Optimized layer architecture for an extended fatigue life of ultrafine-grained AA1050/AA5005 laminated metal composites

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Abstract. The influence of interfaces on the fatigue life in AA1050/AA5005 ultrafine-grained laminated metal composites was investigated. At constant sheet thickness, the layer thickness and the number of material interfaces was varied by performing different cycles of accumulative roll bonding. It is found that crack deviation occurs if the crack approaches the soft to hard (AA1050/AA5005) material interface resulting in strongly enhanced fatigue lives compared to the mono-material. The most favourable layer architecture for enhanced fatigue life strongly depends on the applied stress amplitudes. At intermediate stress amplitudes a large layer thickness of 500 µm (N4) and 8 material interfaces gives the longest fatigue life. In contrast, at low stress amplitudes the sheets with 32 material interfaces and a layer thickness of 125 µm (N6) shows the longest fatigue life.

1. Introduction

Ultrafine-grained (UFG) materials are widely known for their high specific monotonic strength compared to their coarse grained (CG) starting material, see i.e. refs. [1–3]. But also the cyclic mechanical properties can be strongly enhanced [4–6]. The accumulative roll bonding (ARB) process enables the production of UFG reinforced [7] and/or layered [8–10] metallic structures with tailored or graded properties. As the cyclic properties are regarded only limited data is available in the literature for such UFG laminated metal composites up to now. Previous publications by the authors [11,12] revealed that the fatigue life of AA1050/AA5005 UFG laminated metal composites can be significantly enhanced compared to their CG and their UFG mono-material counterparts. This is caused by an arresting of the plastic zone in front of the crack tip at the material interface and thus a crack branching if the crack approaches the soft to hard material interface. Consequently, the composites show significantly longer fatigue lives compared to their mono-material sheets [11]. Fatigue tests on AA1050/AA5005 and AA1050A/AA2024, in which the interlayer material was varied, revealed that an increasing hardness gradient at the material interface enhances this crack deviation mechanism if the crack approaches the interface [12]. This is associated with a strongly enhanced fatigue life at medium stress amplitudes. This cracking behavior is quite similar to the results reported by Sugimura et al. [13] and Pippan et al. [14], who investigated the cracking behavior at coarse grained bimetallic interfaces. Both authors found that, if the fatigue crack approaches the layer interface from a plastically softer to a stronger material, the crack propagation rate diminishes in the vicinity of the interface [13,14]. In the
current work the influence of the number of material interfaces and layer thickness on the fatigue properties of UFG laminated metal composites is investigated by producing AA1050/AA5005 composites with different numbers of ARB cycles.

2. Experimental Procedure

2.1. Processing of the UFG laminated metal composites
The laminated metal composites in this work, made of the technical pure aluminum AA1050 (Al99.5) and the solution hardening alloy AA5005 (AlMg1), were produced by the accumulative roll bonding process using a four high rolling mill (BW 300, Carl Wezel, Germany) at a nominal thickness reduction of 50 % per cycle. The sheets had an initial geometry of length × width × height of 300 × 200 × 4 mm³. Prior to roll bonding the surfaces were cleaned by acetone and then wire brushed in order to remove the oxide layer and to ensure a sufficient bonding. Subsequently, the treated surfaces were stacked on each other and roll bonded at room temperature. The bonded aluminum sheets were air cooled and halved before performing the next cycle. In the first ARB cycle (N1), an AA1050A sheet was roll-bonded with an AA5005 sheet. In the second cycle (N2), the two AA5005 surfaces were stacked together and roll-bonded to receive a sandwich like structure with AA1050A outer layers. Consequently, in the following ARB cycles (N > 3), always two AA1050A surfaces were roll-bonded. In order to prevent necking and rupture of the harder AA5005 layer recrystallization by annealing for 10 min at 500 °C was used in addition after different ARB cycle numbers. Details on the processing can be found in previous papers published by the authors [11,15]. Hence, all final composites exhibit an UFG condition, which is very similar to an UFG sheet processed by only 4 ARB cycles. The number of layer interfaces with dissimilar materials and the theoretical layer thickness of the processed composites are given in Table 1 a). For reference, AA1050A with 4 ARB cycles and AA5005 mono-material sheets with 0 and 4 ARB cycles were also investigated.

