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Impact of rotary swaging and age hardening on mechanical properties of EN AW 2024

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ABSTRACT

Purpose: Invention of severe plastic deformation methods led to increased interest in ultra-fine grained materials. The hardenable aluminium alloys were extensively studied in the last decade. It was revealed that combination of severe plastic deformation and age hardening can significantly improve the material properties of these alloys. In this article we performed such progressive thermo-mechanical treatment and following mechanical testing and metallographic analysis. The aim was to evaluate the influence of this treatment on mechanical properties, mostly the effect of various age hardening temperatures and time. Aluminium alloy EN AW 2024 was chosen for the experimental procedures. Impact of processing parameters on mechanical properties was determined by tensile testing. Metallographic analysis was used for evaluation of the straining influence on grain morphology. In the conclusion we denoted significant strain hardening effect, present shear bands and change in aging kinetics.

Design/methodology/approach: The experimental material was processed by progressive thermo-mechanical treatment. The evaluation was performed by simple tensile testing and light microscopy. The first conclusions were derived from determined mechanical properties and based on similarities in available publications with related topic.

Findings: The research results roughly confirm the recovery-precipitation complementary effect, observed in other hardenable aluminium alloys or the same hardenable alloy deformed by other SPD technique. The impact of both parts of processing – deformation and age hardening on mechanical properties was evaluated.

Research limitations/implications: Future detailed investigation of secondary phase particles and dislocation-precipitate interaction should be performed. This investigation was not performed as it requires transmission electron microscopy.

Originality/value: The paper contains first impression on promising SPD technique. As the technique appeared only recently, very few articles were published, considering few light alloys. The paper can help to set parameters for other researchers in this field and promote commercialization of this progressive thermo-mechanical processing

Keywords: Strain hardening; Age hardening; Rotary swaging; EN AW 2024; Mechanical properties

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PROPERTIES

1. Introduction

In last decades various methods of severe plastic deformation (SPD) were widely used for improvement of material properties in pure metals and their alloys [1-6]. One of the aims in this field is the commercialization of the procedures. Recently introduced rotary swaging [7-12] can be considered as one of methods available for commercial production.

In single-phase alloys the strengthening through SPD is a result of grain refinement and increase of dislocation density only. However, in multi-phase systems, such as hardenable alloys the final properties depend on interaction of secondary phase particles or alloying elements with lattice defects. The available studies of hardenable aluminium alloys [13-25] suggest that introduction of severe plastic deformation between quenching and artificial aging might result in both - strengthening and increase of ductility. This is due to the complementary effect of precipitation hardening and strain hardening from SPD. The results as well suggest decrease of processing time and necessary lower aging temperature. The faster precipitation kinetics is a result of increased dislocation density, the lower temperature is required mostly due to the structural recovery during artificial aging.

Although for detailed investigation of these phenomenon (microstructure evolution, precipitate identification and precipitate-dislocation interaction) transmission electron microscopy is necessary, valuable information can be derived as well by simple methods, such as mechanical testing and light microscopy. Moreover, these methods can be used for simple estimation of suitable processing parameters.

2. Experimental description

Rods of alloy EN-AW 2024 with length 1 m and diameter of 12 mm were used for the experimental procedure. Chemical composition of the alloy is visible in Table 1.

Table 1.
Chemical composition of the experimental alloy (wt.%)

Si	Fe	Cu	Mn	Mg
0.047	0.074	4.206	0.465	1.349

The alloy was solution treated (SA) at 520°C for 1 hour and water quenched (Q). Then rotary swaging (RS) was performed. For comparison to the heat treatment, some rods were not swaged, but stored during the time necessary for this operation. The diameter of deformed rods was reduced from 12 mm to 10 mm with processing rate 3m/minute. After this procedure surface temperature of the processed rod was measured with thermometer. Temperature increase to 80°C was recorded. All samples were then subjected to artificial aging at various temperatures (120°C and 160°C) for various times (1, 24, 48 and 72 hours). After artificial aging tensile specimen were produced. Testing was performed 24 hours after aging. Schematic representation of the processing is visible in Fig. 1.

