Structure and strength of the 1570C aluminum alloy after complex SPD processing

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Abstract. The effect of severe plastic deformation (SPD), realized via multi-directional forging (MDF) at a constant temperature of 325 °C, as well as via a combination of MDF with subsequent room temperature rolling or high pressure torsion, on the microstructure, static and fatigue strength parameters of an ingot of non-age-hardenable commercial aluminum alloy 1570C (Al-5Mg-0.18Mn-0.25C-0.08Zr) was studied. It is found that the most effective treatment to enhance the balance of the alloy properties involves a sequence of hot MDF and cold rolling due to the development of a work hardened ultrafine-grain structure with uniformly distributed nanosized aluminides of transition metals. The role of precipitates in the alloy structure- and property-formation is discussed.

1. Introduction

Non-age-hardenable Al-Mg alloys with complex additions of transition metals (TM) belong to the class of advanced structural materials with a high potential for a wide range of industrial applications due to the unique balance of their service properties [1-3]. The behavior of the alloys is conventionally conditioned by the chemical (phase) composition, the parameters of the cast microstructure and their changes during thermomechanical processing (TMP). Commercial TMPs are primarily aimed at the control of the dislocation structures, which limits the fabrication of annealed and work-hardened semiproducts only. For going beyond these limits, the modern strategies are also aimed at tailoring the grain size distributions and the grain boundary structure - altogether combined under the term “structuring”. The latter is frequently called “deformation (nano)structuring” referring to a large group of processing methods and schemes, involving severe plastic deformation (SPD) to strains e>>1 as a pivotal component capable of imparting the nanosized phase components into a wide range of structural materials [4,5]. When applied to aluminum alloys, the SPD approach requires the sufficient content of TMs and dispersion of secondary TM aluminides, which stabilize the dynamically and/or statically recrystallized/polygonized microstructures formed during processing [6]. It has been well documented, that the most capable grain refinement technique is high pressure torsion (HPT), which is usually performed at ambient temperature to produce the crystallite size of the nanometer scale in the small disc-shape samples of various metals and alloys [4,5,7]. Meanwhile, for the efficient processing of the ultrafine grain (UFG) bulk billets with a grain size less than few
micrometers, multi-directional forging (MDF) is extremely attractive among other SPD techniques due to its excellent scalability and cost-effectiveness [7].

Owing to the Hall-Petch type relations between the strength and grain size [5,6], the deformation nanostructuring increases the strength of pure metals and solid solutions. However, the significance of SPD is less obvious for the complex alloyed systems due to a number of simultaneously affected structural factors. For instance, the loss in their dispersion hardening under TMP can be much higher than the positive effects gained from work hardening or grain size strengthening. Thus, the point is to develop the TMP effectively exploring most of the known strengthening mechanisms in a single route. The present study is aimed at comparative analysis and assessment of the efficiency of TMP based on MDF and its combinations with conventional cold rolling (CR) and HPT to enhance the static and cyclic performance of the structural Al-Mg-TM alloys at room temperature via their nanostructuring and strengthening during SPD processing.

2. Material and procedure
A commercial ingot of the 1570C alloy (Al-5Mg-0.18Mn-0.20Sc-0.08Zr, wt.%) was solution treated at 360 °C for 6 hours and furnace-cooled. The rod billets of ø80×150 mm were then MDF processed in the isothermal conditions for 12 cycles at 325 °C with a total equivalent strain of e ~12. Cold rolling with a total reduction of ~80% was performed at room temperature on plate shape billets of 10 mm thick. HPT was also performed at room temperature with 10 revolutions and a pressure of 6 GPa applied to the disk-shape samples ø20×2 mm cut from the MDFed billets.

The microstructure of the alloy was investigated by conventional methods of optical, transmission and scanning electron microscopy (OM, TEM and SEM) and by X-ray analysis. Most parameters of the microstructure (grain size, fractions of the low- and high-angle boundaries (LABs and HABs), mean misorientation angle) were determined by the SEM-EBSD analysis. The size and number fraction of secondary phases were measured using the computerized analysis of TEM images with not less than 2000 precipitates. The microhardness of the alloy was determined at 10 sec loading with 1N. The static and cyclic (dynamic) tension (fatigue ratio R = 0.1, and frequency ν = 60 Hz) tests were performed at ambient temperature of the flat mechanically pre-polished dog-bone and corset samples with a gauge part of 1.5×3×6 mm³ and a minimum cross-section of 1×0.9 mm², respectively.

3. Results and discussions
The TEM analysis showed that the abnormally supersaturated by TM aluminum solid solution was decomposed during the homogenization annealing, and Al₃(Sc, Zr) compact precipitates were formed with a mean diameter of 10-15 nm and a volume density of 1×10⁴ μm³. Owing to the delta-zero contrast, most of them were found to be coherent to the matrix. Their size distribution was unimodal, and the volume distribution was quite uniform with the frequently observed grain boundary precipitate free zones (PFZs). The alloy matrix is constructed by equiaxed grains with a mean size of 25 μm. The grain boundary misorientation spectrum reveals the prevalence of high-angle boundaries (table 1).

It has been shown that the chief process of the grain refinement of the alloy under MDF is the continuous dynamic recrystallization [3]. New fine subgrains and grains, surrounded by LABs and HABs, were formed in the vicinity of the initial grain boundaries with PFZs volumes involved. An increase in the strain resulted in the rise of the crystallites misorientations and the gradual replacement of the coarse-grain microstructure by the fine-grain one (figure 1a). One can notice that even after 12 forging cycles, the microstructure was still partially recrystallized with near 2 μm subgrains inside the fragments of the initial grains surrounded by slightly coarser new grains.

