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Effects of non-isothermal annealing on microstructure and mechanical properties of severely deformed 2024 aluminum alloy

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Abstract: Microstructure and mechanical properties of AA2024 after severe plastic deformation (SPD) and non-isothermal annealing were investigated. The non-isothermal treatment was carried out on the severely deformed AA2024, and the interaction between restoration and precipitation phenomena was investigated. Differential scanning calorimetry, hardness and shear punch tests illustrate that static recovery and dissolution of GPB zones/Cu−Mg co-clusters occur concurrently through non-isothermal annealing. Scanning electron microscope and electron backscatter diffraction illustrate that non-isothermal annealing of deformed AA2024 up to 250 °C promotes the particle-free regions and also particle stimulated nucleation. Results show that through heating with the rate of 10 °C/min up to 250 °C, the ultimate shear strength and the hardness are maximum due to the presence of *S′*/*S* phases which have been detected during non-isothermal differential scanning calorimetry experiment. Also, recrystallization phenomenon occurs in temperature range which includes the dissolution of *S′*/*S* phases. The concurrent recrystallization and dissolution of *S′*/*S* phase at 380 °C have been verified by differential scanning calorimetry, mechanical properties, and optical microscope.

Key words: AA2024 alloy; severe plastic deformation; non-isothermal annealing; microstructure; mechanical properties

1 Introduction

Interest in the production of ultra-fine grained bulk metals through severe plastic deformation processes has been grown in the last decades [1]. Multi-directional forging (MDF), as a severe plastic deformation method, can be used to produce ultra-fine grained bulk metals [1]. KIM et al [2] investigated the low temperature ageing effects on the mechanical properties of AA2024 alloy after equal channel angular pressing (ECAP). Their research illustrated that solution treatment prior to ECAP and post low temperature ageing improved the strength and the ductility of equal channel angular pressed AA2024 alloy. The dissolution of second phase during severe plastic deformation can occur and this can change the ageing behavior of aluminum alloy [3]. MURAYAMA et al [3] investigated the dissolution behavior of θ' phases during ECAP in Al−Cu binary alloy. Also, LIU et al [4] measured the dissolution content of θ' in Al−Cu during ECAP and MDF processes. Their results suggested that θ' phase in the multi-directional forged sample dissolved more rapidly than that in the equal channel angular pressed sample and they attributed this difference to stress state between ECAP and MDF. KANG et al [5] studied the initial heat treatment effect on the mechanical properties of equal channel angular pressed AA2024. They demonstrated that the hardness of equal channel angular pressed samples in super saturated solid solution AA2024 alloy is higher than that of equal channel angular pressed samples in peak-aged and over-aged conditions and this is due to the dynamic precipitation occurrence during ECAP [5].

However, many works have been carried out on the isothermal annealing of severely deformed metals and alloys, and most of the heat treatments performed on the age hardenable aluminum alloys after severe plastic deformation are isothermal [6−11]. For example, LEE et al [12] illustrated that by severe plastic deformation and isothermal annealing at 373 K, AA7075 could achieve the ultimate tensile strength of ~600 MPa. Furthermore, in Al−4%Cu (mass fraction) alloy after high pressure torsion (HPT) and annealing at 353 K, the strength is further improved, but the thermal stability of HPT-processed sample is unsatisfactory because of fast

