NUMIFORM 2016, Université de Technologie de Troyes, France, July 4-7 2016

Use of Gleeble MAXStrain unit for study of damage development in hot forging

Hubert Geijselaers[1a], Chao Wang[1], Alexis Miroux[2], Victor Recina[3] and Ton van den Boogaard[1]

[1]Universiteit Twente, Enschede, the Netherlands, [2]Aleris, Antwerpen, Belgium, [3]SKF, Göteborg, Sweden

Abstract. The standard Gleeble MAXStrain unit has been modified to allow axial elongation. Analyses indicate that in this way both positive and negative hydrostatic stresses can be achieved during forging simulations, depending on the amount of strain per hit. This opens the way to the study of the effect of hydrostatic stress on development of damage and healing. In this contribution we will show results of finite element simulations of this test at different settings as well as experimental results, which seem to confirm this.

1 Introduction

The Gleeble MAXStrain multi-axis hot deformation system is a tool that can subject materials to very high strain under control of strain rates and temperature (Figure 1). Grips are used to supply the electric current, which heats the specimen. Successive perpendicular deformations are applied while the specimen is rotated over 90° along its axis. The grips in the original system restrain the specimen against elongation.

Figure 1. Gleeble MAXStrain multi-axis deformation system showing specimen and anvils (courtesy Dynamic Systems Inc.).

In hot forging usually the work piece is not subject to this constraint. Elongation is even a desired effect of the traverse forging strokes. Therefore the clamping system has been modified to release the longitudinal restraint by insertion of ceramic pads. The specimen is more or less kept in place by stiff Cu wires, which were added to substitute the electrical contact in the grips (Figure 2).

The resulting deformation of two specimens is shown in Figure 3. Only in the area where the anvils hit, deformation is visible. Elongation of the specimen is not restrained.

Two different series of hits were programmed, 'strong' hits, aiming at 20% strain per hit, and 'shallow' hits, aiming at 2% per hit. The tested material is highly alloyed 100CrMnMoSi steel, of which the ingots show a highly segregated part.

The objective of this research is to study damage evolution in the material during hot forging as a function of the applied deformation.

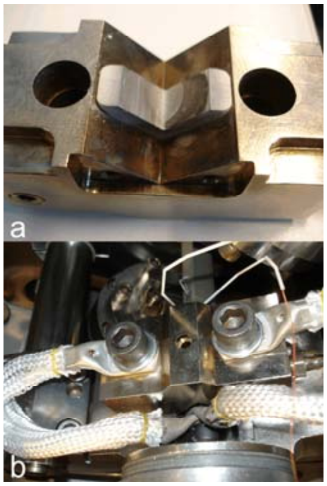

Figure 2. Modified grips, a) ceramic pad, b) Cu electric wires.

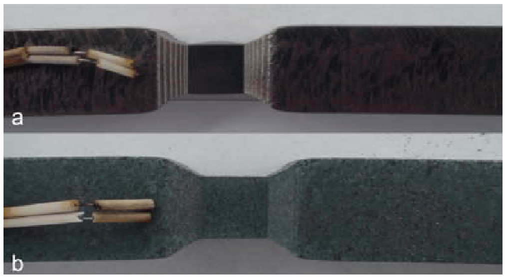

Figure 3. Two specimens, subjected to a) 15 'strong' hits and b) 80 'shallow' hits.

---

[a] Corresponding author: h.j.m.geijselaers@utwente.nl

2. Test procedure

All tests were done at a temperature set at 1150°C. Two types of samples were used, one set from the segregated part of an ingot, the other set from a clean part of the ingot. Each test was executed once on either of these. The programmed test settings are show in Table 1. The test software allowed a maximum of 80 hits per test, which is the reason for the higher strain per hit in the second shallow hits test. After applying the deformations the specimens were cooled down slowly to obtain a bainitic micro structure.

Table 1. Test settings

Type	Total strain	Strain per hit	Number of hits	Strain rate (s^{-1})
strong	1.0	0.2	5	20
	3.0	0.2	15	20
shallow	1.0	0.02	50	2
	3.0	0.0375	80	3.75

After the tests every specimen was inspected, by X-ray micro tomography. By micro tomography a data set is obtained, which contains 2-D grey-scale slices of the 3-D volume of the gauge section. In these grey-scale images voids and irregularities show up as 'dark' voxels. The dark voxels are subjected to a 3-D filter to discern clusters of dark voxels from artefacts. From the amount of remaining dark voxels a void volume fraction (VVF) is calculated.

3. Finite element simulations

3.1. The finite element model

The mechanical behaviour of the specimens during testing was studied by implicit static isothermal 3D finite element simulations in Abaqus. 1/8 of the specimen has been modelled using 8-node fully integrated elements. 20x20 elements are used to model the cross section. The material behaviour is described by an over-stress elasto-viscoplastic model [1,2]. The model is supported by three-fold symmetry conditions while no other displacements are suppressed. The contact between anvils and specimen is simulated using a penalty based contact algorithm. A friction coefficient μ=0.4 is specified.

3.2 Finite element results

The main difference between the simulations with strong hits and those with shallow hit can be seen when the hydrostatic stress in the centre of the specimen gauge area is monitored. A stress triaxiality state variable, connected to different damage evolution models [3-6] is evaluated:

$$\mathrm{d}D = \frac{\sigma_{\mathrm{h}}}{\sigma_{\mathrm{eq}}} dp, \qquad (1)$$

where σ_{h} is the hydrostatic stress component, σ_{eq} the von Mises equivalent stress and p is the equivalent plastic strain. The results are summarized in Table 2 and the evolution is shown in Figure 4, both for the case of strong hits and shallow hits. Note that the total equivalent plastic strain in the centre of the specimen exceeds the intended applied strain. This is due to the inhomogeneous strain distribution in the gauge cross section (Figure 5).

