods

Material Preparation

Aluminum-matrix-composites were prepared by ball milling of two water atomized aluminum powder mixtures (99,98 wt.%), with 25 µm and 45 µm mean diameter fractions produced by gas atomization (TLS Technik Spezialpulver, Bitterfeld, Germany), and 0.35 vol.% BN powder of about 500 nm mean diameter, in a planetary ball mill (PM400, Retsch, Haan, Germany) under air atmosphere. The two aluminum powder fractions, each of 50 vol.%, were mixed together with BN to achieve a secondary powder convenient for subsequent consolidation. An austenitic steel milling cup with 500 ml volume was filled with the powders and 7 mm diameter and 13 mm diameter light corundum balls. The ratio of mass of powder to ball 7 mm to ball 13 mm was 1:1.5:1.5, respectively [4]. The powder volume in the milling cup being about 20% of the whole volume was milled for 6 hours at 150 – 200 rpm. Oxidation, plastic deformation and fracture of the aluminum powder particles took place during milling and lead to a fine BN nanoparticle distribution in the plastically deformed aluminum particles. Thus a non-agglomerated secondary metal matrix composite (MMC) powder with flake like particles of about 20 µm diameter and 5 µm thickness was produced.

After ball milling the secondary MMC powder was filled into aluminum capsules of 70 mm diameter, 2 mm wall thickness and about 220 mm height, and closed at one end with a circular plate of 5 mm thickness. Afterwards the capsules were closed by another circular plate of 5 mm thickness with a small hole of 2 mm diameter in the middle using fitting threads in the capsules and plates. The small hole acted as gas outlet during hot extrusion. Contrary to the consolidation procedure used in earlier investigations [4] the powder mixture was not cold pre-pressed resulting in better consolidation results during sub sequential hot extrusion.

The encased powder mixtures were hot extruded to rods of 20 mm diameter (1:3.5 extrusion ratio) using a horizontal 6300 kN hot extrusion press. Extrusion temperature and velocity were 350°C and 2 mm/s, respectively [4, 5]. It has to be stressed that the given volume fractions are additions or nominal values. Moreover the secondary powder and in the consolidated rods contained some amounts of Alumina due to the surface oxides on the used aluminum powder and oxidation of aluminum during milling.

Material Characterization

Micro hardness measurements, tensile tests, rotating bar fatigue tests and strain dependent damping tests were used to characterize the PM produced material. Samples for tensile testing with 5 mm diameter and 56 mm long were machined out of the rods. Tensile tests were carried out with a universal testing machine (UTS Zwick, Ulm, 250 kN). Tensile Yield Strength was determined using standard DIN EN 10002-1.

Shot peening was carried out with a combined peening machine, (OSK, Oberhausen) in injection mode. The shot peening media was spherically conditioned steel cut from wire (SCCW14) with a diameter of about 180 µm. All samples were peened with an air pressure of 5 bar, resulting in an Almen intensity of 0.3 mmA. Peening time was chosen in order to guarantee coverage of 100%. This was realized in 45 s for the hour-glass samples and 135 s per side for the damping samples. For the rotating bending tests four-point-bending machines (Sincotec, Clausthal) with steel springs for restoring force were used. The tests were intercepted in case of failure or after 10^7 cycles.

Strain amplitude dependent damping was determined by measuring the logarithmic decrement of freely decaying vibrations of bending beams clamped at a strengthened end. The specimens were excited into resonance of the first mode by a permanent magnet fixed at the free end of the bending beam and a sinusoidially alternating magnetic field. The resonance frequency depending mainly on the specimens´ geometry was about 20 Hz. Damping was measured as the logarithmic decrement δ of freely decaying bending vibrations. The experimental setup is given in more detail in refs. [6, 7].

Experimental Results and Discussion

Tensile tests were performed with samples produced from hot extruded rods of Al and Al - 0.35 vol.% BN. The corresponding stress strain curves are shown in fig. 1.

