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Microstructure evolution of friction boundary layer during extrusion of AA 6060

Vidal Sanabria[a,*], Soeren Mueller[a], Walter Reimers[b]

[a] *Extrusion Research and Development Center, Technical University of Berlin, Gustav-Meyer-Alle 25, 13355 Berlin, Germany*
[b] *Department of Materials Science and Technology, Technical University of Berlin, Ernst-Reuter-Platz 1, D-10587 Berlin, Germany*

Abstract

The tribological behavior between the aluminium alloy AA 6060 and the hot working steel 1.2344 has been recently studied using a new *axial friction test* for extrusion processes. With this new test, the friction forces as well as the specimens' plastic deformations generated during sliding tests can be investigated. Selected specimens tested at high temperature (300-500 °C), normalized normal stress (σ_n/kf_o=1.5) and high relative speed (0.1, 50 mm/s) have been sectioned and the microstructure on their mid-planes has been investigated. Light optical microscope analysis of the friction boundary layer revealed highly stretched grains and a thickness variation of the shear layer from 750 to 1600 μm depending on testing conditions. Moreover, EBSD analysis showed a grain refinement in the high shear zone especially at 300 °C with a grain size about 4 μm. Dynamic recrystallization was observed at 400 °C and an abnormal grain growth at 500 °C. Hardness measurements revealed a light hardening effect of 8 % at 300 °C as well as a softening effect of 6 % at 400 °C and 500 °C.

Keywords: Friction boundary layer; Microstructure evolution; Aluminium alloy AA6060; Axial friction test; Extrusion

1. Introduction

The accurate calculation of the friction force plays an important role in extrusion processes. In the direct extrusion, the friction represents a great portion of the total extrusion force and therefore it becomes relevant for the total extrusion power estimation. Moreover, most of the friction force is generated due to the relative movement and the strong junction between the billet and the container (Mueller, 2004). On the other hand, the friction also takes place in the die, where multiple variables interact to control the material flow especially in portholes (Valberg, 2014) and multi-hole dies (Mueller et al., 2012).

* Corresponding author. Tel.: +49-30-31472516 ; fax: +49-30-31472503
E-mail address: vidal.sanabria@fzs-berlin.de

The combination of variables such as temperature, sliding speed, normal force and surface conditions, defines the mechanical and chemical interactions generating the sticking and sliding friction mechanisms (Wuttke, 1987). When sticking friction occurs the contact surfaces remain together because of the strong junction force, whereas the sub layers of the softer material experience a severe shear deformation. This phenomenon produces a peripheral shear zone, which has been displayed in extrusion processes using grid pattern techniques. For instance, Kammler et al. (2012) revealed a thick peripheral shear zone around 10 mm in the border of the billet. Moreover Valberg (2009) found a thin shear zone in the inlet side of the bearing channel related with the sticking zone. According to the Tresca friction model, in presence of sticking behavior the friction stress should be equivalent to the shear strength, and therefore proportional to the flow stress. Moreover, the flow stress in hot working processes is not only affected by the temperature and the strain rate in accordance with the Zener-Hollomon model, but also by microstructural changes. Different mechanisms of recovery and recrystallization are present during hot deformation, especially in metals with high stacking fault energy such as aluminium and it alloys (Humphreys and Hatherly, 2004). Dynamic recrystallization was reported by Kayser et al. (2010), who observed a continually decrease of the main grain size along the center path of a cylindrical billet during extrusion of AA6060 aluminium alloy. Moreover, Donati et al. (2013) found strongly elongated grains on the profile surface due to the double effect of the high deformation firstly in the shear zone and posteriorly in the bearing channel caused by the high friction.

