EXPERIMENTAL INVESTIGATION OF NOTCH SENSITIVITY OF THERMOMECHANICALLY TREATED ALUMINIUM ALLOY

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ABSTRACT

A thermomechanically treated aluminium alloy containing 4.5% Cu, 0.6% Mn, 0.6% Mg and 0.4% Si has been experimentally investigated with regard to its notch sensitivity. The thermomechanical treatment consisted of quenching and ageing with different periods of precipitation, and different degrees of a cold plastic deformation afterwards. Five series of smooth and notched specimens were tested on a standard tensile machine and fracture surface were studied by TEM replicas. The Notch-Yield Ratio (NYR) and the fracture appearance were used as a measure of the notch sensitivity. It was found that certain thermomechanical treatments cause notch sensitivity and brittle fracture of notched specimens, even in the case of the low value of $\sigma_{0,2}/\rho$ ratio. Thermomechanical treatment consisting of 120 minutes precipitation and 30% or 40% deformation degree of cold rolling deformation can be recommended as the most suitable for structural application.

KEYWORDS

Aluminium alloy, Thermomechanical treatment, Notch sensitivity, Notch Yield Ratio (NYR), Structural changes, Dislocations

INTRODUCTION

Thermomechanically treated aluminium alloys are used as a structural material due to their high strength-to-density ratio. The notch sensitivity, i.e. the notch toughness, has not yet been thoroughly investigated for a variety of thermomechanically treated states of aluminium alloys, in the first place because of ratio $\sigma_{0,2}/\rho$ being lower than 180, the recommended value by ASTM E-338/68. However, even with significantly lower values of this ratio, certain thermomechanical treatment can increase notch sensitivity due to the structural changes and the high degree of cold plastic deformation, possibly inducing brittle fracture. Therefore, this paper presents the results of notch sensitivity of the selected aluminium alloy in a different thermomechanically treated states, chosen in accordance with previous investigation of the first author, Šijački-Žeravčić, 1983.

EXPERIMENTAL PROCEDURE

An aluminium alloy containing 4.5% Cu, 0.6% Mn, 0.6% Mg and 0.4% Si is investigated. After the previous treatment consisted of homogenization, hot rolling and machining, the alloy has been thermomechanically treated according to the scheme shown in Fig. 1. Thermal treatment was performed in a salt bath (solid solution) and in an oil bath (ageing), using different ageing periods 1, 10, 60 and 120 minutes. The cold plastic deformation was performed by rolling with different deformation degrees : 10%, 30%, 40% and 70%. The mechanical schedule of deformation process was defined by the ratio $l/\bar{h}=2$, where l is a projected lenght of a contact between roller and material, $\bar{h}$ is the mean value of a specimen thickness, and by the deformation rate $v=0.73s^{-1}$.

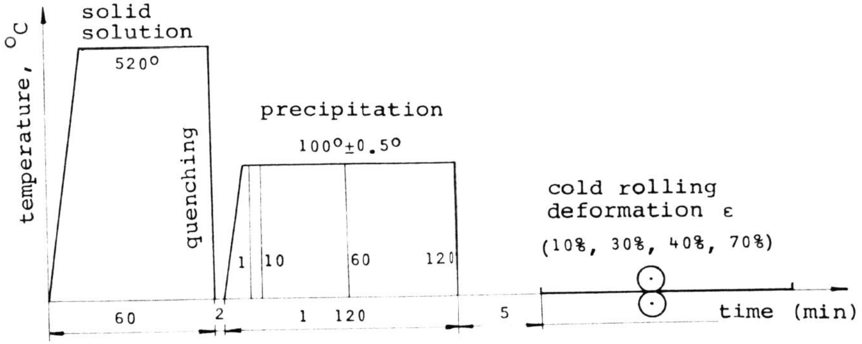


Fig. 1 Scheme of thermomechanical treatment

Both smooth and notched specimens were cut out from the strips in the rolling direction. The shape and the dimensions of specimens are shown in Fig. 2. The thickness of 0.5 mm, adopted here in order to maintain the same conditions as in the previous investigation, Šijački-Žeravčić, 1983, is slightly lower than minimum thickness (0.6 mm) required by ASTM E-338/68 Standard.

All experiments were carried out using a standard tensile machine.

ANALYSIS OF THE RESULTS

There are five series of differently thermomechanically treated specimens. I series contains only thermally treated specimens and the four other series are characterized by a different periods of precipitation (II series - 1 minute, III series - 10 minutes, IV series - 60 minutes and V series - 120 minutes), having the same degree of cold plastic deformation : 10%, 30%, 40% and 70%. Table 1 shows the results for smooth specimens (Yiels Strength), notched specimens (Sharp-Notch-Strength), the Notch-Yield-Ratio (NYR) and Yield Strength-to-Density ratio.