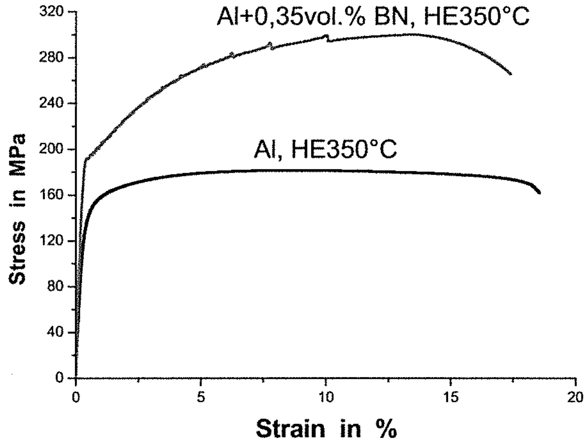

Fig. 1 Tensile tests with samples produced from hot extruded rods of Al and Al - 0.35 vol.% BN; strain rate $0.017s^{-1}$

It can be seen from the figure that the addition of this small amount of hexagonal BN has resulted to 26% increase of yield strength and 65% increase of tensile strength although the loss of plasticity is almost negligible. The reduction of plastic strain turned out to be only 6% (1% in absolute values). Furthermore the addition of BN let to higher work hardening, a distinct yield point, and jerky flow being untypical for dispersion hardening. These results show that dispersion hardening by BN particles has been very effective and it can be assumed that the BN particles have been fragmented and mixed by the ball milling and hot extrusion process. Jerky flow indicates the quick diffusion of atoms during plastic deformation. It is not clear up to now what these species are, but it may be assumed that they are nitrogen atoms due to their quick diffusion. Therefore for the investigated Al-BN-MMCs we assume mainly three hardening mechanisms working, dispersion hardening [1], Hall-Petch hardening by small grains, and maybe some solid solution hardening with and perhaps also quickly moving diffusion species. Work hardening can be excluded for the hot extruded material because the high temperature at hot extrusion leads to severe dynamical recrystallization.

Therefore there is still substantial potential for work hardening. This can be observed in fig. 2 in the hardness course of Al-0.35vol%BN rotating bending samples that have been shot peened and afterwards fatigued by rotation bending at 50 Hz rotation frequency. A considerable increase of hardness can be observed for the fatigued and shot peened compared to the untreated material.

Additionally increases of hardness in direction of the surface with increasing slopes can be observed. This is due to the rotational bending fatigue exerting alternating stresses of 150 MPa to the sample that decrease from the surface to the inner parts of the sample and lead to small plastic deformations. This effect is also called training. It is obvious too, that the hardness of the near surface region of about 300 µm is increased additionally by plastic deformation caused by the shot peening treatment.

Alternating loading with amplitudes of 150 MPa cannot destroy the PM Al reinforced with 0.35 vol.% BN. This is shown in fig. 3 representing S-N-curves of both materials, unpeened and shot peened.

It can be seen that the fatigue strength has been increased by about 30 MPa (20%) by the performed shot peening surface treatment. Low cycle fatigue was improved by shot peening too, as can be seen in fig. 3

All damping results are shown in figs. 4 to 6. In figs. 4 the logarithmic decrement (damping) is plotted versus strain amplitude in semi-logarithmic scale. All curves show an increase of damping with increasing strain amplitude. For small strain amplitudes damping becomes constant. This behavior is typical for metals, can be attributed to mobile dislocations and is successfully modeled by the theory of Granato and Lücke [8, 9].

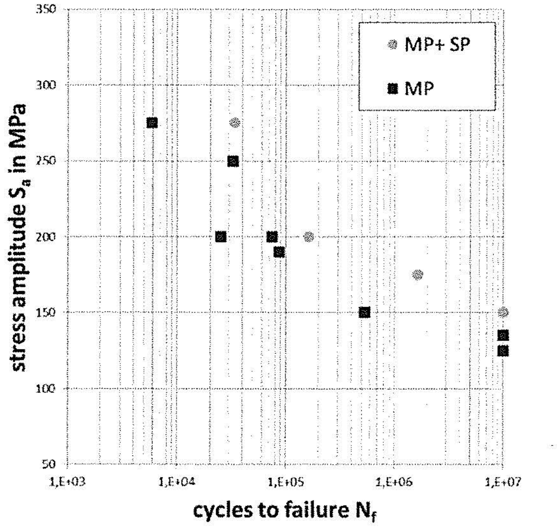

Fig 2 Hardness vs. distance from surface of Al-0.35vol%BN for shot peened and unpeened samples