Recently, friction experiments with the aluminium alloy AA6060 have been carried out using a new axial friction test (Sanabria et al., 2014). The normalized normal stress (σ_n/kf_o=1.5) and temperature (300 °C – 500 °C) were enough to generate sticking conditions as was also found by Widerøe et al. (2012). The results revealed a thin aluminium layer on the die, as well as a thin peripheral shear zone in the specimens. The focus of the present work is the microstructural investigation of the AA6060 aluminium alloy during friction tests. Special emphasis is put on the grain size evolution and the hardness in the thin boundary layer under high temperature and severe shear deformation.

2. Experimental procedures

Small cylinders with initial diameter 7.8 mm and length 10.5 mm were extracted from homogenized cast billets of AA6060 aluminium alloy. In each experiment, the sample was heated up inside a steel liner in 20 minutes and set up by two counteracting stems with a constant strain rate of 0.0006 s^{-1} (Fig. 1a). The stems were fixed and the liner was pulled down 5 mm with a constant slide speed of 0.1 and 50 mm/s, whereas the friction force was measured (Fig. 1b). Around 90 seconds after each friction test the specimens were quenched in water. The experiments were carried out at 300 °C, 400 °C and 500 °C and the samples were axially compressed until 3900 N, 1600 N and 760 N respectively, to achieve a normalized normal (radial) pressure around σ_n/kf_o=1.5. Each specimen was longitudinally sectioned, and the mid-plane (Fig. 1c) polished and etched before analyzing using light optical microscopy. The mid-planes were posterior electrolytic polished and analyzed with electron backscatter diffraction (EBSD). Additionally, the Vickers microhardness was measured at 100 μm, 300 μm, 500 μm, 700 μm, 1200 μm and 4000 μm from the border to the center (normal force 1 N). A detailed description of the *axial friction test* was reported by Sanabria et al. (2014).
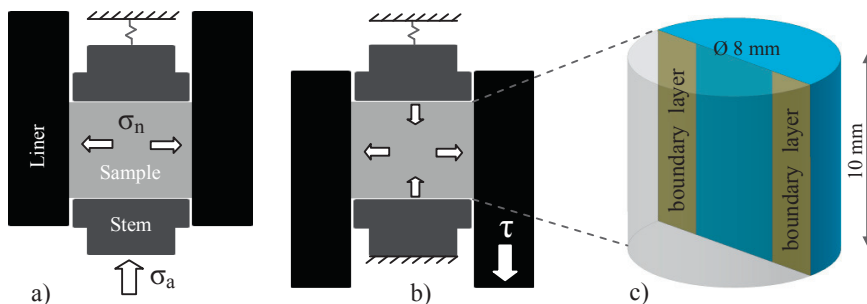

Fig. 1. Schematic procedure of the *axial friction test*. a) Set up, b) friction test, c) tested sample.

3. Results and discussion

After the friction experiments, the specimens were sectioned and the microstructure was revealed. Fig. 2a shows the typical friction boundary layer of the studied cylindrical specimens, which were subjected to an axial friction stress τ under sticking conditions. The friction boundary layer (~2.7 mm) is formed by a nondeformed area a and the shearing layer h. In the area a no shearing is visible, however, microstructural changes may be possible. On the other hand, in the shearing layer a low and high shear zones are generated due to the sticking friction. Moreover, the low shear zone is difficult to delimit because it is the transition section between the non-deformed and highly deformed grains. Nevertheless, the high shear zone is well defined and characterized by a grain refinement as a consequence of the severe shearing. The plastic deformations on the top and bottom of the specimen are generated by the tension and compression forces respectively, produced during the friction test. Therefore, the plastic deformation at the top and bottom areas was neglected for the shearing measurements.

