Materials Science Forum Vol. 762 (2013) pp 590-595
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/MSF.762.590

Physical and Numerical Simulations of the Microstructure Evolution in AA6082 During Friction Stir Processing by Means of Hot Torsion and FEM

Friedrich KRUMPHALS[1,a], Zeng GAO[1,3,b], Hassan ZAMANI[1,c], Stefan MITSCHE[2,d], Norbert ENZINGER[1,e] and Christof SOMMITSCH[1,f]

[1]Institute for Materials Science and Welding, Graz University of Technology, Kopernikusgasse 24/I 8010 Graz, Austria

[2]Institute for Electron Microscopy and Fine Structure Research (FELMI), Graz University of Technology, Steyrergasse 17, 8010 Graz, Austria

[3]School of Materials Science and Engineering, Henan Polytechnic University, Jiaozuo, Henan, 454000, China

[a]friedrich.krumphals@tugraz.at, [b]gaozengtongxue@163.com, [c]hassan.zamani@tugraz.at, [d]stefan.mitsche@felmi-zfe.at, [e]norbert.enzinger@tugraz.at, [f]christof.sommitsch@tugraz.at

Keywords: friction stir spot welding, AA6082, hot torsion tests, FEM

Abstract. A reproduction of the conditions occurring during friction stir processing, where a fine grained structure according to the process parameters rpm, transverse speed and pressure develops is the main focus in the present work. To physically simulate such a friction stir process, hot torsion tests at constant temperatures were carried out in a Gleeble ® 3800 machine at different strains and strain rates. The specimens were immediately water quenched after hot deformation to avoid any static recrystallization. The microstructure was investigated to characterize the grain size evolution and misorientation as a function of the local strain, strain rate and temperature. Dynamic recovery was observed followed by continuous dynamic recrystallization at large deformations. By means of DEFORM™3D the occurring strain, strain rate and temperature distributions, which are decisive for the observed microstructure evolution, were evaluated.

Introduction

The physical and numerical simulation of metal processing techniques is still an important tool for design and development of required products, such as predicting the microstructure and subsequent properties of the component [1-4]. Accurate prediction of the grain size due to hardening and softening processes is very helpful in the improvement of the mechanical properties. Therefore, many studies for modelling of hot deformation and microstructure evolution have been carried out so far [5-8]. Recently, studies also have been concentrated on the prediction of the microstructure evolution during friction stir welding (FSW) and friction stir spot welding (FSSW) [9-10]. During the hot deformation of aluminium alloys, such as hot rolling, forging or extrusion processes, dynamic recovery is the main restoration process. At increasing strain, the distance between the original grain boundaries will eventually be in the order of magnitude of the subgrain size. In friction stir processing (FSP), the microstructure in the stir zone is deformed to a very large extend, lattice rotation at high strains and strain rates takes place and new grains are formed by continuous dynamic recrystallization. In terms of physical simulation, hot torsion as well as compression tests are suitable experimental methods to reproduce the material flow behaviour in the FSW process.

Experimental

Material. The alloy used for the present investigation was an aluminium alloy AA6082, which exhibits a texture because it is hot rolled to a thick sheet. The hot torsion specimens were taken parallel and transverse to the rolling direction. The chemical composition is given in Table 1. The same material condition has been used for FSSW experiments in prior investigations to allow for a direct comparison of the evolved microstructure according to the same initial microstructure, which showed elongated grains dependent on the prior rolling with an average grain size of 81.7 µm [10].

Table 1 Chemical composition of AA6082 (wt%)

Material	Mg	Al	Si	Mn	Fe	Cu	Cr	Zn	Ti
AA6082	0.6-1.2	balance	0.7-1.3	0.4-1.0	0.5	0.1	0.25	0.2	0.1

Physical Simulation. Since the material rotationally flows in the FSSW process, a hot torsion experimental program was set up to generate a similar deformation pattern, i.e. similar strain, strain rate and temperature. To carry out these tests, a Gleeble ® 3800 machine was utilized. The input parameters, such as strain, strain rate and temperature, obtained from the numerical FSSW simulation, were introduced as boundary conditions for the hot torsion experiments. In the physical hot torsion simulation, the effective strain and strain rate can be described as a function of experimental input data in the following Eqs. 1 and 2:

$$\varepsilon = \frac{2\pi N_e}{\sqrt{3}L_0} r \quad (1)$$

$$\dot{\varepsilon} = \frac{\pi}{30\sqrt{3}} \frac{N_v}{L_0} r \quad (2)$$

where N_e denotes the number of rotational circles, r the radius in work area, L_0 the working length and N_v is the rotational speed [11]. Fig. 1 shows the geometry and dimension of a torsion specimen as well as the evolved microstructure pattern.

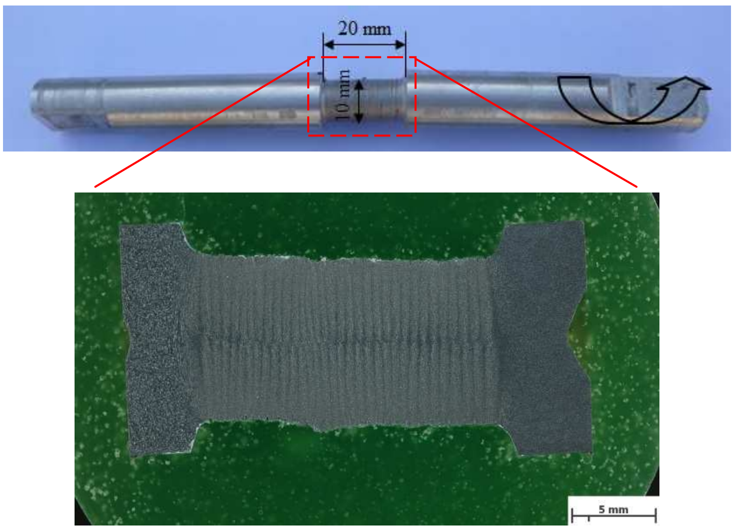
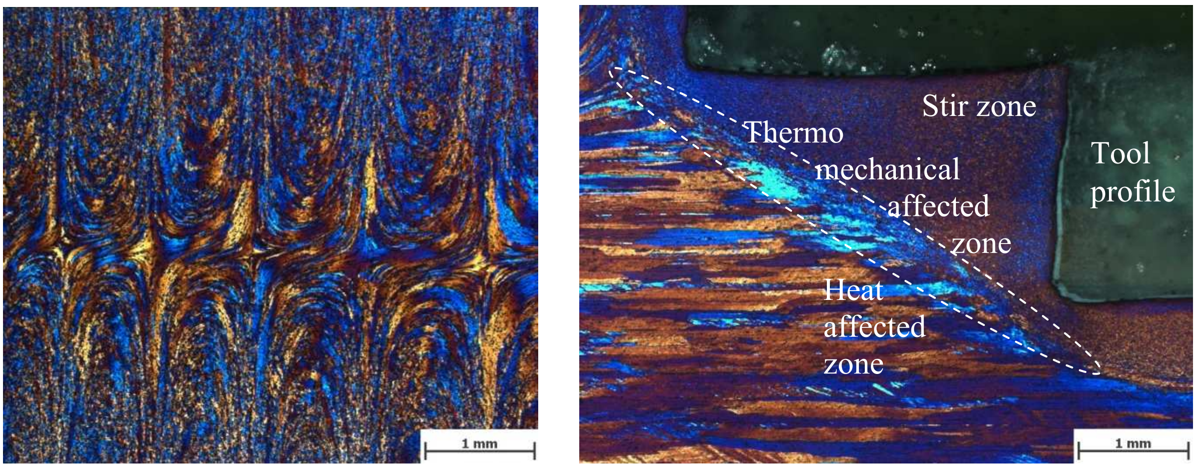


Figure 1: Hot torsion specimen of AA6082 after the experiment. The area where the torsion is located can be clearly seen (above) and the non-uniform deformation pattern is shown in a micrograph (below), which was taken parallel to the torsion axis.