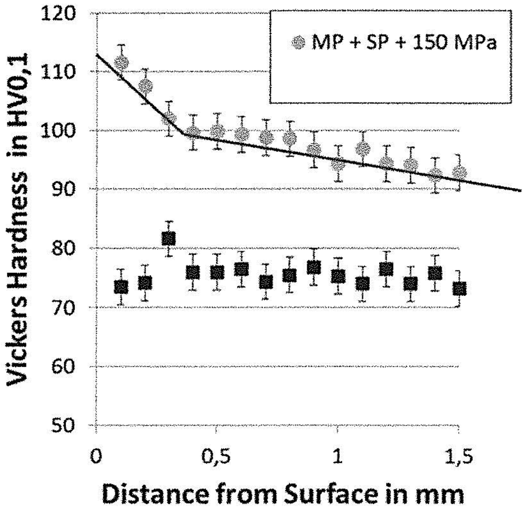

Fig. 3 S-N-curves of Al and Al - 0.35 vol.% BN

For small strains they reversibly bow out between weak pinning points like point defects under the cyclic stress leading to constant damping. When the stress amplitude is high enough to break free from the first pinning points the dislocations bow out progressively and the damping increases with increasing stress or strain.

The increase of damping with strain amplitude is much lower in case of the reinforced material. This is -together with the observed jerky flow- another evidence that not only dispersions are present in the MMC but also some solid solutes.

After shot peening the strain dependent damping was measured again. Figs. 4 show that shot peening increases the whole damping curve by about the same amount. Repeatedly measuring after increasing times shows an ageing effect which can better be observed in fig.5, where the damping at a strain amplitude 10^{-4} and the squared and normed frequency (being proportional to the young´s modulus) is plotted versus time.

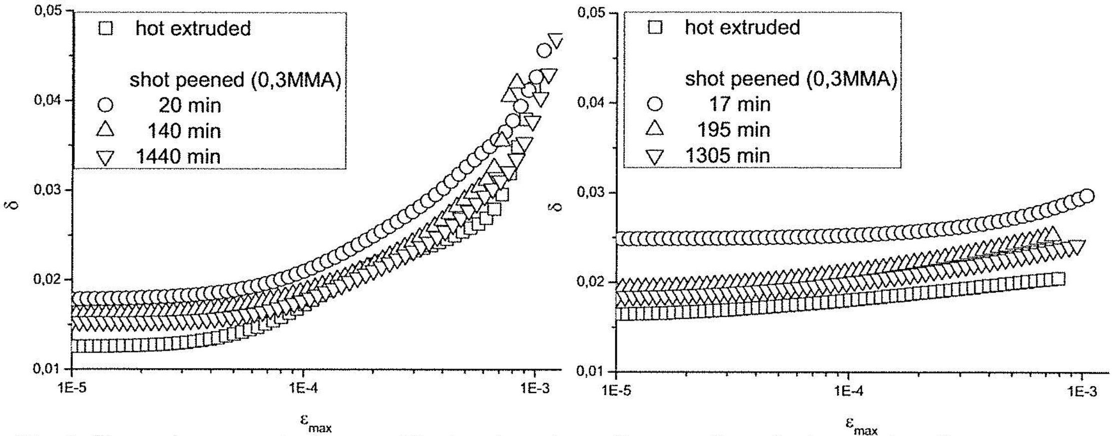

Fig 4: Damping vs. strain amplitude at various times after shot peening for:

a) Al hot extruded

b) dispersion hardened material Al0.35vol.%BN

The ageing effect appears in the dispersion hardened and in the not dispersion hardened material. Because this effect is attributed to quickly diffusing atoms one can assume that they must be present in both materials.

