The Effect of Cold Deformation and Surface Treatment on Fatigue Behaviour of Al$_2$O$_3$-Al6061 Composite Material

Gaofeng Quan, Wolfgang Brocks
Institute for Materials Research, GKSS Research Center, Geesthacht, Germany

1 Abstract

An investigation of rotating beam fatigue was carried out on alumina particulate reinforced aluminum alloy 6061 after bulk cold and hot work and surface treatments. It is found that the cold work (swaging) decreases both the low-cycle-fatigue (LCF) life and fatigue limit at $10^7$ cycles. Shot peening improves the fatigue performance quite a lot, regarding both LCF life and fatigue limit for both undeformed and deformed materials. Post heat treatment also improves the fatigue behavior of deformed material. The observation of crack paths illustrates that the cracks tend to direct to the micro crevices through the matrix. Both post-heat treatment and mechanical surface treatment can cure some defects and in turn improve the fatigue behavior. It is found from macro and micro hardness measurements that the improvement in fatigue behavior is induced more or less by work hardening of surface microstructure.

2 Introduction

Shot peening is one of most efficient processes to improve the fatigue behavior regarding both LCF life and fatigue limit of most metallic materials, from magnesium, aluminum, and titanium alloys [1], various steels [2], to nodular cast iron [3]. During shot peening, set-up of compressive residual stresses and heavy cyclic plastic deformations, which lead to higher dislocation density and refined structure in the surface zone of the components or specimens, are the major factors of the better fatigue resistance. The increase in surface roughness by shot peening seems to have more or less effect on fatigue crack nucleation and no effect on the crack propagation.

Particulate reinforced metal matrix composite materials (PRMMCs), especially aluminum alloys reinforced by ceramic particulates, have attracted extensive attention of various research and development fields, due to their ratio of properties to costs being higher than in other reinforced metallic materials. Due to their low ductility, the deformability of this type of materials is poor compared with conventional metallic materials. The reported investigations on cold work (CW, namely, cold rolling, extruding, swaging, compression and so on) of PRMMCs have dealt with microstructure evolution [4-6] and mechanical property features [7-9]. The present authors have reported on the microstructural damage and its effect on mechanical properties of cold worked PRMMCs [10], in which the breaking of particles during cold work is
the essential factor for the deterioration of mechanical properties. Up to now, there are few reports on the effect of mechanical surface treatment of PRMMCs, together with cold working. In this paper, the effect of shot peening on aluminum oxide particulate reinforced aluminum alloy is reported and some hardness investigation is discussed.

3 Experimental Procedure

The material used in this work was aluminum oxide particulate (Al₂O₃) reinforced aluminum alloy Al-Mg-Si-Cu (AA6061). It was originally fabricated by the powder metallurgical route and then hot extruded into round bars with a diameter of 22 mm. The volume fraction of the alumina particles was 0.22 with an average particle size of 13.7µm. Cold working was conducted by swaging (round-die forging) at room temperature, whereas the hot working was carried out in lab air at an original temperature 450°C of the work piece. The working length of the die (hammers) was 12 mm. The final diameter of the worked piece was 10 mm. Part of the material was first cold worked and then given a T6 temper (0.5h 530°C/WQ, 9h 160°C). This condition is called CWT. Other was first given the T6 temper and then cold worked (condition TCW). For comparison, a cold worked condition (CW) was tested as well as a T6 temper (T) without cold work. The tensile and fatigue test specimens were taken solely in longitudinal direction. The specimens for optical and SEM analysis were cut from the worked bars in longitudinal and transverse sections. The statistical measurements of particle size and distribution were conducted automatically by ImageC system or manually in two orthogonal directions on the micrographs under magnifications of 1000 to 2000x. Fatigue tests were carried out on a rotating beam test machine with a frequency of 60 Hz at a stress ratio of -1. Shot peening and roller burnishing were conducted on the specimens after machining. The Almen intensity in shot peening was 0.150 mmA, and the pressure during roller burnishing is 50 bar. The fatigue limit is defined as the highest stress level at which the number of life cycles is higher than 10⁷. To monitor crack nucleation and early propagation, some shot peened specimens were mechanically polished to facilitate microscopic observation.

4 Results and Discussion

Microstructural features

Cold work (swaging) refines the microstructures of PRMMCs in two ways: first by breaking and re-distributing the particles, which separates the particle clusters and reduces the size of particles, and second by refining the matrix grains. Figures 1 and 2 show these features. However, cold work induces microstructure damage, which is detrimental to mechanical properties, especially to fatigue resistance and ductility. The post heat treatment can heal most of the damage [10] and release almost all micro residual stresses among the constituents. In Figure 2 the refined recrystallized matrix grain structure can be seen. The average grain size decreases...
from 16.5 μm of as received to 8.6 μm of cold work plus T6 temper (CWT). Shot peening fractures the particles in surface area very markedly (see Figure 10b, upper side).

** Mechanical properties **

The mechanical properties of the various conditions are shown in Table 1. TCW has highest strength properties, but lowest ductility and lowest apparent elastic modulus. The advantage of cold work can be seen through comparing the data of T6 with TCW and CWT.

** Table 1. Mechanical properties **

<table>
<thead>
<tr>
<th>Condition</th>
<th>( \sigma_{0.2} ), MPa</th>
<th>UTS, MPa</th>
<th>El, %</th>
<th>RA, %</th>
<th>E, GPa</th>
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<tbody>
<tr>
<td>As-received</td>
<td>113</td>
<td>194</td>
<td>10.4</td>
<td>21.6</td>
<td>118</td>
</tr>
<tr>
<td>CW</td>
<td>300</td>
<td>308</td>
<td>1.8</td>
<td>3.5</td>
<td>89</td>
</tr>
<tr>
<td>T</td>
<td>340</td>
<td>366</td>
<td>2.5</td>
<td>9.6</td>
<td>96</td>
</tr>
<tr>
<td>TCW</td>
<td>390</td>
<td>397</td>
<td>0.4</td>
<td>1.2</td>
<td>86</td>
</tr>
<tr>
<td>CWT</td>
<td>340</td>
<td>390</td>
<td>3.6</td>
<td>7.0</td>
<td>114</td>
</tr>
</tbody>
</table>

** Fatigue curves for the various conditions and surface treatments **

The S-N curves for the various thermal and thermo-mechanical treatments are illustrated in Figures 3 to 5 comparing shot peened (SP) with electropolished (EP) conditions. For the T6 temper (Fig. 3), the fatigue life for all stress amplitudes tested is improved by more than one order of magnitude due to shot peening.

Tempering a cold worked condition is seen to markedly improve fatigue performance (Fig. 4, compare conditions CW and CWT). This result can be explained by yield stress and ductility values of CWT being higher than those of CW (Table 1). Again, shot peening strongly improves fatigue performance of the CWT condition (Fig. 4), particularly at intermediate stress amplitudes. For the condition TCW (Fig. 5), this improvement of the fatigue performance by shot peening is somewhat less pronounced.
Roller burnishing of the T6 temper results in fatigue life improvements, which are not as marked as after shot peening (Fig. 6). The effect of swaging at 450°C (HW) as opposed to cold swaging (CW) on the S-N curves is illustrated on tempered and shot peened conditions in Fig. 7. The fatigue performance after shot peening of the condition HWT is slightly superior to the condition CWT. Overall however, the best fatigue performance after shot peening is shown by the T6 temper (Fig. 3).

**Figure 3.** Fatigue curves of T6 condition

**Figure 4.** Fatigue curves of CW and CWT condition

Hot swaging (Hot working, HW) as opposed to cold swaging (CW) clearly improves the fatigue performance in the electropolished reference condition, especially in LCF regime (Fig. 7). After shot peening, the condition HW appears to be only slightly superior to CW (Fig. 7).

**Figure 5.** Fatigue curves of T6 + CW condition

**Figure 6.** Comparison of different surface treatments

**Figure 7.** Comparison of CW and HW by EP and SP
Hardness distribution

Shot peening PRMMCs heavily changes both the material and the mechanical state in the surface zone. Figures 8 and 9 illustrate the hardness distribution after shot peening. The macro hardness distributes in a normal way that the hardness peaks appear at the surface (AR and T4) or subsurface (T6, CWT and TCW) area in a depth of 0.4–0.7 mm. This indicates that the work hardening effect in the latter decreases at the surface by the cyclic hammering of the shots, i.e., the very surface layer of the specimen experiences a hardening (heat treatment)-work hardening (shot peening)-softening (shot peening) process. In originally unhardened materials, the macro hardness after shot peening increases from the bulk to the surface. In contrast, the micro hardness distributes in a decreasing pattern from the surface to the center, and the gradient is much steeper and it seems that the hardened depth is only half of that of the apparent macro hardness. This fact illustrates that the matrix response to shot peening is different from the bulk material, which consists of both particles (fully elastic) and the matrix (elastic-plastic), so that the hardness peaks in subsurface of hardened materials result from cyclic softening of the surface.

Crack nucleation site observation

From the fatigue results presented above, one can conclude that after shot peening, fatigue performance is generally improved for all conditions. The hardness measurements on both bulk materials (HV₁, indentations cover 10 or more particles) and matrix (HV₀,₀₅₅, diagonals of indentations are less than a half of the distance to nearest particles’ surfaces) reveal different hardening distributions in different scales. That is to say, not only the metallic matrix is hardened to affect the fatigue behavior, but also the particles are re-distributed and broken and residual stresses build up between them. Figure 10a and b show the crack nucleation cases (fatigued and failed specimens). The crack nucleates at the surface for EP treatment (Figure 10a and usually stops at the particles, whereas the crack nucleates in some depth below the surface, which is a generally accepted fact for shot peened specimen (as arrow points, Figure 10b).
Figure 10. Crack nucleation morphology of a) T6, EP and b) T6 + CW, SP. Both upper sides are free surfaces. In b) there are still two small cracks linked.

5 Conclusions

1. Cold work increases the strength of PRMMCs quite a lot for both as received and T6 tempered conditions, due to particle refinement and matrix strengthening. The reduction in ductility and fatigue life by cold work is mainly induced by microstructural damage.

2. Both shot peening and roller burnishing improve the fatigue performance from LCF stress level to fatigue limit level for all conditions involved, due to microstructural refinement and possible residual stresses.

3. More improvement of fatigue performance of cold worked materials is achieved by shot peening, compared with un-worked material.

4. Crack nucleation site was moved from the surface to subsurface regions about 120-200 μm by shot peening treatment.

5. Multiple crack nucleation is still an important characteristic of the crack nucleation mechanism for PRMMCs.

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7 References