SEVERE PLASTIC DEFORMATION OF Al ALLOYS

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Abstract
Severe plastic deformation with self-recovery or post-deformation recovery has been frequently applied in the last two decades to manufacturing of nano-structured materials, inspired by the Hall-Petch relation between the strength of alloys and their grain size. Relatively soon was realized that natural limits occur imposed by the processed materials and it was early defined that ultimate grain refinement of single-phase alloys makes little sense as it leads to fast deterioration of properties or failure of the material due to dynamic release of energy stored in it. Therefore efforts were directed towards development of new compositions of multi-phase alloys in which dynamic recovery and recrystallisation processes could be hampered by precipitation. To study these processes with their adequate control, a working device was developed called MaxStrain, combined with Gleeble physical simulator. The MaxStrain uses two-directional deformation to reach accumulated strains of 50 and more, depending only on the ductility of processed alloy, applying plane strain compressions with constant strain rates of up to 100/sec, combined with various programmable thermal cycles. In this paper examples are given of processing Al-6061 grade wrought alloy and Al-319 grade cast alloy, and resulting microstructures described. The precipitation processes accompanying the recovery and recrystallisation during deformation of these alloys were studied by mainly metallography, including transmission electron microscopy.

Keywords: SPD, Al-alloys, Gleeble, MaxStrain, metallography

1. INTRODUCTION

Manufacturing of ultra-fine-grained materials is now a hot issue in materials science. Since two decades an explosive boom has been observed in development of techniques producing kilogram(s) of nano-grained materials as well as publishing results obtained by these techniques, most of which applying severe plastic deformation with self-recovery or post-deformation recovery. In the noise created by this explosion was omitted that the nano-structured metal alloys exist in World’s technology since ages and these have been used from ancient swords and mediaeval arms till more recent high-carbon martensitic tool steels, medium-tempered spring steels as well as patented near-eutectoidal wires, altogether produced annually in thousands of tons. Soon this initial run for manufacturing a kilogram of nano-material was replaced by better defined challenging tasks, like how to make the nano-structured materials further process-able and afterwards stable during exploitation, as well as more efforts have been directed towards development of better compositions for this last purpose. The ultimate grain refinement of single-phase alloys often leads to fast deterioration of mechanical properties or consistency of the material due to release of deformation energy stored in it [1]. Also the Hall-Petch relation [2] appeared to have limits – below certain grain size further refinement results in softening and decrease of strength [3]. Thus more attention was recently given to multi-phase alloys in which the dynamic recovery and recrystallisation processes coincide with strain-induced precipitation. For light-metal alloys important appeared observing adiabatic heating effects and their influence on self-recovery as such alloys usually have high strain-rate sensitivity. The most frequently used for light metal alloys ECAP (equal channel angular pressing) technique forces alloys to deform predominantly by shear localized in deformation bands, which process coincides with generation of adiabatic heat [4]. The ECAP does not allow measuring the rise of temperature in the processed material, while additionally friction conditions between the workpiece and die remain unknown. As long as the adiabatic shear bands persist, the uniform grain size cannot be achieved. For this the saturation strain must be determined, while in the ECAPed material the amount of accumulated strain is usually given as a number of passes with unknown true strain in each pass. To study these processes a tool was developed – the MaxStrain device combined with Gleeble simulator [5]. The principle of the MaxStrain is to deform from two perpendicular directions the central portion of the bar-like sample while restraining its ends, Fig.1. Without the restraint the material would flow unidirectionally (A), while with restraint it flows transversely (B). The sample mounted like in Fig.2 rotates 90 degrees between each hit, accumulating in its central portion compressive strains. The
MaxStrain executes such two-directional plane-strain compressions to reach accumulated strains of 50 and more, limited only by the ductility of processed alloy. Constant strain rates up to 100/s can be achieved during various programmable thermal cycles.

In a MaxStrain study on deformation of Al-Mg-Si alloy grade 6061 a substantial grain refinement was achieved together with softening of this alloy [6]. This material in the initial state had non-uniform coarse grains of 40 to 300 µm size, and in its matrix large particles of Mg₂Si and Al₃Mg₂ phases were present, Figs 3 & 4.

**Fig.1** Bar-like sample deformed without restraint (A) and with restraint (B)

**Fig.2** Mounting of a sample in MaxStrain device

**Fig.3** Elongated Mg₂Si particles in the matrix of Al-6061 alloy in as-hot-rolled state

**Fig.4** Large Al₃Mg₂ particles appearing in the matrix of as-hot-rolled Al-6061 alloy

**Fig.5** Fine grains with some wide-angle boundaries after strain of 40 at 50°C

**Fig.6** Force-time-temperature plot of MaxStrain deformation at programmed 50°C
The total strain of 40 at 50°C generated fine grains of sizes from 100nm to 200nm, with many of these grains having wide-angle boundaries, Fig.5. Intermetallic phases were refined to less than 100nm size particles. Strain was mainly localized in deformation bands and this was accompanied by substantial adiabatic heating effect - the temperature rose from the programmed 50°C to ~80°C at accumulated strain of 12-16, followed by a slow decrease to ~75°C at the end of experiment, Fig.6. The adiabatic heating vanished at saturation strain, which e.g. at 100°C was about 24, Fig.7, and above this strain the grain sizes were homogeneous as seen crosswise to the deformation bands. In the length direction of the bands elongated grains formed by dynamic recovery / recrystallisation, Fig.8. The microstructure generated by deformation from room temperature up to 100°C was fairly unstable; just focusing of the TEM’s 200kV electron beam on thinner parts (<250nm thick) of the specimen caused its local transformation to almost dislocation-free grains of the matrix, Fig.9.