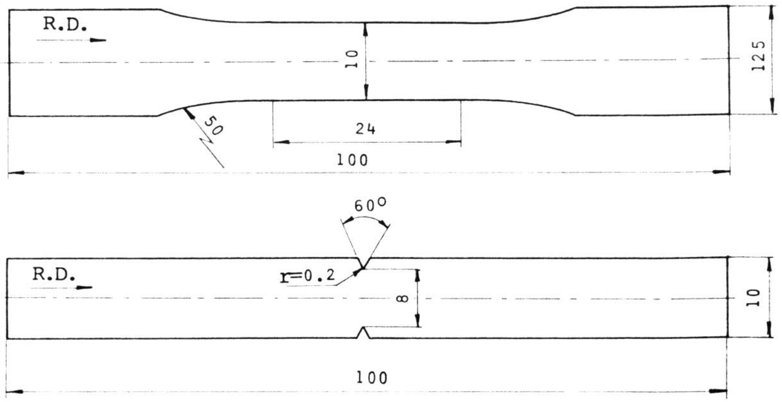


Fig. 2 Shape and dimensions of specimens

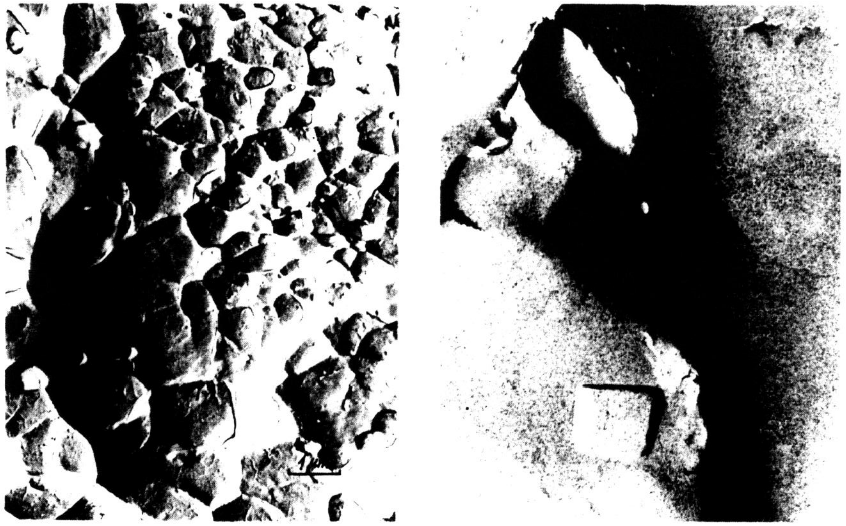
TABLE 1 Results of Testing the Smooth and Notched Specimens

Series	Thermomechanical treatment (°C-minutes-%)	Yield Strength (MPa)	Sharp-Notch Strength (MPa)	NYR (-)	Yield Strength-to-Density Ratio (MPa/g/cm^3)
I	100-1	299	452.5	1.51	99.7
	100-10	313.5	392	1.25	104.5
	100-60	289	428	1.48	96.3
	100-120	264	337	1.28	88
II	100-1-10	345	359	1.04	115
	100-1-30	423	494	1.17	141
	100-1-40	438	431	0.98	146
	100-1-70	483.5	334	0.79	161.1
III	100-10-10	332.5	360	1.10	110.8
	100-10-30	447	264	0.59	149
	100-10-40	505	350	0.69	168.3
	100-10-70	525	212	0.40	175
IV	100-60-10	356	128	0.36	118.7
	100-60-30	432	330	0.76	144
	100-60-40	480	322	0.67	160
	100-60-70	517	388	0.75	172.3
V	100-120-10	278	356	1.28	92.7
	100-120-30	444	525	1.18	148
	100-120-40	482	540	1.12	160.7
	100-120-70	484.5	467	0.96	161.5

The results indicate a high value of NYR for I series of specimens and a low value of yield strength. The NYR values decrease as a function of the deformation degree increase (except for 10% of deformation) for the specimens from II series previously precipitated 1 minute as well as the NYR lower average value comparing to the corresponding values obtained for I series of specimens. The yield strength increases significantly, proportionally to the deformation degree. III series of specimens, previously precipitated 10 minutes, has a low value of NYR (only with 10% deformation degree NYR is greater than 1), the average value being even lower for the specimens of IV series. The yield strength is slightly higher for both these series comparing with II series.