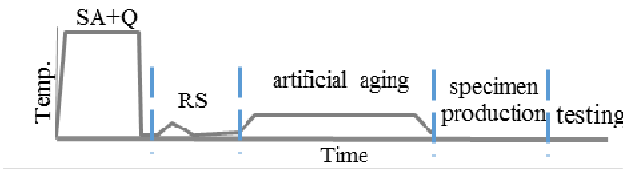

Fig. 1. Schematic representation of alloy processing

Threaded cylindrical specimens (M8) with gage length of 25mm and diameter of 5mm were produced for tensile testing. Length change was measured with strain gauge clip-on extensometer. Yield strength (YS), ultimate tensile strength (UTS), total elongation (TE) and uniform elongation (UE, elongation up to UTS) were determined from the stress-strain data. According to the material behaviour the yield strength was determined as 0.2% proof stress.

Metallographic analysis was performed in light microscope. The samples were cold embedded and after preparation the anodization (J=0.2 A/cm^2 for 60 s) in Baker's reagent (5ml HBF4+200ml. H_2O) was performed. The observations were performed in polarised light mode. Longitudinal sections were observed.

3. Results

3.1. Tensile testing

RS results in strengthening of the processed alloy (Fig. 2, Table 2), with yield strength increase by 56% and ultimate strength increase by 21% in comparison to the non-deformed specimen. However the ductility decreses. Artificial aging results in strengthening of both deformed and non-deformed specimens (Figs. 3 - 4). The strengthening trend differs for each processing parameters. Changes of total elongation and uniform elongation are visible in Fig. 5 and Fig 6.

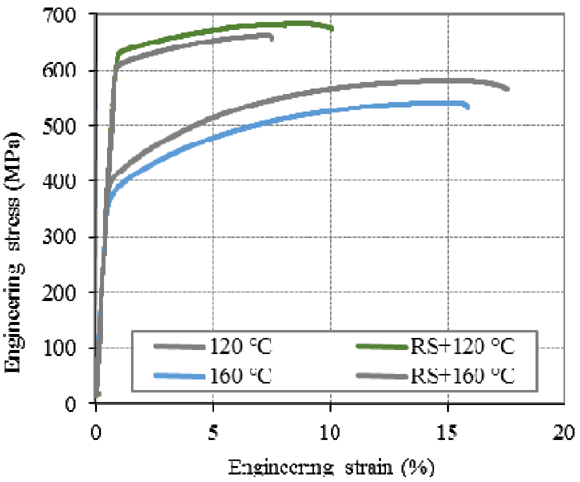

Fig. 2. Strengthening effect of rotary swaging, specimens aged for 1 hour

Table 2
Mechanical properties - comparison of RS and non-deformed specimens after 1 hour of aging and in peak condition

Specimen	YS [MPa]	UTS [MPa]	UE [%]	TE [%]
120 °C, 1 h	404	579	14.6	21.1
F+120 °C, 1 h	630	683	7.9	14.3
160 °C, 1 h	375	541	14.4	18.6
F+160 °C, 1 h	609	662	6.4	8.2
120 °C, 48 h	384	545	9.8	9.9
F+120 °C, 48 h	697	706	5.0	8.8
160 °C, 24 h	425	592	13.8	16.7
F+160 °C, 24 h	650	673	1.6	3.4