Force-time-temperature graphs in Figs 5 & 7 show softening of the alloy with increase of strain; this occurred at all temperatures of processing. At 150°C and higher the accumulated strains at first induced precipitation and then assisted coagulation of precipitates, both contributing to stabilization of the grain sizes, Fig.10. Earlier was observed that at high strain rates of plane-strain compressions on hypereutectic Al-27Si-9Ni PM alloy, in shear bands hard phases became “milled” by dynamically deformed matrix, with gain of ductility and without loss of material’s consistency [7]. In other study on processing of bainitic HSLA steel, the strain localized in shear bands followed by recovery and recrystallisation gave stable dual-phase microstructure with sub-micron size grains [8].
2. **MAXSTRAIN DEFORMATION OF AL-319 ALLOY**

The Al-Si-Cu-Zn cast alloy of Al-319 grade is considered as non-deformable. Following the technologic idea of making cast pre-forms of this alloy and then finishing them by e.g. net-shape warm forging, thus improving some of its properties, the MaxStrain device was used to find out if any formability range does exist for this alloy. In as-cast and stress-relieved state the alloy has at room temperature the UTS of over 200MPa, which after solution treatment and artificial ageing can rise to almost 400 MPa [9]. Its elongation in tensile test at room temperature is only 1.5%. In tests on MaxStrain device to plane strain of 0.5, on surface of specimens’ bulge portion cracks appeared, Figs 11 & 12, from curvature of the bulge and depth of cracks the critical strain-to-fracture could be calculated as ~0.22 for temperature 250°C and ~0.36 for temperature 450°C.

![Fig.11 Sharp deep cracks on bulge surface of Al-319 sample plane-strain compressed at 250°C](image1)

![Fig.12 Cracks on bulge surface of Al-319 sample plane-strain compressed at 450°C](image2)

![Fig.13 Dendritic microstructure of Al-319 alloy in the initial as-cast state](image3)

![Fig.14 Large eutectic of Si and intermetallics in Al-319 alloy in the initial as-cast state](image4)

Microstructure of the as-cast Al-319 is dendritic with eutectics of Si and intermetallic phases, Figs 13 & 14, and contains numerous porosities. The porosity assists nucleation of cracks during deformation and has negative effect on fatigue life of the Al-319 components [10]. So the main question is how to make the Al-319 formable and eventually reduce the amount and size of pores.
With increase of accumulated strain at 250°C and 450°C the alloy visibly softens, Figs 15 & 16, while the strain localizes mainly in deformation bands, Fig.17, along diagonals of sample’s cross-section.

Fragmentation of the eutectic phases is more intensive at 250°C, Fig.18, than at 450°C, Fig.19. Images observed in TEM revealed that at 450°C the matrix is fully recrystallised, Fig.20.
To reduce susceptibility to surface cracking incremental hits on MaxStrain were applied, starting from strain rate of 0.1/s and ending with 3.0/s, all executed at 475°C. Total accumulated strain of ~16 was achieved and well recrystallised microstructure generated, Figs 21 & 22.

![Fig. 21 Recrystallised grains in deformation bands after strain of ~16 at 475°C](image)

![Fig. 22 Recrystallised grain with medium dislocation density and few fine precipitates](image)

3. DISCUSSION

In both cases of studied aluminum alloys the accumulated strains resulted in the plastification, particularly visible with progress of strain at the elevated testing temperature. The lower-alloyed Al-6061 generated finer grains that the higher-alloyed Al-319. The multi-hit two-directional deformation applied by MaxStrain allowed achieving the grain refinement in Al-6061, from 40 to 300µm size in the initial as-hot-rolled state to less than 200nm average grain size after plane-strain compressing in temperature range of 50 to 100°C. At temperatures 150°C and higher the accumulated strain of 40 caused dynamic recovery and recrystallisation, and stimulated precipitation as well as growth of the precipitates, resulting in softening of the alloy particularly noticeable at elevated temperatures of the processing. In all studied cases in the temperature range from 50 to 250°C the Al-6061 material allowed achieving in 80 hits with strain rate 5/s the total accumulated strain of 40 without failure and homogeneous microstructure in whole sample. The MaxStrain processing of Al-319 alloy also plastified it however a serious grain refinement was not achieved. At room temperature the 319 alloy had very low ductility and up to 250°C intensive surface cracking occurred after its plane-strain compression. Better ductility this alloy had above 400°C. The strains of 0.5 applied in each hit with constant strain rate 5/s allowed substantial fragmentation of eutectic phases at 250°C but not at 450°C. Applied incremental deformation in each hit, starting with strain rate of 0.1/s and ending at strain rate of 3/s, allowed to reduce susceptibility of 319 alloy to surface cracking and substantially enhanced its ductility. Further study on enhancing the ductility by incremental deformation is to be continued and will include identification of micro-mechanisms governing the plasticity of such difficult to deform materials like the Al-319 alloy.

4. CONCLUSIONS

1. Severe plastic deformation in plane-strain mode enhances ductility of Al-6061 and Al-319 alloys at elevated temperatures of processing.
2. Strains to a large extent localize in shear bands and only after strain saturation homogeneous grain sizes are achieved.
3. The MaxStrain device implemented on Gleeble thermo-mechanical simulator allows determining the saturation strains while simultaneously providing adiabatic heating information.
4. Deformation of Al-319 alloy to accumulated large strains e.g. 16 is possible at elevated temperatures of 400°C and higher, in particular when incremental strain rates are applied.
References:


