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Original scientific paper

INVESTIGATION OF THE INFLUENCE OF RESIDUAL STRESSES ON THE MECHANICAL PROPERTIES OF ALUMINUM ALLOY STRIPS

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Abstract
In the paper, the influence of residual stresses on the mechanical properties of cold-rolled strips made from 2024 and 5083 alloys was investigated. The relatively low values of residual stresses (≤ 75 MPa) and the large number of influencing parameters make it difficult to precisely determine their impact on mechanical properties. The initial material properties, deformation hardening, and relaxation parameters have a significantly greater influence than the values and distribution models of residual stresses. It is reasonable to assume that the effect of residual stresses is manifested only at the onset of plastic flow and is limited to 5–10% of the total energy accumulated during plastic deformation.

***Keywords**: 2024 and 5083 alloys, residual stresses, mechanical properties*

1. INTRODUCTION

Previous research has shown that residual stresses can significantly affect the behavior of metal parts during processing and exploitation [1, 2]. To analyze these phenomena, modeling of the residual stress distribution across the cross-section of the part and the effects of superposition with external loads is applied, based on which correlations with mechanical properties are derived [3].

In the process of cold rolling of strips, a plane state of residual stresses is induced, with stress components in the longitudinal (rolling) direction and transverse direction. The longitudinal residual stresses have a dominant influence on the appearance and properties of the strips [4].

In this paper, the influence of longitudinal residual stresses on the mechanical properties of strips made from aluminum alloys 2024 and 5083 was analyzed. Alloys 2024 and 5083 are widely used in the aerospace and automotive industries for component production. A significant number of these components are manufactured through cold rolling. The investigation was conducted on samples in cold-rolled, mechanically relaxed, and thermally relaxed states.

2. EXPERIMENTAL

For the investigation, commercial aluminum alloys 2024 and 5083 were selected. The starting materials for both alloys were 1.28 mm thick sheets in the annealed condition. Samples for rolling were cut from these annealed sheets. These samples were cold rolled with reduction rates of 20% and 50% in a single pass on a laboratory duo rolling mill.

One part of the cold-rolled samples was subjected to mechanical relaxation of residual stresses through uniaxial tension with a plastic deformation degree of 0.66÷1.1%. The other part of the cold-rolled samples underwent thermal relaxation of residual stresses under the conditions of 140°C/5 min for alloy 5083 and 130°C/5 min for alloy 2024. The relaxation temperature was chosen from the lower range of the recovery temperature interval (0.25÷0.3)·T_{melt}, which enables relaxation effects up to 75% [5].

Tensile testing for all conditions was conducted on a universal testing machine type FPZ/100 and included the determination of yield strength ($R_{p0.2}$), tensile strength (R_m), and total elongation (A), as well as the construction of strain-hardening curves.

Residual stresses were measured using the deflection method. This method is based on disturbing the stress balance by removing metal layers from one side of the sample and subsequently measuring the resulting elastic line. The equation for the calculation of the residual stresses is derived from the equality of the moment load from the residual stresses and the equivalent external moment load corresponding to the given elastic line model. A detailed description of the procedure is given in a previous study [6].

3. RESULTS AND DISCUSSION

Longitudinal residual stresses in flat-rolled strips have an approximately linear distribution across the cross-section, with tensile stresses in the surface layers, compressive stresses in the central layers, and maximum value at the surface of the strip (Figure 1) [6]. Under external loading, for mechanical behavior, the resultant load of the effective external and effective residual stress is relevant. According to this model, residual stresses represent a pre-load that affects the resultant stress, and consequently, the onset of plastic flow as well as other mechanical properties.

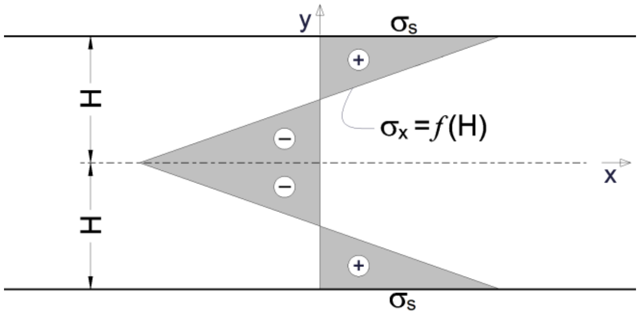

Figure 1. Model of longitudinal residual stress distribution across the strip thickness

Figures 2a and 2b show the experimental strain hardening curves for all tested conditions in both alloys. The recognizable influence of deformation processes (cold rolling, mechanical relaxation) and thermal treatments on the yield stress and the course of strain hardening curves is clearly visible. Table 1 presents the results of mechanical properties testing, average values of residual stresses (σ_s), and approximations of strain hardening curves using the Ludwik equation:

$$\sigma = \sigma_0 + K \cdot \varphi^n \tag{1}$$

where: σ - yield stress, σ_0 - experimentally measured initial value of yield stress, K - strength coefficient, and φ - true logarithmic strain in tension, n - strain hardening exponent.

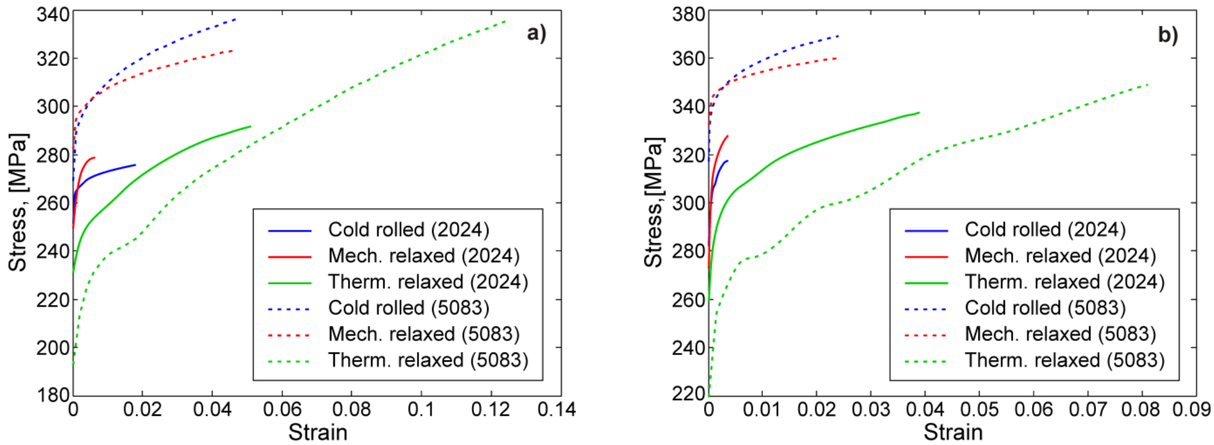

Figure 2. Stress-strain curves for conditions with reduction ratios of 20% (a) and 50% (b)

In processes involving strain hardening, a large number of influential parameters complicates the precise analysis of the impact of residual stresses on mechanical characteristics. The initial properties of the material, strain hardening, type of loading, and relaxation conditions have a significantly greater influence than the value and distribution model of residual stresses [7]. This is particularly evident in cold-rolled strips of the tested alloys where residual stresses reach relatively low values of up to 75 MPa [6].

Table 1. Mechanical properties, strain hardening curve equations, and average values of residual stresses

States	ε [%]	Mechanical properties			$\sigma = \sigma_0 + K \cdot \varphi^n$, [MPa]	σ_s [MPa] [6]
		$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]		
Alloy 2024						
Cold rolled	20	267.05	273.34	2.62	$\sigma = 251.14 + 55.41 \cdot \varphi^{0.203}$ (± 0.3)	36.2
MR ($\varphi_t = 0.66$ %)	20	270.43	273.76	2.34	$\sigma = 250.97 + 468.34 \cdot \varphi^{0.528}$ (± 1.2)	0
TR (130°C/5 min)	20	243.11	277.94	5.22	$\sigma = 231.80 + 265.42 \cdot \varphi^{0.492}$ (± 1.0)	28.3
Cold rolled	50	312.97	317.37	1.10	$\sigma = 286.65 + 445.37 \cdot \varphi^{0.469}$ (± 1.1)	31.8
MR ($\varphi_t = 0.47$ %)	50	321.76	324.16	1.25	$\sigma = 279.97 + 872.97 \cdot \varphi^{0.489}$ (± 2.0)	0
TR (130°C/5 min)	50	294.43	324.85	3.87	$\sigma = 262.61 + 251.74 \cdot \varphi^{0.352}$ (± 3.0)	25.2
Alloy 5083						
Cold rolled	20	290.64	318.54	5.44	$\sigma = 269.34 + 179.36 \cdot \varphi^{0.323}$ (± 2.3)	68.5
MR ($\varphi_t = 1.10$ %)	20	298.16	312.32	5.47	$\sigma = 282.69 + 107.98 \cdot \varphi^{0.318}$ (± 0.9)	0
TR (140°C/5 min)	20	212.70	297.73	12.68	$\sigma = 194.01 + 357.09 \cdot \varphi^{0.459}$ (± 2.3)	25.3
Cold rolled	50	345.35	355.42	1.81	$\sigma = 317.23 + 131.03 \cdot \varphi^{0.248}$ (± 0.8)	40.8
MR ($\varphi_t = 0.72$ %)	50	345.63	354.43	2.75	$\sigma = 331.45 + 72.51 \cdot \varphi^{0.260}$ (± 0.9)	0
TR (140°C/5 min)	50	258.39	323.81	8.13	$\sigma = 222.75 + 303.26 \cdot \varphi^{0.357}$ (± 2.1)	15.5

ε - reduction ratio; MR - mechanically relaxed; φ_t - deformation degree during mechanical relaxation; TR - thermally relaxed; σ_s - average values of residual stresses.