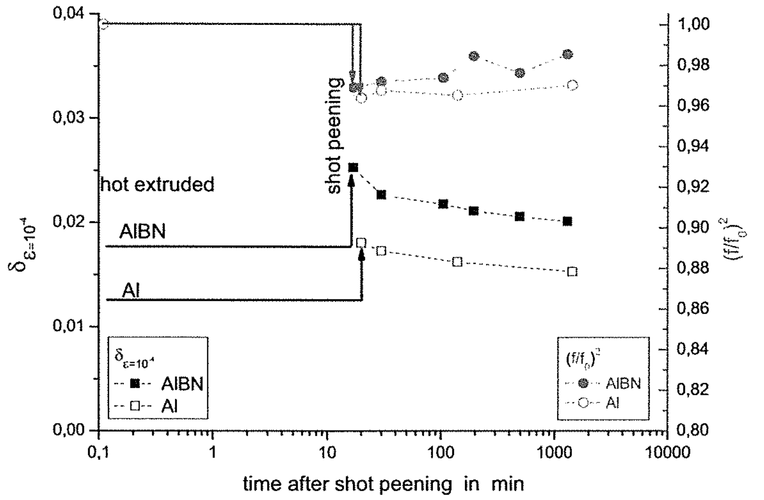

Fig 5: Damping at strain 10^{-4} and normed modulus versus vs. ageing time at room temperature

The development of damping after increasing cycles to fatigue was investigated too, because damping is not only sensitive on the interaction of point defects and dislocations [8, 9] but also on the nucleation and growth of cracks [10,11]. Opening and closing of cracks can be the source of energy dissipation i.e. damping too. This can be observed for the dispersion hardened materials in figs 6a,b where the damping and modulus at strain amplitude of 10^{-4} is plotted versus the number of cycles with 140 MPa amplitude. For both materials two regimes of strain amplitudes can be distinguished. The first one for small numbers of cycles to fatigue where the damping increases slowly with increasing numbers to fatigue and the second following one, where damping increases progressively strong leading to inevitably breaking of the sample. So breaking of the sample can be predicted before it breaks.

The reason for the slow increase of damping is not really clear. It can be due to increasing dislocation density, an effect connected to training or work hardening but also to increasing dislocation length due to the election of pinning centers with longer distance during repeatedly bowing out and depinning of dislocations with increasing number of cycles.

Conclusions

Shot peening can improve fatigue strength of aluminum matrix composites produced powder metallurgically by hot extrusion. Damping is increased after shot peening and ages with time. Ageing of damping is not affected by dispersoids. Ball Milling is a suitable tool for successful dispersion hardening. Small amounts of BN dispersoids can substantially increase strength and fatigue strength. The measurement of damping is a suitable tool for investigation of fatigue and shot peening.

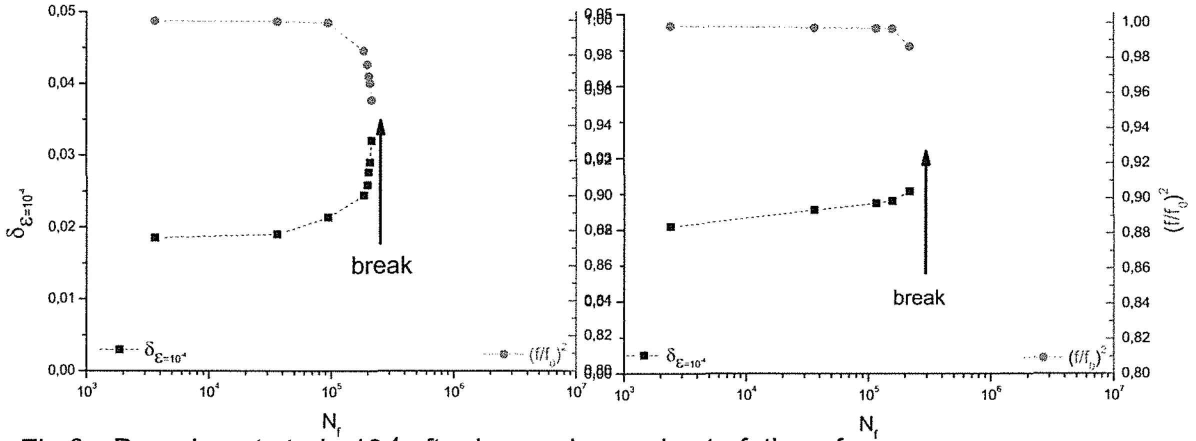

Fig 6: Damping at strain 10^{-4} after increasing cycles to fatigue for:

a) hot extruded Al b) hot extruded Al0.3vol.%BN

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