Fig. 2a, 2b and 2c show the friction boundary layers of specimens tested with a high sliding speed of 50 mm/s at 300 °C, 400 °C and 500 °C. Measurements revealed that the shear zone h increases with the temperature, probably due to the strength reduction at higher temperatures. Thus, h was 1300 μm at 300 °C, but 1500 μm and 1600 μm at 400 °C and 500 °C respectively. Another experiments carried out at 0.1 mm/s revealed no significant variation of h at 400 °C and 500 °C, however a reduction of 40 % was found at 300 °C.
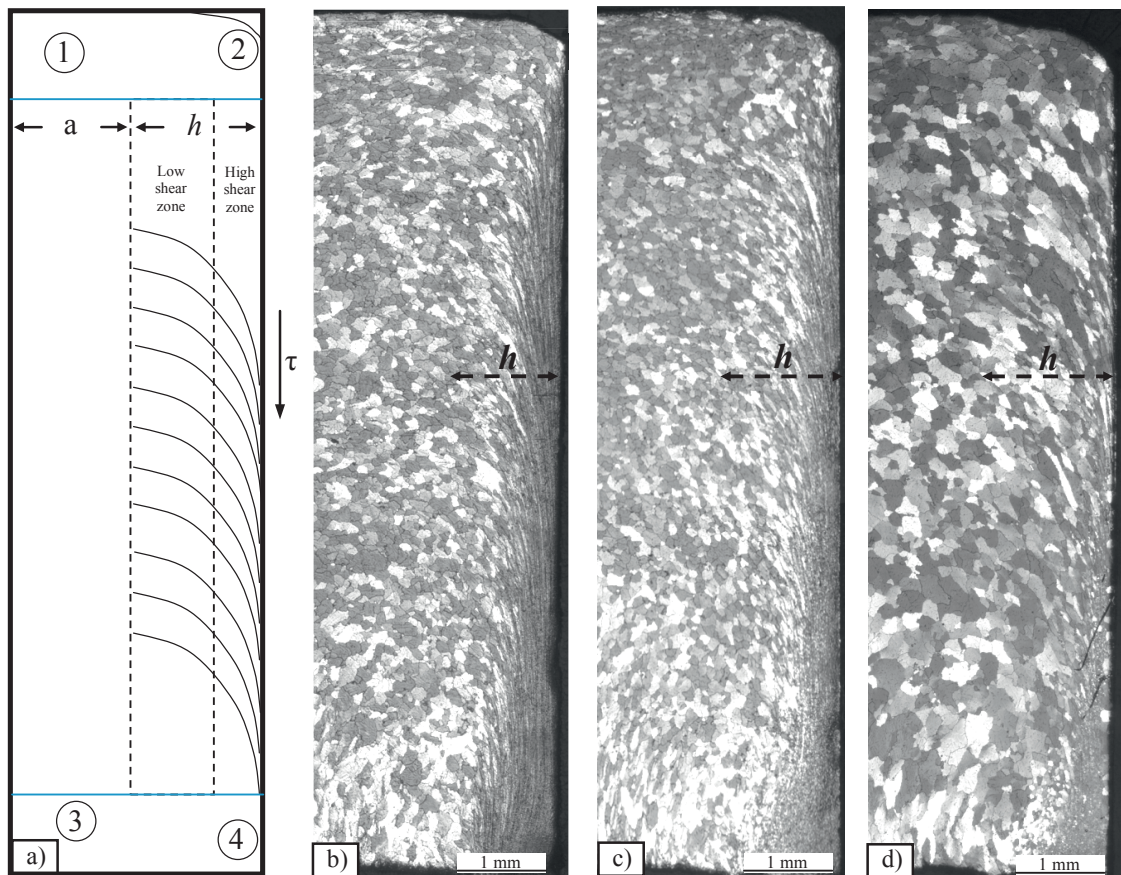