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precipitation [13]. Through non-isothermal heat treatments, the samples experience a non-isothermal cycle before the temperature reaches the target temperature. Thus, the behavior of materials before reaching isothermal temperature is important and must be known, especially for severely deformed materials in which the precipitation and restoration phenomena may occur at higher kinetics. HUANG et al [14,15] studied the effect of microchemistry of Mn and the concurrent precipitation during non-isothermal annealing and two-stage annealing on the microstructure and the mechanical properties of cold-rolled Al−Mn−Fe−Si. They found that the nucleation and growth of grains strongly depend on the microchemistry and annealing temperature. The heating rate effect on the recrystallization and concurrent precipitation in Al−Mn alloy was investigated by HUANG and MARTHINSEN [16] and it was found that increasing the heating rate leads to finer grain size, and the dominant texture component depends on the concurrent precipitation which is defined by heating rate. During welding, the materials also experience the non-isothermal condition. GENEVOIS et al [17] investigated the precipitation and mechanical behavior of AA2024 alloy during friction stir welding (FSW) in which the temperature history and deformation rate in weld zone are varied. By quantification of the microstructure, they developed a model for yield strength evolution during welding. Non-isothermal ageing differs in a number of ways from the classically studied isothermal precipitation: 1) during non-isothermal ageing, all parameters such as nucleation barriers and driving force of diffusion are evolved simultaneously. Thus, precipitates which nucleate at a given time step may be unstable in the next time step; 2) the nature and composition of phases may change with temperature during non-isothermal ageing, and 3) depending on the temperature history, nucleation sites may have limited stability, this is important when precipitates form on the pre-existence precipitates or clusters which may dissolve during heating ramps [18,19]. In addition to precipitation phenomena, restoration phenomena, recovery and recrystallization can occur in severely deformed aluminum alloy during non-isothermal annealing. Thus, it is necessary to investigate the interaction between restoration and precipitation phenomena which occur during non-isothermal annealing. In non-isothermal experiment, heating rate is one of the important parameters which influences the precipitation, recovery and recrystallization phenomena [20]. For instance, a research carried out on the AA6061-T4 illustrated that heating rate increasing shifts the peak ageing temperature to the higher temperatures and the maximum hardness is decreased due to the formation of coarse β'' at high temperatures [21]. The similar results were reported by DAOUDI et al [22] in Al−Mg−Si alloy.

Since there are limited studies on the non-isothermal annealing of severely deformed age hardenable aluminum alloys, in this research, the non-isothermal annealing of severely deformed super saturated aluminum alloy 2024 is investigated, and the interaction between recovery, recrystallization and precipitation phenomena is studied.

2 Experimental

The chemical composition of 2024 aluminum alloy used in this research is given in Table 1. The rectangular cubic samples with initial dimensions of 10 mm × 10 mm × 15 mm were cut from cold-rolled billet (Fig. 1). In order to reduce the dislocation density from manufacturing history of the alloy, isothermal annealing was carried out at 420 °C for 2.5 h in the electrical furnace and then cooled to room temperature in the furnace. The samples were solution-treated at 495 °C for 1.5 h following by room temperature water quenching. To inhibit natural ageing, just after the solution treatment, the two-dimensional multi-directional forging was carried out on the samples at room temperature. In plane or two dimensional multi-directional forging, the compression force was applied only on two specific planes. In the first stage or pass of MDF, the compression force was applied on the first plane and in the next pass

Table 1 Chemical composition of investigated AA2024 alloy (mass fraction, %)

Al	Si	Fe	Cu	Mn
Base	0.112	0.348	3.86	0.449

Mg	Cr	Ni	Zn
1.23	0.0195	0.0172	0.297

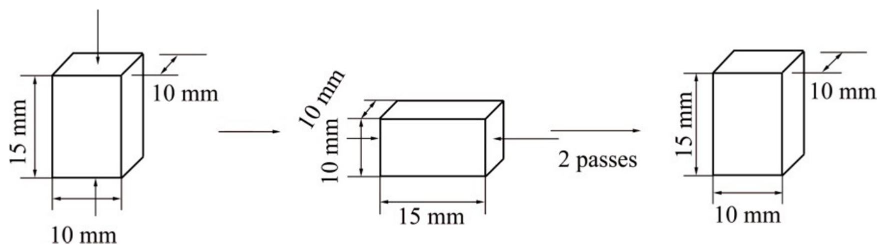

Fig. 1 Schematic of MDF process