After the hot torsion tests, the specimens were immediately water quenched in order to freeze the microstructure and to avoid any static recrystallization. When the forming limit was exceeded the specimen failed too early and the intended strain was not achieved, see Fig. 2.

Figure 2: A broken hot torsion specimen after quenching in the Gleeble ® 3800. For temperature measurement and heat control, thermo-couples were mounted in the middle and edge of the twisted area.

Hot torsion tests with similar rotational deformation conditions than with FSSW have been accomplished in order to reproduce a similar microstructure in defined samples, however in the hot torsion tests it was not possible to achieve such high strains and strain rates due to specimen failure [10]. In contrary, during FSSW shear stresses as well as compressive stresses are acting, which allows high deformation rates without damage. Fig. 3 shows a micrograph of a AA6082 hot torsion sample taken along the symmetry axis and Fig. 4 depicts the higher deformed outer radius.



(a) (b)

Figure 3: Microstructure of (a) a deformed hot torsion sample of AA6082 with 8 rotations at a strain rate of 20 s^{-1} at 480°C in the center of the specimen. The torsion axis is clearly visible in horizontal direction (a), in which the original large grains are only twisted. (b) FSSW specimen of the same material [9].

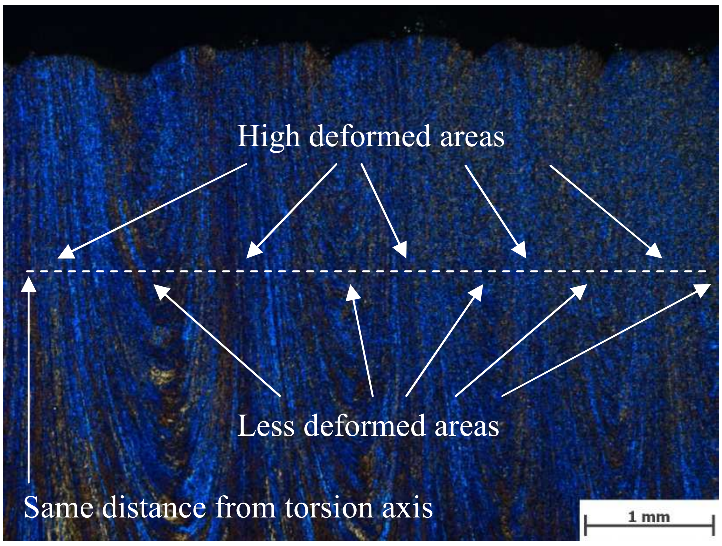


Figure 4: Overview of the evolved microstructure at the outer radius of the specimen according to a global strain rate of 50 s^{-1} at 480°C and 4 rotations. Local differences occur as afore described.

Numerical Simulation

Prior attempts to model the hot torsion tests with DEFORM^{TM}2D were agreed to adequately simulate the strain and strain rate distribution as a function of the radial distance from the torsion axis. However, besides the radial dependency of the plastic deformation, the 3D simulation also shows a non-uniformity along and parallel to the axis direction. To account for suchlike complex deformation patterns occurring during hot torsion, the commercial FEA software DEFORM^{TM}3D was applied to model the FSSW process. Temperature data were compared between simulation and experiment during prior investigations to validate the accuracy of the model [9]. The numerically simulated non-uniform deformation along the radial as well as along the axial direction of the specimen (Fig. 5) can be somehow related to the obtained microstructures shown Figs. 3a and 4, where areas with higher and lower deformations alternate at the same radial distance from the torsion axis. In the microstructure investigations, higher strained areas can be identified by zones of smaller grain size, see Fig 4. The resulting grain size in torsion tests at the strain rate of 50 s^{-1} is larger than the one in the stir zone of the FSSW, compare Figs. 3b and 4 [10]. Fig. 5 shows the simulated strain, strain rate and temperature distributions during a hot torsion experiment at 480°C initial temperature with a strain of 7 at a strain rate of 5 s^{-1} and also with a strain of 3.5 at a related strain rate of 50 s^{-1}.