2.2. Microstructural and mechanical characterization
The layer architecture of the composites were characterized by scanning electron microscopy (Crossbeam 1540 EsB, Zeiss, Germany) using secondary electron imaging. All sheets were analyzed in side view (rolling direction × normal direction). Therefore, the specimens were mechanically ground down to a grit size of 6 µm and then mechanically polished up to 1 µm. In the final step, the specimens were chemo-mechanically polished using an OPS suspension.

The local mechanical properties of the layers were measured by nanoindentation experiments (Nanoindenter XP, MTS Nano Instruments, USA) using a three-sided Berkovich pyramid with the continuous stiffness method. In each sample the hardness profile across the material interface was measured in an angle of 30° to the rolling direction. The indentation depth was 500 nm and the distance between the indents was always the twentyfold of the indentation depth.

The fatigue tests were carried out on a vibrophore testing machine (HFP 5100, Roell Amsler, Germany) in 3-point bending mode. The specimen had a geometry of 20 × 9.5 × 4 mm³ in length, width and height and were ground mechanically down to a grid size of 6 µm before testing. All tests were conducted under force control with an R-value of 0.1 leading to a permanent tension stress at the lower part of the sample. The maximum bending stress amplitudes, which are in the middle at the bottom of the sample, ranged in between 100 MPa and 200 MPa. Furthermore, a frequency observation enabled the detection of macro-crack nucleation and propagation. After fatigue testing the crack path was analyzed by scanning electron microscopy under secondary electron contrast conditions.

3. Results and Discussion

3.1. Characterization of the initial state after ARB processing
All composites consist of continuous layer architecture up to 12 ARB cycles. Due to the intermediate recrystallization steps at higher numbers of ARB cycles pronounced necking of the harder AA5005 layer
could be suppressed effectively. The layer thicknesses of the two different materials are very similar, see Table 1 b). The AA5005 layer thickness is only slightly higher than that of the AA1050 layer. This is due to the higher hardness of these layers leading to a slightly preferred deformation of the softer AA1050 layers, especially during the first ARB cycles. Furthermore, the experimental determined thickness is in good accordance to the theoretical values, c.f. Table 1 a) and b).

In Table 1 c) the hardness of the materials in the AA1050/AA5005 composites after different numbers of ARB cycles are listed. It is clearly visible that the hardness of the AA5005 layer is higher compared to the AA1050 layer. In the AA5005 layers, the hardness is quite constant at 1.2 GPa after all ARB cycles. In the AA1050 layers, the hardness stays almost constant in between ARB cycle 4 and 8 at about 0.9 GPa. After 12 ARB cycles the hardness of the AA1050 layer slightly rises to about 1.0 GPa. This probably is a result of the strong increase in the number of material interfaces. Previous investigations on ARB processed laminated metal composites revealed that the grain refinement near the material interface is strongly enhanced compared to the evolution in the middle of the layers leading to a higher hardness in these areas [16]. This leads to an improvement of the macroscopic mechanical properties at higher ARB cycles, where the fraction of the material that is affected by the interfaces is significantly larger, see refs. [15,17]. The hardness of the AA1050 and AA5005 ARB processed N4 mono-material sheets are very similar to the one in the composites, see Table 1 c). This was also observed in many other investigations, especially at lower numbers of ARB cycles, see for example refs. [15,18].

Table 1: Calculated and experimentally determined parameters of the AA1050/AA5005 LMCs and the AA1050 and AA5005 mono-material sheets after different numbers of ARB cycles.

|          | N4  | N6  | N8  | N12 | Mono-material |
|----------|-----|-----|-----|-----|--------------|
| a)       |     |     |     |     |              |
| Material interfaces | 8   | 32  | 128 | 2048 | 0            |
| Layer thickness / µm | 500 | 125 | 32  | 2    | 4000         |
| b)       |     |     |     |     |              |
| AA1050   | 510 ± 18.5 | 127 ± 17.6 | 33.6 ± 1.6 | 2.0 ± 0.7 | -            |
| AA5005   | 539 ± 34.9 | 137 ± 10.9 | 34.8 ± 4.7 | 2.2 ± 0.7 | -            |
| c)       |     |     |     |     |              |
| AA5005   | 1.19 ± 0.09 | 1.22 ± 0.05 | 1.21 ± 0.07 | 1.24 ± 0.06 | 1.14 ± 0.07 |
| AA1050   | 0.91 ± 0.02 | 0.91 ± 0.03 | 0.93 ± 0.04 | 1.04 ± 0.05 | 0.86 ± 0.05 |