Under HPT, the fine-grain structure was transformed into a typical non-equilibrium nanofragment one comprising of nearly equiaxed crystallites of 150 nm in diameter, which were surrounded predominantly by LABs and characterized by the highly increased dislocation density and the lower lattice parameter (table 1 and figure 1). In spite of the specific TEM contrast from the work hardened matrix, the TM aluminides were easy to observe in the majority of nanofragments. Meanwhile, the decomposition of the aluminum solid solution with the β-phase precipitation was not detected. Thus, it
could be concluded that the decrease in the lattice parameter under HPT is mainly caused by the changes in amounts of crystal defects, and not by the level of solid solution alloying.

The effect of cold rolling on the microstructure of the matrix of the MDF processed alloy was somewhat less pronounced than that of HPT. The fine-grain structure obtained by MDF was also transformed into the severely hardened one with the high dislocation density and non-equilibrium grain boundaries (table 1 and figure 1). However, the cellular character of the structure with the cell size of about three times larger than the fragment size in the HPT-ed specimens, i.e. quite far beyond the nano-range, was preferably noticed. The TM aluminides were also detected and near homogeneously distributed in the aluminum matrix as in the HPT processed condition.

The mechanical tests reveal good correlation between the microstructures discussed above and the alloy static and dynamic strength parameters presented in table 2. The work-hardening effect originating from the increasing dislocation density is considered to be the main factor controlling the mechanical behavior of the alloy. This conclusion follows from several consistent observations highlighting, in particular, the insignificance of the grain size effect. In particular, the high temperature MDF did not result in any alloy strengthening despite the remarkable grain refinement (table 1). This finding can be only explained as a result of compromised grain boundary strengthening and the alloy softening due to the reduced dispersion strengthening because of the coagulation of TM aluminides under MDF. Besides, the alloy behavior after MDF is also conditioned by the formation of near completely recrystallized equilibrium microstructure where the work hardening effect is absent, and, consequently, the lowest static and fatigue strength is observed along with the largest ductility. Further rolling at ambient temperature was accompanied by a noticeable increase in the strength of the alloy. Particularly, the yield stress increased remarkably while the ductility reduced by a factor of two or so (table 2). Nevertheless, the elongation to failure remains reasonably high (of 18%), which is worth noting for the significantly strengthened material. The increasing monotonic strength results in the concomitant increase of the fatigue life in the high-cycle regime. In line with common trends, such a behavior was reasonably anticipated from SPD processing leading to the UFG microstructure [5,8]. A strong enhancement of the hardness and static strength was also reasonably expected for the MDF + HPT processed alloy due to the extreme grain refinement. However, such a pronounced effect was found below the yield point owing to the nullified ductility. The alloy brittleness accounts for the

Table 1. Structure parameters of the alloy 1570C.

| Condition       | Grain/Subgrain size, μm | Mean misorientation angle, degree | Fraction of HABs, % | Lattice parameter, Å | Dislocation density, m⁻², ** | * derived from TEM analysis |
|-----------------|-------------------------|----------------------------------|---------------------|----------------------|-------------------------------|---------------------------|
| Initial         | 25/-                    | 40                               | 90                  | -                    | -                             |                          |
| MDF             | 2.2/2.0                 | 29                               | 67                  | 4.073±0.001          | 5.0×10¹²                     | *                         |
| MDF + HPT       | ~0.15*                  | -                                | -                   | 4.069±0.003          | 5.1×10¹⁴                     | **                        |
| MDF + CR        | 2.4/0.4*                | 14                               | 27                  | -                    | -                             | *                         |

Figure 1. 1570C alloy TEM structures processed via MDF (a), MDF+HPT (b) and MDF+CR (c).
fatigue limit reduction (table 2), despite the increasing static strength. Since the fatigue is a substantially local phenomenon, and the fatigue limit is governed by the “weakest link” in the microstructure, this is most likely associated with the accumulation of defects in the course of cold SPD, leading to the local increase in the internal stresses, which might be critical for premature fatigue crack initiation.

The observed mechanical behavior permits us concluding that the excellent balance of the static and dynamic properties is obtained after TMP combining hot forging and cold rolling. After this treatment, the alloy exhibits a uniform work-hardened (ultra)fine-grain microstructure with homogeneously distributed nanosized TM aluminides, which is favorable for fatigue performance. It should be also noted that the obtained mechanical properties are outstanding, considering the strength of the alloy comparable with that of high-strength, age-hardenable alloys of the 7xxx series, while their ductility and fatigue resistance are remarkably enhanced.

4. Conclusions

The MDF processing of the alloy 1570C at 325 °C up to a total equivalent strain of ε ~12 led to a significant grain refinement with a grain size reduction by an order of magnitude down to the UFG range. The grain size reduction was found favorable for ductility, however the Hall-Petch strengthening was simultaneously compensated by softening of the materials resulted from a decrease in the disperse strengthening due to the TM aluminides coagulation. The TMP, involving hot MDF followed by room temperature straining, led to remarkable strengthening of the alloy, which was primarily caused by work-hardening and associated with the dislocation accumulation and the evolution of dislocation structures. The TMP comprising MDF and cold rolling is found preferable for the enhancement of both the static and dynamic properties of the alloy. The observed effect is explained by the formation of a uniform UFG structure with retained strain hardening ability and ductility, which appears to be in sharp contrast with the severely work hardened and brittle nanostructure obtained by hot MDF and cold HPT.

Acknowledgments

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