The hot torsion parameters combinations, which were applied and finally achieved during the physical investigations were numerically simulated, as shown in Fig. 5. With ongoing deformation and heat generation, the specimens experience higher deformation and fail in half length position (Fig. 5d-f). During the FSSW process, strain rates in the range of 300 s^{-1} which result in effective total strains of approx. 100 were numerically observed and are usual for friction stirring processes [9]. On the Gleeble machine, however, either maximum strain values of more than 20 in combination with strain rates of 5 s^{-1} or less or high strain rates with local peak values of more than 100 s^{-1} at low total strains of 3 are possible during hot torsion testing.

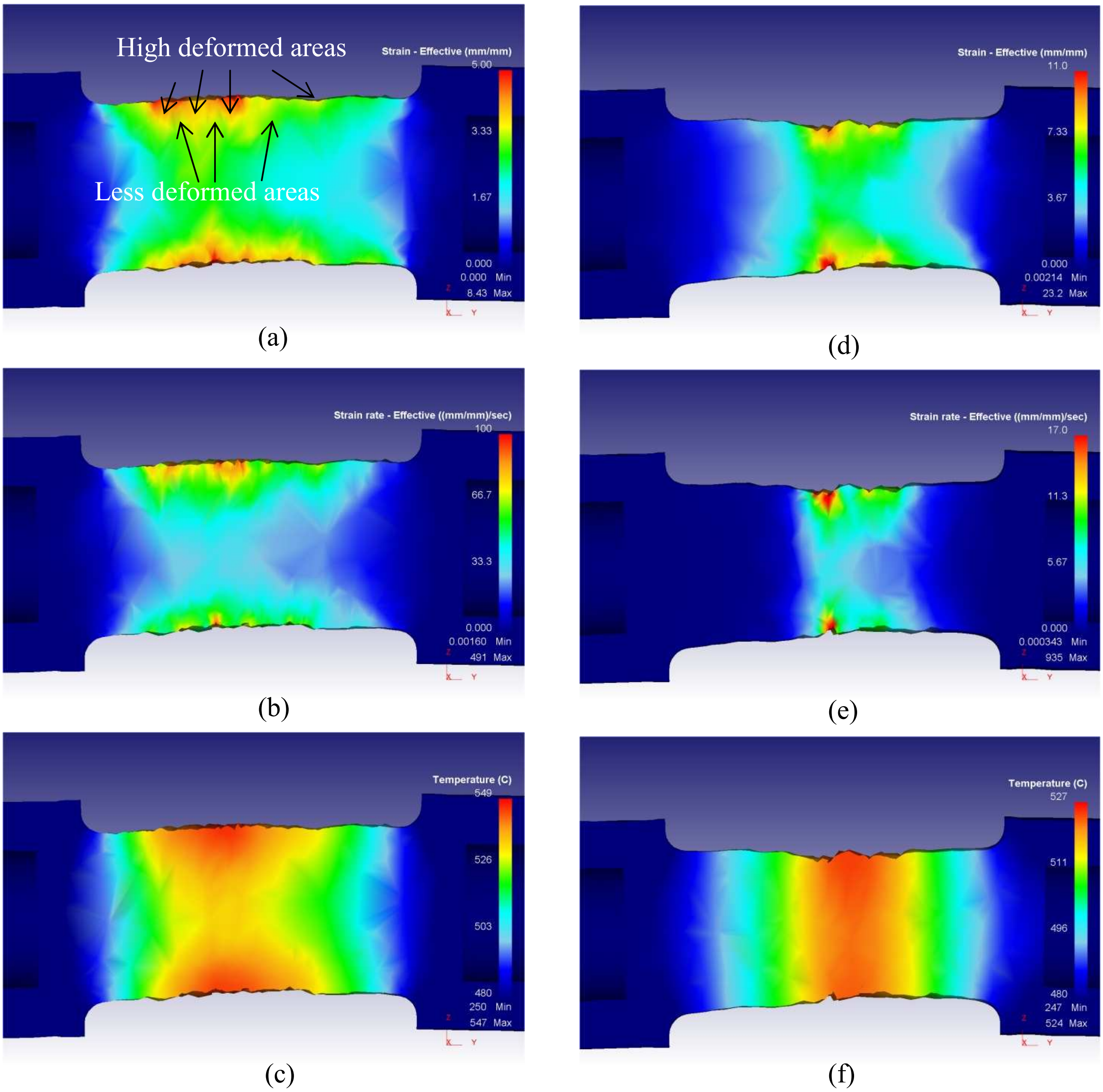


Figure 5: DEFORM™3D simulation of (a) effective strain, (b) strain rate and (c) temperature distributions during hot torsion for an initial temperature of 480°C for a global strain according to machine setting of 3.5 and strain rate of 50 s^{-1}. In diagrams (d,e,f) the same output parameters are represented with the same initial temperature but a global strain of 7 and a strain rate of 5 s^{-1}.

Summary and Outlook

Physical hot torsion experiments were performed to reproduce conditions occurring in friction stir processing. However, during the pure hot torsion testing, conditions equal to those in the stirring zone of the FSSW could not be achieved, but conditions similar to those in the thermo-mechanical affected zone, which exhibit moderate strains and strain rates, can be simulated very well. In contrary to shear stresses in hot torsion, the stir zone is under both shear and compressive stresses during severe deformation. Therefore, such high deformation rates as occurring during FSSW without damaging the material are possible during the whole FSSW process, which counteract both the formation