Fig. 2. Microstructure of the entire friction boundary layer after friction test at 50 mm/s and σ_n/kf_o=1.5 (LOM). a) Deformed zones in the friction boundary layer, b) at 300 °C, c) at 400 °C and d) at 500 °C.
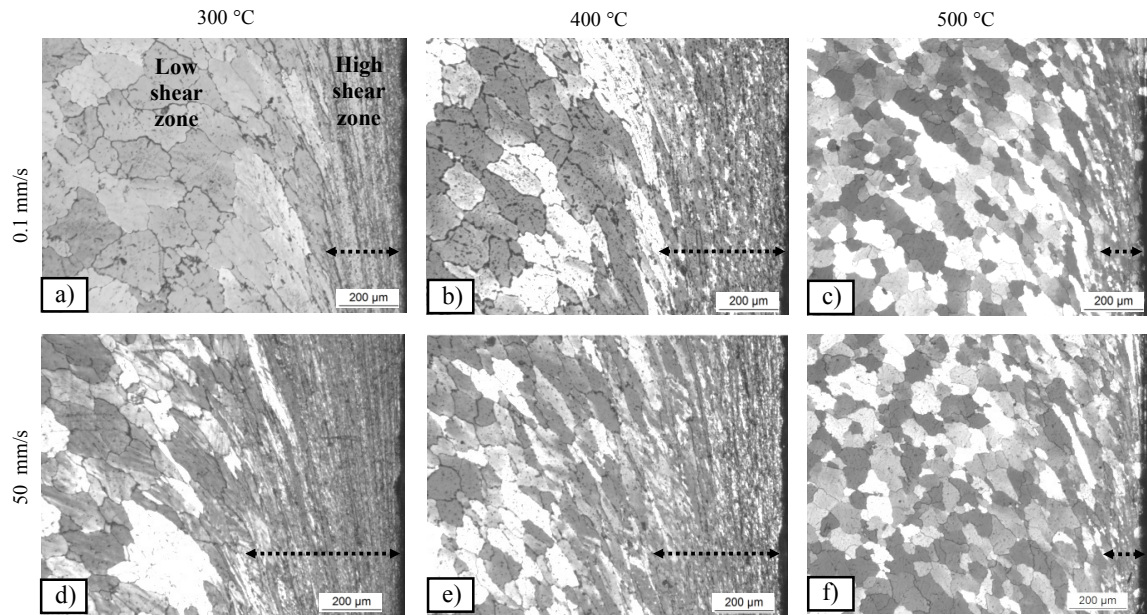
Fig. 3. Microstructure of the friction shear layer at the middle of the sample at σ_n/kf_o=1.5 (LOM). a) at 300 °C, 0.1 mm/s, b) at 400 °C, 0.1 mm/s, c) at 500 °C, 0.1 mm/s, d) at 300 °C, 50 mm/s, e) at 400 °C, 50 mm/s and f) at 500 °C, 50 mm/s.