3.2. Fatigue life and damage mechanism of the ARB processed samples

The fatigue life curves of the AA1050/AA5005 composites after different numbers of ARB cycles and, for reference, of the AA1050 after 4 ARB cycles and AA5005 mono-material sheets after 0 (as received) and 4 ARB cycles are shown in Figure 1 a). In this Wöhler S-N curve the maximum stress amplitude Δσ/2, which is calculated by the linear-elastic bending theory, is plotted versus the number of fatigue cycles to failure Nf. It should be noted that the UFG microstructure and the hardness of all composites are very similar among each other and also comparable to the N4 mono-material reference sheet, as all samples were subjected to 4 ARB cycles after a final recrystallization step. Therefore, differences in the fatigue lives have to be related to the different number of material interfaces and/or layer thicknesses. The fatigue life curves of all samples can be divided by characteristic threshold stresses σthreshold into two regimes with clearly different slopes. Furthermore, the fraction of macro-crack initiation on the total fatigue life, which was determined by a drop in the testing frequency, strongly differentiates in between these areas. At higher stresses, macro-crack initiation spans about 90 % of Nf in all composites and 95 % of Nf in the mono-material sheets. At stresses lower than the threshold stresses macro-crack initiation
periods above 98% of $N_f$ are found for all samples. The fatigue life of all UFG samples is clearly enhanced compared to the CG AA5005 N0 mono-material sheet. The threshold stress of the UFG AA5005 N4 mono-material sheet lies about 50 MPa above its CG counterpart. This is related to the much higher strength of the UFG samples and was already observed by many other authors on uniaxial fatigue tests, see i.e. refs. [4–6]. A comparison of the fatigue lives of the composites and the AA1050 N4 mono-material sheets is only possible at lower stresses ($\Delta\sigma/2 < 160$ MPa). As all tests were performed at a $R$-value of 0.1 a mean stress of about 200 MPa is achieved, which exceeds the ultimate tensile strength of UFG AA1050, see i.e. refs. [15,19,20], leading to early crack initiation and failure of the AA1050 N4 mono-material sheets. The fatigue lives are increased by a factor of 5 for the N4 composite and of 4-18 for the N6 composite in comparison to that of the UFG AA1050 N4 mono-material sheet. In contrast, the fatigue lives of the N8 and N12 composites are very similar to the AA1050 N4 mono-material sheets for the whole testing regime. At higher stress amplitudes the N4 composite shows a fatigue life even in the range of the AA5005 N4 mono-material sheet. The most favorably LMC architecture strongly depends on the applied stress amplitudes. At higher maximum stress amplitudes ($\Delta\sigma/2 > 125$ MPa), where macro-crack propagation extends a larger period of the fatigue life, an increasing number of ARB passes leads to a decreasing fatigue life. Concurrently, at lower maximum stress amplitudes, where the fatigue life is almost entirely determined by the macro-crack initiation period, the longest fatigue life is achieved for the N6 composite followed by the N4 composite and, at last, the N8 and N12 composites. This is related to the highest threshold stress in the N8 composite, which means that the onset of the formation of macro-crack is shifted to higher stress amplitudes. The same trend is also found for the endurable fatigue strength for $5\times10^6$ cycles of the different samples, see Figure 1 b). Again, it is shown in this diagram that the fatigue properties at lower stress amplitudes are clearly enhanced in the N6 composite compared to the other composites and the AA1050 mono-material sheet.

![Figure 1: a) Fatigue life curves of the AA1050/AA5005 composites after 4, 6, 8 and 12 ARB cycles. For comparison, the fatigue life for AA1050 and AA5005 mono-material sheets after 0 and 4 ARB cycles are also plotted. b) Endurable fatigue strength for $5\times10^6$ cycles of the different samples.](image-url)

The difference in fatigue life and in the threshold stresses of the composites at higher and lower stress amplitudes can be directly correlated to the different cracking behavior of the samples. In Figure 2 the fatigue crack paths of the N4, N6 and N8 composites are depicted that are typical for samples fatigued at an intermediate stress amplitude ($\Delta\sigma/2 = 200$ MPa) or at a low stress amplitude ($\Delta\sigma/2 = 120$ MPa). For N8 composites, where the layer thickness is rather small, a straight crack path forms for the whole testing regime. Therefore, the reinforcement by the AA5005 layers has no influence on the cracking
behavior in this composite. This applies also for the N12 composite, where the layer thickness is even smaller than in the N8 composites. The fatigue lives of these composites are very similar to the AA1050 mono-material sheets. Thus, it becomes obvious, that a rather thin layer thickness is detrimental for the fatigue life of the composites at intermediate stress amplitudes. Contrary to that, the N4 composite shows crack branching when the crack approaches the soft to hard material interface for all stress amplitudes. This leads to a drastically increased fatigue life compared to the N8 and N12 composites. The cracking behavior of the N6 sample shows a strong dependency on the applied stress in the testing range. At higher stress amplitudes the fatigue crack grows very straight across the layer thickness, whereas at lower stress amplitudes a pronounced crack branching can be observed. This is associated with a lower fatigue life at intermediate stress amplitudes and an increased fatigue life at lower stress amplitudes compared to the N4 composite.

This different behavior can be explained by a shielding of the damage zone in front of the crack tip when the crack approaches the soft to hard layer interface. At high stress amplitudes the size of the damage zone in front of the crack tip is relatively large. Consequently, a high AA5005 layer thickness is necessary to shield the plastic zone in front of the material interface and to hinder crack bridging in between the softer AA1050 layers. Thus, crack propagation is effectively delayed. For this reason, only the N4 composite with a layer thickness of about 500 µm shows clear crack deviation in front of the material interfaces leading to the highest fatigue life at these amplitudes. Concurrently, the crack propagates very straight across the material interfaces in the N6, N8 and N12 composites, as the layer thickness is too thin. Furthermore, crack initiation and propagation at discontinuities at the bonding interfaces is observed at higher stress amplitudes. Both factors lead to a decrease in fatigue life with an increasing number of ARB cycles, see Figure 1. At lower stress amplitudes the plastic zone in front of the crack tip is significantly smaller. At these amplitudes, the fatigue crack deviates from the straight crack path in front of the material interface in both the N4 and N6 composites. However, due to the much higher number of material interfaces in the N6 composite crack deviation is more pronounced leading to the delayed macro-crack propagation in this composite. In the N8 and N12 composites the crack again spreads very straight across the whole sheet thickness. As a consequence, the N6 composite shows the highest fatigue life at lower stress amplitudes, as crack deviation at the material interfaces is most pronounced.

![Figure 2](image_url)

**Figure 2:** Crack paths of the N4, N6 and N8 AA1050/AA5005 composites fatigued at a stress amplitude of 200 MPa (top row) and 120 MPa (bottom row). Please note that all pictures were taken at the side view of the sample. At the left margin, the different layers are indicated by red (AA5005) and blue (AA1050) bars. The maximum tensile bending stresses are located at the top in the middle of each micrograph.
4. Conclusion
In this study the influence of the layer architecture (number of material interfaces and layer thickness) on crack propagation and the fatigue life of ultrafine-grained AA1050/AA5005 laminated metal composites (LMCs) was investigated. A clear correlation between the crack propagation mechanisms and the fatigue life was observed: strongly enhanced fatigue lives are achieved in the LMCs that showed pronounced crack deviation at the material interface. The most favorably LMC architecture strongly depends on the applied stress amplitudes. At higher stress amplitudes, a high layer thickness is necessary to effectively block the plastic zone at the AA1050- AA5005 material interface leading to a deviation of the crack path. Therefore, the LMC after 4 ARB cycles shows the longest fatigue life. Concurrently to that, at lower stress amplitudes the layer thickness of the N6 composite is already sufficient to effectively hinder straight crack propagation. However, due to the much higher number of material interfaces in the N6 composite, crack path deviation is much more pronounced leading to a strongly enhanced fatigue life. By optimizing, the number of material interfaces and layer thickness in the composite the fatigue life is significantly enhanced in comparison to the UFG AA1050 mono-material sheets. At higher stress amplitudes, the fatigue lives of the composites almost reach the ones of the UFG AA5005 sheets although the volume fraction of this harder material is only 50 % in the composites. Compared to the GC AA5005 mono-material sheets, strongly enhanced fatigue lives were achieved in all UFG samples.

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