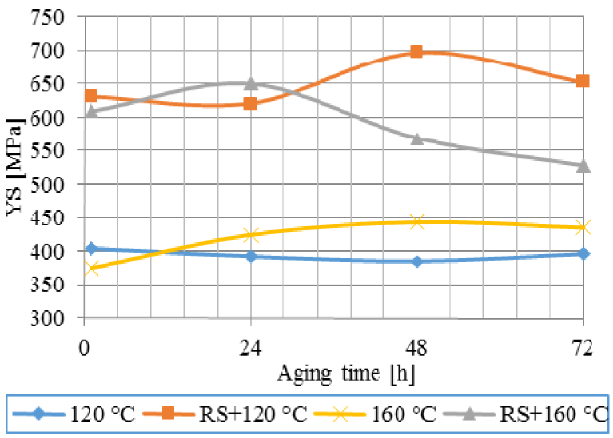

Fig. 3. Influence of aging time and temperature on yield strength

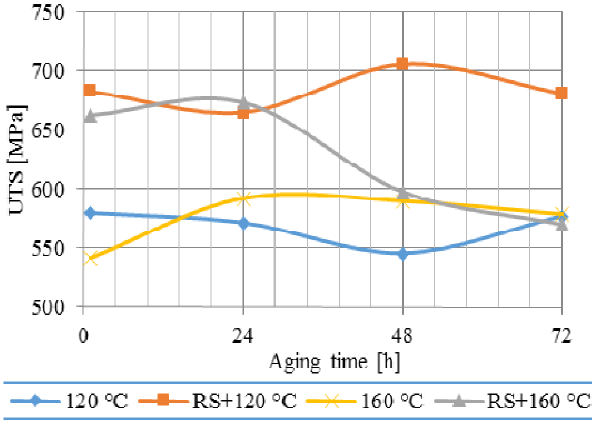

Fig. 4. Influence of aging time and temperature on ultimate tensile strength

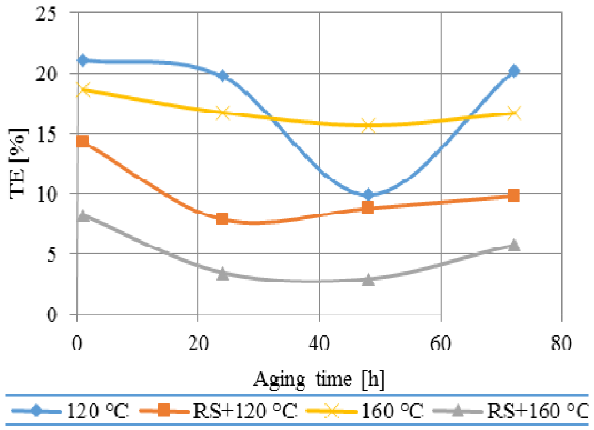

Fig. 5. Change of total elongation with aging time for 120°C and 160°C

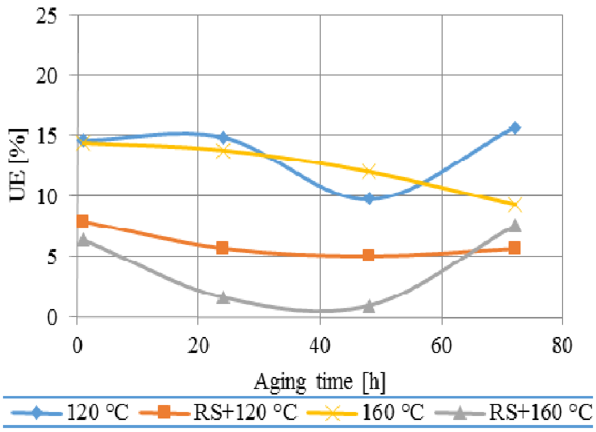

Fig. 6. Change of uniform elongation with aging time for 120°C and 160°C

3.2. Metallographic analysis

The grain size, distribution and orientation are visible in Fig. 7 to Fig. 10. In the RS specimens shear bands (slip lines) were observed across (Fig 9) and inside (Fig 10) of the grains.

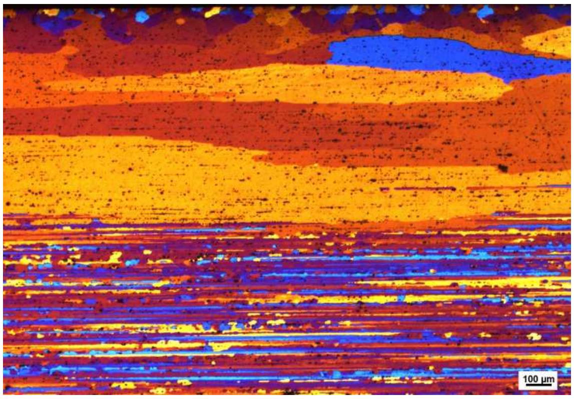

Fig. 7. Microstructure of non-deformed specimen (120°C, 1h), 50x magnification, longitudinal section near surface

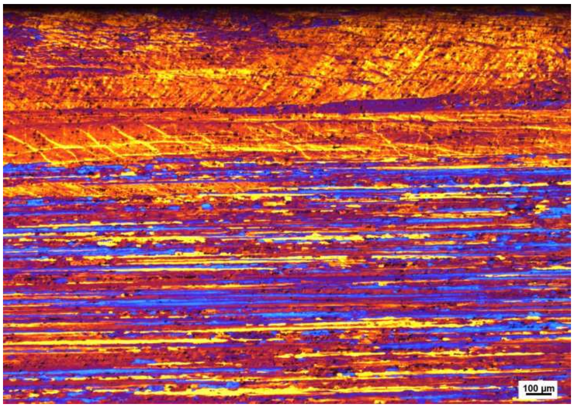

Fig. 8. Microstructure of RS specimen (RS+160°C, 1h), 50x magnification, longitudinal section near surface