As in the case of the shear layer *h* at 300 °C, the high shear zone also increases with the sliding speed. Fig. 3a and 3d show how the high shear zone increases from 250 μm to 550 μm when the sliding speed is varied from 0.1 mm/s to 50 mm/s respectively. Furthermore, the high shear zone remains almost constant with the sliding speed with values of 400 μm and 150 μm at 400 °C and 500 °C respectively. The results show that *h* and the high shear zone have a similar tendency of increasing with higher sliding speeds at 300 °C. On the other hand, *h* and the high shear zone are not sensible to the sliding speed at 400 °C and 500 °C. The grain size evolution in the high shear zone revealed bigger grains at higher temperatures and fine grains at higher sliding speed (Fig. 4). The smallest grains were found in the specimens tested at 300 °C and at a sliding speed of 50 mm/s (Fig. 4d). The high strain at 300 °C generates interaction and multiplication of the dislocations, increasing the grain boundary area and producing a grain refinement (Humphreys and Hatherly, 2004). Moreover, when the same experiment but at 0.1 mm/s is carried out, bigger grains (4 μm) were appeared, possible due to dynamic recovery (Fig. 4a). At 400 °C a grain fragmentation occurs possibly due to dynamic recrystallization, generating grain size of 5 μm at 50 mm/s (Fig. 4e). However at 0.1 mm/s 9 μm was measured as a result of sub grain growth during the friction test. Nevertheless, at 500 °C dynamic recrystallization with discontinuous and abnormal sub grain growth was observed in the specimens tested at 0.1 mm/s (Fig. 4c) and at 50 mm/s (Fig. 4f). Measurements carried out in a homogeneous area reveal grain size of 20 μm at 0.1 mm/s and 12 μm at 50 mm/s. Because the grain growth occurs very fast at high temperature (500 °C), it is possible that the abnormal grain growth (Fig. 4f) was caused by static recrystallization during the 90 s before quenching (Humphreys and Hatherly, 2004).
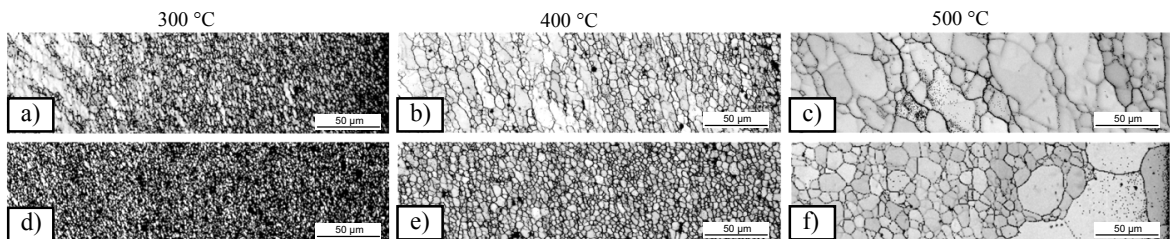

Fig. 4. Microstructure of the high shear zone at the middle of the sample at σ_n/kf_o=1.5 (EBSD-Band contrast). a) at 300 °C, 0.1 mm/s, b) at 400 °C, 0.1 mm/s, c) at 500 °C, 0.1 mm/s, d) at 300 °C, 50 mm/s, e) at 400 °C, 50 mm/s and f) at 500 °C, 50 mm/s.
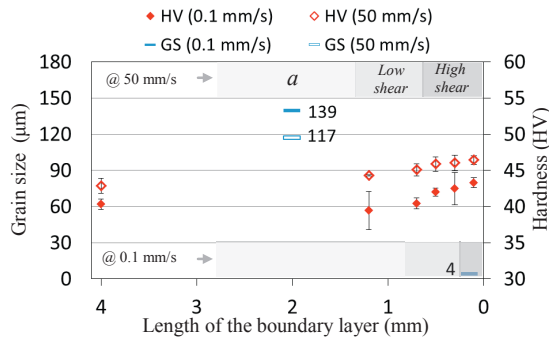
Fig. 5. Hardness and grain size of the friction boundary layer at 300 °C.
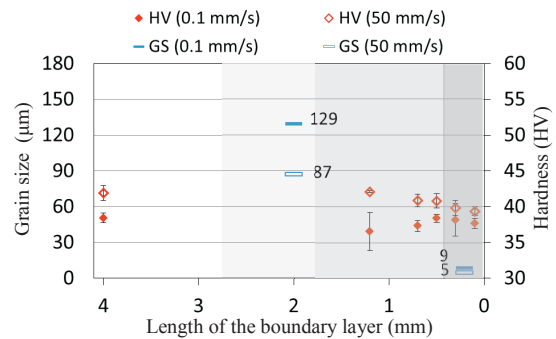

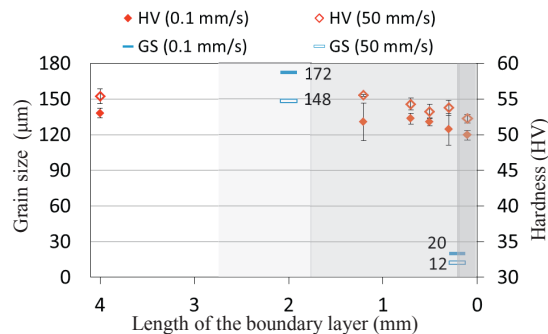Fig. 6. Hardness and grain size of the friction boundary layer at 400 °C.

