Fatigue lifetime improvement of aluminium alloys by mechanical surface treatment

Patiphan Juijerm\textsuperscript{1,2}, Igor Altenberger\textsuperscript{2*}, Ulf Noster\textsuperscript{3} and Berthold Scholtes\textsuperscript{2**}

\textsuperscript{1}Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900
E-Mail: fengppj@ku.ac.th

\textsuperscript{2}Institute of Materials Engineering, University of Kassel, Mönchebergstr. 3, 34125 Kassel, Germany
E-Mail: juijerm@uni-kassel.de, i.altenb@uni-kassel.de* and scholtes@uni-kassel.de**

\textsuperscript{3}ARC Leichtmetallkompetenzzentrum Ranshofen GmbH, 5282 Ranshofen Postfach 26, Österreich
E-Mail: ulf.noster@arcs.ac.at

Abstract

The wrought aluminium alloys AA5083 (non-precipitation-hardenable) and AA6110-T6 (precipitation-hardenable) were mechanically surface treated (deep rolled) at room temperature. Deep rolled specimens were cyclically deformed at room temperature using push-pull stress-controlled fatigue and compared to the polished condition as a reference. It was found that deep rolling can dramatically enhance the fatigue behavior of aluminium alloys as compared to the polished condition due to near-surface compressive residual stresses as well as work hardening states and increased hardness induced by mechanical surface treatment (deep rolling).

1. Introduction

It is well-established that fatigue lifetime of components is very strongly influenced by the surface finish and surface treatment. Practically all fatigue failures start at the surface. For these reasons, if the surface of materials can be modified against crack initiation, fatigue lifetime improvement can also be expected. Therefore, surface treatments for fatigue lifetime improvement are the advanced topics which are eventually discussed. Mechanical surface treatments such as shot peening, laser shock peening or deep rolling are very effective and well-known surface treatment methods. They can enhance fatigue lifetime for metallic materials i.e. steels [1], titanium alloys [2,3], magnesium alloys [3,4] and aluminium alloys [3,5,6]. However, for Thailand’s industries particularly automotive industries, mechanical surface treatments are not well established. The main purpose of this paper is to address these issues, introduce as well as suggest an effective mechanical surface treatment and illustrate the effects of mechanical surface treatment on the fatigue behavior of metallic materials using deep rolling treatment on aluminium alloys as an example.

2. Experimental procedures

Cylindrical specimens of the wrought aluminium alloys AA5083 and AA6110-T6 with a diameter of 7 mm and a gauge length of 15 mm were prepared. The loading direction during fatigue investigations corresponds to the rolling/extrusion direction. The non-mechanically surface treated specimens were electrolytically polished in the gauge length leading to material removal of 100 µm to avoid any influence of machining. For deep rolling, a hydraulic rolling device with 6.6 mm spherical rolling element (see Fig. 1) and a pressure of 100 bar was applied at room temperature.

Tension-compression fatigue tests were conducted with a servohydraulical testing device under stress control without mean stress ($R = -1$) and with a test frequency of 5 Hz. Residual stresses and work hardening states (FWHM-values) were measured using X-ray diffraction with the classical $\sin^2\Psi$-method with Cu K\textalpha radiation at the \{333\}-...
planes and $\frac{1}{2} s_2 = (1+v)/E = 19.77 \times 10^{-5} \text{mm}^2/\text{N}$ as an elastic constant.

Hardness-depth-profiles were achieved using micro-hardness testing machine with an applied load of 50 grams.

**Fig. 1.** A hydraulic deep rolling device and a schematic spherical rolling element [7].

### 3. Results and discussion

#### 3.1 General concepts of mechanical surface treatment

As mentioned above, fatigue lifetimes can be improved, if the surface of materials can be modified against crack initiation as well as retard crack propagation. Mechanical surface treatments principally induce compressive residual stresses as well as work hardening states at the surface and in near-surface regions, which serve to inhibit or retard surface crack initiation as well as fatigue crack growth [8,9]. Therefore, fatigue lifetimes of metallic materials can be considerably enhanced through mechanical surface treatments. Currently, various mechanical surface treatments, e.g. shot peening, laser shock peening as well as deep rolling, are provided and intensively investigated to achieve the optimized surface conditions.

#### 3.2 Fatigue behavior of polished AA5083 and AA6110

Before studying the effects of deep rolling, the cyclic deformation behavior of polished condition of AA5083 and AA6110 was investigated and clarified. Non-statistically evaluated s/n curves at room temperature of AA5083 and AA6110 are shown in Fig. 2. During fatigue tests, plastic strain amplitudes of the polished condition were also measured. Due to increased dislocation densities and dislocation-dislocation interaction, aluminium alloy AA5083 exhibits cyclic hardening (see Fig. 3) whereas aluminium alloy AA6110-T6 shows cyclic softening during fatigue at room temperature (see Fig. 4). The major precipitates in the AA6110-T6 alloy are metastable phases, $\beta'$ as well as $\gamma'$ which are ordered and coherent with the aluminium matrix [10]. During cyclic deformation, the to-and-fro motion of dislocations through the ordered precipitates causes a mechanical local disordering or scrambling of the atoms in the precipitates.

**Fig. 2.** Non-statistically evaluated s/n curves of polished AA5083 and AA6110-T6 at room temperature.

**Fig. 3.** Cyclic deformation curves of polished AA5083 for different stress amplitudes at room temperature. ($\sigma_{oo} = 1 \text{ in } 1000$)
The structure of the precipitates becomes disordered and degraded [11]. The hardening due to the ordering contribution is lost, therefore cyclic softening was the result of polished AA6110-T6. Afterwards, cyclic hardening was detected due to increasing dislocation densities and dislocation-dislocation interactions during cyclic loading. [12]

**Fig. 4.** Cyclic deformation curves of polished AA6110-T6 for different stress amplitudes at room temperature.

3.3 Near-surface properties of the deep rolled condition.
After deep rolling, from X-ray diffraction measurements, compressive residual stresses as well as work hardening states (increased FWHM-values of X-ray diffraction peaks) were observed, for example, in Fig 5 which presents near-surface compressive residual stresses and FWHM-values of deep rolled AA6110-T6. FWHM-values of X-ray diffraction peaks represent inhomogeneous microstresses e.g. work hardening, dislocation densities. Moreover, deep rolling led not only to compressive residual stresses and increased FWHM-values but also increased the hardness at the surface and in near-surface regions (see Fig. 6).

**Fig. 5.** Residual stress- and FWHM-depth-profile of deep rolled AA6110-T6.

3.4 Fatigue behavior of deep rolled condition.
From all effects of mechanical surface treatment (deep rolling) as above mentioned, fatigue lifetime improvement should be expected. Lower plastic strain amplitudes of the deep rolled condition are detected as compared to the polished condition (see Fig. 7). Therefore, deep rolling enhances certainly the fatigue lifetime of AA5083 and AA6110-T6 [6] according to Coffin-Manson law [13,14].

**Fig. 6.** Hardness-depth-profile of deep rolled AA6110-T6.
Non-statistically evaluated s/n curves of deep rolled specimens are presented in Fig. 8. From this diagram in Fig. 8, unquestionably, the beneficial effects of a deep rolling treatment on fatigue lifetime enhancement are seen particularly for in the high cycle fatigue (HCF) regime.

Fig. 7. Cyclic deformation curves of polished and deep rolled AA5083 at a stress amplitude of 205 MPa.

Fig. 8. Non-statistically evaluated s/n curves of polished and deep rolled AA5083 and AA6110 which serve to inhibit or retard surface crack initiation as well as fatigue crack growth [8,9]. Consequently, the fatigue lifetime can be improved considerably through mechanical surface treatments.

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