of cracks and local damage progress. Higher strains and strain rates experienced in the FSSW process result in a finer subgrain and grain size compared to the Gleeble experiments performed at lower strain and strain rates. The grain refinement in both cases takes place through ongoing lattice rotation and formation of new grain boundaries during the process. Regarding future investigations to be able to entirely generate FSSW process conditions by means of hot torsion tests, the hot torsion has to be carried out under concurrent compressive stresses and axial symmetry and stability have to be guaranteed, too.

Acknowledgement

The authors would like to thank to FWF (Austrian Science Fund) for partially support this work through project P22238-N22.

References

[1] S. Khosa, T. Weinberger, N. Enzinger: *Proc. of 5th Int. Conf. Heat Transf. Fluid Mech.* (2007)

[2] R. Pschera, J. Klarner, C. Sommitsch: Steel Res. Int. 81 (2010), pp. 686-690

[3] F. Krumphals, B.Reggiani, L. Donati, T. Wlanis, C. Sommitsch: Comp. Mat. Sci 52 (2012), pp 40-45

[4] F. Krumphals, T. Wlanis, C. Sommitsch, I. Holzer, B. Sonderegger, V. Wieser: Comp. Meth. Mat. Sci. = *Informatyka w technologii materiałów* 9 (2009), pp. 228-233

[5] M. Candic, B. Tian, C. Sommitsch: Mat. Sci. Forum 715-716, (2012), pp.611-616

[6] A. Krumphals, M. Stockinger, C. Sommitsch, F. Warchomicka: *Ti-2011 Conference*, Bejing (2011), pp. 493-496

[7] M.C. Poletti, M. Rodriguez-Hortala, M. Hauser: Mat. Sci. Eng. A 528 (2011), pp. 2423-2430

[8] P. Sherstnev, C. Melzer, C. Sommitsch: Int. J. Mech. Sci. Vol. 54 (2012), pp. 12-19

[9] Z. Gao, F. Krumphals, P. Sherstnev, N. Enzinger, J.T. Niu, C. Sommitsch: Key Eng. Mater. 504-506 (2012), pp. 419-424

[10] Z. Gao, J.T. Niu, F. Krumphals, N. Enzinger, C. Sommitsch, in: *Mathematical Modelling of Weld Phenomena* 10 (2012)

[11] W.M. Li, Z.B. Liu, H.Y. Liu: J. Plast. Eng. Vol. 5 (1998) pp. 36-39.