Fig. 7. Hardness and grain size of the friction boundary layer at 500 °C.

The grain size in the zone *a* was also measured. Though, this zone was not directly subjected to shearing its grain size was also affected during the friction tests. The zone *a* is characterized by big grains with dendritic formed by the cast process. Hence, the grain size of the specimens tested at 0.1 mm/s are: 139, 129 and 172 μm, at 300, 400 and 500 °C respectively (Figs. 5, 6 and 7). Additionally, experiments carried out at a sliding speed of 50 mm/s showed a grain size reduction of almost 15 % at 300 and 500 °C, and even 30 % at 400 °C. The grain size reduction could be due to the increase of dislocation density as a result of higher induced stress at 50 mm/s. Additionally, this effect could also be caused by reducing the time for grain growth, considering that at 0.1 mm/s the test is carried out in 50 s.

In order to investigate the possible changes in the mechanical properties especially in the shear layer at different temperatures and sliding speeds, radial hardness mappings of the tested specimens were carried out. Fig. 5 depicts how at 300 °C the hardness increases progressively in the shear zone *h* until about 8 % comparing with the hardness in the specimen's center. Moreover, the hardness increases at higher sliding speed at the same temperature. These results at 300 °C agree with the Hall–Petch relation, observing higher hardness values only where the fine grains (shear zone) were found.

In the experiments carried out at 400 °C and 500 °C a drastic reduction of grain size was also observed from the zone *a* to the high shear zone about 94 % and 90 % respectively (Fig. 6,7). However, despite the grain refinement in the high shear zone, a hardness reduction about 6 % at 400 and 500 °C was found. Nevertheless, the hardness reduction in this case is due to the drop of the dislocation density as a result of the dynamic recrystallization at high temperatures and strain. On the other hand, the hardness values measured at 500 °C were about 25 % higher than at 400 °C possibly due to solid solution strengthening. When the temperature is higher than the solvus temperature (T_{solvus}=400 °C for AA6060) the precipitations and impurity atoms are dissolved into the solid solution. Therefore, the dislocation movement is restricted by the lattice strain field interactions between dislocations and the impurity atoms (Garrett, et al., 2004).

4. Conclusions

The investigation of the friction boundary layer of the AA6060 aluminium alloy under extrusion conditions was successfully carried out. Small cylindrical specimens were subjected to axial friction tests at different temperatures (300 – 500 °C) and sliding speed (0.1 – 50 mm/s). After testing the samples were quenched in water to avoid static recovery and static recrystallization. Microstructural analysis revealed a shear layer, which was divided into the low and high shear zones. At 300 °C, the shear zone increased from 750 to 1300 μm when the sliding speed was increased from 0.1 mm/s to 50 mm/s. The increase of the shear layer was accompanied by the reduction of the grain size of more than 95 % in the high shear zone. Small grains of about 4 μm and even smaller were found in the high shear zone at 300 °C. The high plastic deformation could cause the multiplication of the dislocations and the increase of the grain boundary area, generating the grain refinement. Furthermore, a hardness mapping revealed an increase of 8 % in the mechanical properties in the highly deformed zone, which is in agreement with the Hall–Petch relation.

Contrary to the experiments at 300 °C, at higher temperature (400 and 500 °C) the shear layer *h* was not sensible to the sliding speed. Due to the strength reduction at higher temperatures, the shear layer was about 1500 μm and 1600 μm at 400 and 500 °C respectively. The recrystallization process decreased the dislocation density and therefore also the hardness, for that reason a reduction about 6 % was found in the high shear zone at 400 and 500 °C. Additionally, the hardness values measured at 500 °C were about 25 % higher than at 400 °C possibly due to solid solution strengthening.

Acknowledgments

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