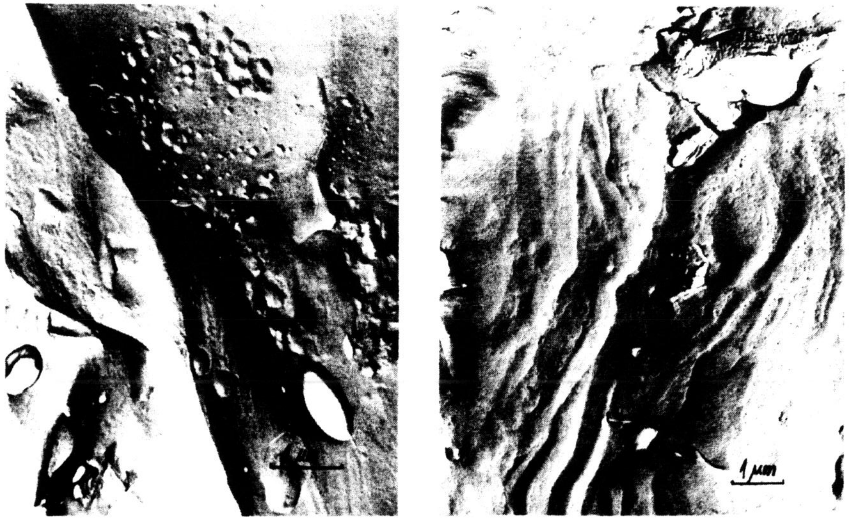
The last series of specimens, previously precipitated 120 minutes, has regained a high notch toughness, what is approved by higher values of NYR (only specimen with 70% deformation degree has NYR slightly below 1). The tendency of decreasing NYR values with increasing deformation degree is obvious in this series, contrary to III and IV series case, where no correlation between them could be established. The yield strength is practically the same as in the previous three series.

The characteristic fracture surfaces of the notched specimens were studied by TEM replicas, shown at Fig. 3a-3f. Figure 3a shows fracture surface of specimen from I series, precipitated 1 minute. A significant amount of plastic deformation is obvious. Next two replicas, Fig. 3b & 3c, are taken from the specimen precipitated 60 minutes and deformed 10%. The appearance of the fracture surface indicates brittle fracture and a certain influence of the precipitated phases. Figures 3d & 3e show fracture surfaces of the specimen from the same series, precipitated 60 minutes and deformed 40% and 70%, respectively. Besides of brittle character of fracture, the effect of deformation degree can be noted. The last replica at Fig. 3f, shows the fracture surface of a 120 minutes precipitated and 10% deformed specimen, which obviously regained capability to deform plastically before fracture.



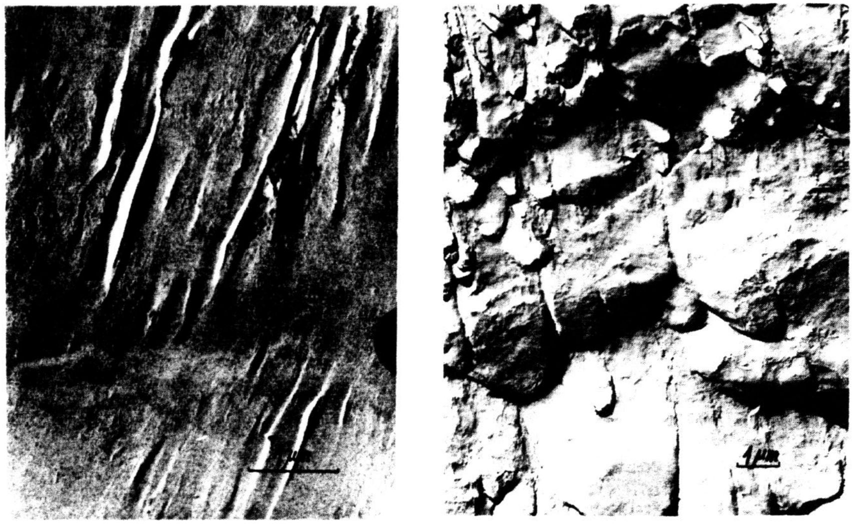
a. precipitation 1 minute b. precipitition 60 min., deformation 10%

Fig. 3 Replicas obtained by TEM (see also the next page)



c. precipitation 60 minutes
deformation 10%

d. precipitation 60 minutes
deformation 40%



e. precipitation 60 minutes
deformation 70%

f. precipitation 120 minutes
deformation 10%

Fig. 3 Replicas obtained by TEM (see also the previous page)