It can be clearly seen, that shallow hits induce a higher D value during the first phase of the tests. In a later phase, negative triaxiality prevails, but in the shallow hit test still to a lesser extent. The evolution of D indicates, that if it plays a role in void growth and healing, specimens subjected to different amounts of deformation should also show different amounts of damage.

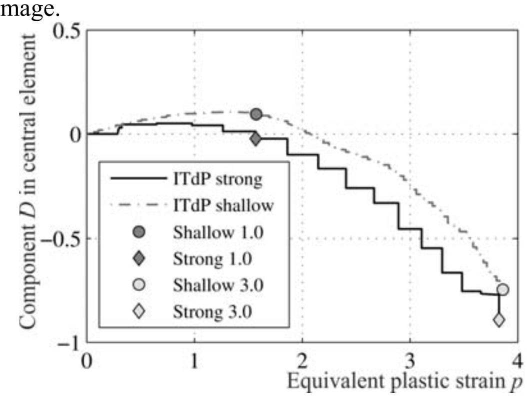

Figure 4. Evolution of damage components for 50 strong and 80 shallow hits in centre of gauge cross section.

Table 2. Simulation results, equivalent plastic strain and triaxiality history in the gauge centre.

Type	Applied strain	Equivalent plastic strain p	Triaxiality variable D
Strong	1.0	1.57	-0.023
	3.0	3.83	-0.891
Shallow	1.0	1.57	0.094
	3.0	3.86	-0.747

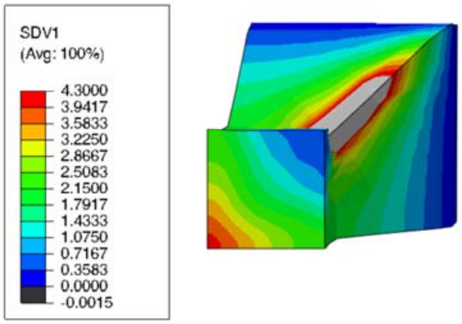

Figure 5. Distribution of equivalent plastic strain in the cross section.

4. Experimental results

4.1. X-ray micro tomography

Four specimens cut from the segregated area of the ingot were inspected by X-ray micro tomography. The void volume fraction is found to decrease with increasing deformation. Clearly four specimens is not a statistically significant experimental population, but the coincidence with the simulation results of Figure 4 is striking. Assuming however, that the results are significant, it offers the possibility to estimate the parameter A in Oyane's ductile fracture model [3].

In the four specimens cut from the 'clean' material no voids could be detected by X-ray tomography. Apparently, they start out clean and stay clean.

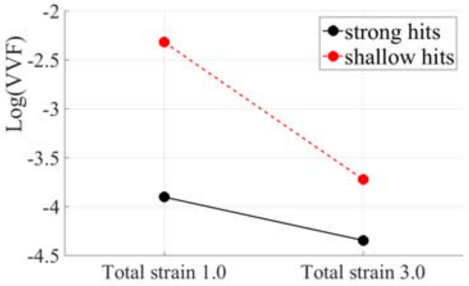

Figure 6. Void Volume Fraction of four specimens determined by X-ray tomography.

5 Implications for damage modelling

A value of the parameter A in Oyane's ductile fracture model function Ω:

$$\mathrm{d}\Omega = \mathrm{d}p + \frac{1}{A}\frac{\sigma_{\mathrm{h}}}{\sigma_{\mathrm{eq}}}\mathrm{d}p, \qquad (2)$$

can be estimated based on the numerical and experimental results. From the strong hit results we may require:

$$\Omega(3.83) > 0 \rightarrow A > 0.23, \qquad (3)$$

and

$$\Omega(3.83) < \Omega(1.57) \rightarrow A < 0.32. \qquad (4)$$

whereas on the basis of shallow hit results:

$$\Omega(3.86) << \Omega(1.57) \rightarrow A < 0.37. \qquad (5)$$

In view of the big difference in void volume fraction found between both shallow hit specimens, a choice of $A \approx 0.25$ seems justified.

6 Conclusions

Numerical simulations of the Gleeble MAXStrain test, modified to allow axial elongation, show that, depending on the depth of applied hits, different triaxiality histories can be obtained. Application of a series of shallow hits initially causes a positive evolution of Oyane's triaxiality based ductile damage function. Upon continuation of the test (more hits), the function gradually changes sign, which indicates that healing of previously applied damage may occur. Experimental results seem to confirm this observation.

The results in this contribution are based on a limited number of experiments. A more extensive experimental program, including optical micrography, should be executed to provide a more firm basis.

Aknowledgement

This research was carried out under the project number M41.1.11418 in the framework of the Research Program of the Materials innovation institute M2i (www.m2i.nl). The industrial partner, SKF Group is gratefully acknowledged for the contributions to this research.

References

1. C. Wang, H.J.M. Geijselaers, E. Omerspahic, V. Recina, A.H. van den Boogaard, J. Mat. Proc. Techn. **227**, 268–280 (2016)
2. F. Dunne, N. Petrinic, *Introduction to Computational Plasticity*, Oxford University Press (2005)
3. M. Oyane, T. Sato, K. Okimoto, S. Shima, J. Mech. Work. Techn. **4**, 65-81 (1980)
4. Y. Bao, T. Wierzbicki, Eng. Fract. Mech. 72, 1049-1069 (2005)
5. A.M. Goijaerts, L.E. Govaert, F.P.T. Baaijens, J. Mat. Proc. Techn. 312-323 (2001)
6. J.R. Rice, D.M. Tracey, J. Mech. Phys. Solids, 201-217 (1969)