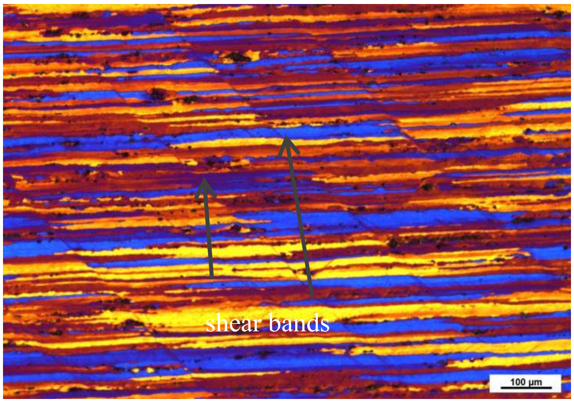

Fig. 9. Shear bands across the grains, RS specimen (RS+120°C, 1h), 100x magnification, longitudinal section in the centre

Fig. 10. Detailed view of shear bands in the grains, RS specimen (RS+160°C, 1h), 500x magnification, longitudinal section in the centre

The microstructure of both - RS and non-deformed, specimens consists of elongated grains with moderate distribution of recrystallized grains.

4. Discussion

The strengthening due to the SPD processing is evident and was expected. Due to intensive strain shear bands are formed in and across the grains. The shear bands are in 45° angle to the longitudinal direction. The diameter reduction and intensive straining resulted in thinning and shearing of the surface layer (Fig. 7 in comparison to Fig 6). The recrystallized fine grains were formed prior to aging (e.g. during solution annealing) and their possible elongation due to the RS was not studied. The grain size was not evaluated as well, although due to the appearance of the shear bands very fine microstructure can be expected. This is suggested as well by the mechanical properties, typical for the SPD material with ultrafine-grained structure.

Further strengthening of RS specimens during artificial aging suggests precipitation hardening or diffusion of the solute atoms to the dislocations. From comparison of the YS trend lines for each temperature we can observe faster strengthening of RS specimens. This can be a result of faster aging kinetics due to the increased dislocation density or different precipitate type and morphology. The strength decrease (YS and UTS) in RS specimens is either an effect of structural recovery or overaging. The increase of total elongation in RS specimens (Fig. 5) suggests as well decrease of lattice defects density. Such behaviour would be in a good agreement with available results [21, 23, 24].

The RS and artificial aging at 120°C results in higher strength and elongation than the one aged at 160°C, although longer aging time is necessary for reaching of these properties (Table 2, Fig. 5, Fig 6). The different strengthening trend is in good agreement with the available studies [12-22], where lower aging temperature in comparison to conventional aging temperature was suggested.

5. Conclusions

The alloy EN AW 2024 was processed by progressive themo-mechanical treatment (rotary swaging and age hardening). The first conclusions were derived from tensile tests and light microscopy. This allows focusing only on some specific specimens during further, more precise investigation.

From the stress-strain curves and determined mechanical properties we concluded:

RS results in significant strengthening response in solution treated and quenched aluminium alloy EN/AW 2024 (YS after RS and 1 hour aging at 120°C was 630MPa, which is 156% of the non-deformed specimen).

Additional strengthening is possible through artificial aging at 120°C and 160°C.

The age hardening after RS results in ductility decrease.

Peak strength (YS, UTS) of RS specimens was reached after 48 hours for 120°C (697 and 706MPa) and 24 hours for 160°C (650 and 675MPa).

The specimen peak aged at 120°C possesses higher strength and ductility than the one aged at 160°C.

Metallographic investigation revealed that:

Microstructure after solid solution annealing and quenching consists of elongated grains with moderate amount of fine recrystallized grains.

Elongated grains are sheared during RS.

The shear bands are present not only inside but as well across the grains

The shear bands are in 45°degree to the longitudinal direction.

More precise metallographic investigation (transmission electron microscopy) of chosen specimens will be used for confirmation of discussed strengthening mechanisms during age hardening and precipitate characterization. The influence of different grain size on material homogeneity will be evaluated by hardness measurements and miniature specimen tensile testing.

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