DISCUSSION OF THE RESULTS

According to the literature, Šijački-Žeravčič (1983), Kelly, Nicholson (1973), Humphries (1972) and Lorimer (1972), the low temperature aged aluminium alloy with Cu, Mn, Mg and Si contains clusters, GPI zones, i.e. θ'' phase with nucleation being homogeneous. Due to the cold plastic deformation a combination of precipitation and deformation hardening results in an increase of tensile properties (Yield and Ultimate Strength) and simultaneously in a decrease of ductility and toughness. The change of these properties is a consequence of an interaction of dislocations (introduced by cold plastic deformation) with already formed precipitate, of a selfinteraction of dislocations and of a reaction of dislocations with vacancies and with solute atoms. Depending on the applied thermomechanical treatment, these interactions cause dissolution and cutting of the precipitate, bonding of dislocations to precipitate and heterogeneous nucleation of precipitate on dislocations. Also, because of a growth of solute atoms concentration in the solid solution, there is a decrease of a stacking fault energy, inhibiting cross slip of dislocations, Hu (1974), Goodman & Hu (1968). Such complex structured states cause different behaviour of this alloy in the presence of a stress concentrations.

According to the analysis of the results it is clear that I series of specimens has the highest average value of NYR. Therefore it is obvious that there is no significant increase of notch sensitivity, regardless on certain lattice distortion due to the precipitation of the new phase and thus the appearance of stress concentrations and local stresses, Yokobori (1968). The data for Residual Elastic Strains (RES) are in accordance with this conclusion, Šijački-Žeravčić (1983). In any case, the low yield strength disqualifies this series as a possible structural material.

Specimens of II series, deformed 10%, 30% and 40% have lower value of NYR comparing with appropriate values for I series, but its absolute value is still sufficient. The decrease of its value is the consequence of the cold plastic deformation, which causes not only much higher number of dislocations, but also inhibits their cross slip and enables a partial dissolution of the small GPI zones. Only by introducing 70% deformation degree there is a further decrease of NYR, below the critical value (0.79 comparing with 1), as a consequence of the significant growth of microstresses, causing an additional amount of RES. The significant increase of the RES characterizes the high deformation degree, being the consequence of a strong selfinteraction between dislocations, of an interaction of dislocations with precipitate and of a simultaneously heterogeneous precipitation, as well as of a decrease of the grain size and their preffered orientation. The presence of the high RES caused by high level of plastic deformations is also observed by Šijački-Žeravčić (1983), and certainly results in a decrese of the notch toughness.

Precipitate in specimens of III and IV series has such magnitude and dispersion that dislocations can freely move and cut the precipitate at the same time, see also Yokobori (1968) chapter 8.4. Thus, the RES also increases, causing a further increase of notch sensitivity, in comparison with II series. It should be emphasized here that there is no correlation between NYR and deformation degree, which is probably a consequence of changing the dominance of certain influencing factors.

The last series of specimens is certainly the most interesting one for a structural application because of its high yield strength and satisfactory notch taughness. After 120 minutes of precipitation it is expected that θ' phase is formed, besides of already formed θ'' phase, and therefore, the decrease of RES and much easier cross slip to dislocations. It is obvious that such structural state is less sensitive to notches and other stress concentrators thus exibiting the higher notch toughness. Due to Table 1, the most suitable deformation degree is between 30% and 40%, assuring simultaneously high levels of Yield Strength and notch toughness.

At the end of the discussion it should be added that certain influence on notch sensitivity belongs also to the other phase possibly precipitated during thermomechanical treatment. TEM replicas indicate clearly this effect, specially Fig. 3b, where almost regular quadrant of size less than 1x1 μm, indicate the presence of an incoherent phase of Mn type. Thin foils should be investigated by TEM for a more detailed analysis in this direction.

CONCLUSIONS

According to the analysis and discussion one can conclude :

- The aged state of an aluminium alloy with Cu, Mn, Mg and Si is not sensitive to the stress concentrators, but it provides unsufficient yield strength for structural application.
- Cold plastic deformation influences notch sensitivity drastically, depending on the structural state.
- The lowest notch toughness is observed for the thermomechanical treatment consisting of 100°-10 to 60 minutes- 10%-70%, due to instability and unsuitable combination of their structural components.
- Only the 100°-120 minutes- 30% to 40% treatment satisfies the requirements both for the high yield strength and low notch sensitivity and is recommended for structural application. The yield strength required for structural application is not reached with 10% deformation, and with 70% deformation the gain in yield strength is much lower than the loss in notch toughness. Therefore, neither large (70%), nor small (10%) deformation state can be recommended for a structural application.
- In all tested specimens it is still necessary to check their notch sensitivity, besides the low value of yield strength-to-density ratio, because thermomechanical treatment can increase notch sensitivity of the tested aluminium alloy. This effect is proved here for a certain combination of thermomechanical treatment, not only for low values of NYR, but also, in the absence of plastic deformations before fracture, indicated by TEM replicas of fracture surfaces.

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