By comparing the values of mechanical properties for rolled and mechanically relaxed states, data on the impact of relaxation by uniaxial tension and residual stresses on the mechanical characteristics of cold-rolled strips can be obtained. Previous research has shown that residual stresses are fully relaxed at very low degrees of tensile deformation (0.5÷1.1%) [5]. Experimental results show small differences in mechanical properties between cold-rolled and mechanically relaxed states (Table 1). Therefore, it is reasonable to assume that the influence of residual stresses is manifested only at the onset of plastic flow, while other changes in the stress-strain curves are a consequence of initial differences and deformation changes during previous tensioning.

If the degree of tensile deformation (φ_t) of rolled strips is inserted into the Ludwik equation for the rolled state and the stress value σ is calculated, then this value should be comparable to the experimentally determined value of the yield stress ($\sigma_{0(MR)}$) in the mechanically relaxed state. The obtained results with differences expressed in absolute and relative terms are shown in Table 2. The calculated values of yield stress (σ) in all cases are higher than the experimentally measured ones ($\sigma_{0(MR)}$), and the differences ($\Delta\sigma$) are within the range of residual stress variations. These results suggest that the influence of residual stresses can be associated with residual elastic energy, which amounts to 5÷10% of the total energy required for deformation.

During thermal relaxation, when the minimum temperature required for thermally activated processes is achieved, the release of energy accumulated during deformation occurs. This is accompanied by the relaxation of residual stresses as well as the softening of the metal. The degree of recovery that can be achieved decreases with increasing previous deformation, and increases with increasing temperature and annealing time. As a result of low-temperature recovery, changes in the yield strength are limited to 10% for the 2024 alloy and 27% for the 5083 alloy, compared to the rolled state.

Table 2. Relationship between calculated and measured yield stress values for mechanically relaxed states

Alloy / state	φ_t	$\sigma = \sigma_0 + K \cdot \varphi_t{}^n$ [MPa]	$\sigma_{0(MR)}$ [MPa]	$\Delta\sigma = \sigma - \sigma_{0(MR)}$ [MPa]	$\Delta\sigma/\sigma$ [%]
2024 / rolled 20%	0.0066	271.1	250.97	20.13	7.4
2024 / rolled 50%	0.0047	322.7	279.97	42.73	13.2
5083 / rolled 20%	0.0110	311.2	282.69	28.51	9.2
5083 / rolled 50%	0.0072	355.7	331.45	24.25	6.8

Relaxation of residual stresses under the same conditions amounts to an average of 21% for the 2024 alloy and 63% for the 5083 alloy (Table 1). It is evident that the ~3 times greater softening and relaxation of residual stresses in the 5083 alloy compared to the 2024 alloy are the consequences of the selected annealing temperature and the more intense occurrence of thermally activated processes in the 5083 alloy. Namely, in these time-temperature conditions, the effects of the recovery of the deformed structure are limited. In alloy 2024, changes occur in the content and size of precipitates (artificial aging), the presence of which has a strengthening effect. On the other hand, in alloy 5083, there is a redistribution of the phases of the alloying elements so that a more homogeneous microstructure is created, which results in an increase in ductility. Since the relaxation of residual stresses under the selected conditions is not complete, especially for the 2024 alloy, the analysis of its impact on mechanical properties is also more challenging. However, it can be confidently stated here that the reduced yield strength primarily arises from softening caused by the thermal activation of structural mechanisms, and to a lesser extent, from the relaxation of residual stresses. Such changes are also reflected in the entire course of the strain-hardening curves (Figures 2a and 2b).

4. CONCLUSION

The research has demonstrated that the influence of residual stresses on the mechanical properties of cold-rolled strips must be considered in the context of the material type, strain hardening, and relaxation conditions. The derived model shows minor differences in mechanical properties between the cold-rolled and mechanically relaxed states, indicating that the effect of residual stresses manifests only at the onset of plastic flow and is limited to 5÷10% of the total energy accumulated during plastic deformation. During low-temperature recovery, the effects of residual stress relaxation on mechanical properties are negligible compared to structural effects. These findings may contribute to the optimization of post-deformation treatments in industrial rolling processes.

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