

## THE EFFECTS OF TEMPERATURE ON THE STRENGTH PROPERTIES OF ALUMINIUM ALLOY 2024-T3

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**Abstract:** This paper presents results of monotonous tensile tests of 0.16" thick samples made of non-clad plates of aluminium alloy for aircraft purposes 2024-T3. Tests were performed for samples cut out from a sheet plate in two different directions: in the parallel and perpendicular direction to sheet plate rolling direction, for eight different temperature values from the range 25°C – 200°C. The tests were performed using the hydraulic-drive testing machine INSTRON 8502 equipped with thermal chamber. The analysis of results included changes of basic strength-related parameters depending on temperature. It was also observed that the intensity of Portevin-Le Châtelier (PLC) effect depends on the temperature.

**Key words:** Aluminium Alloy 2024-T3, Monotonous Tensile Tests, Elevated Temperature, Portevin-Le Châtelier Effect

### 1. INTRODUCTION

Aircraft structures are particularly sensitive to damage, which may significantly reduce flight safety and, as a consequence, increase probability of a catastrophe posing danger to passenger's and crew's life as well as possible significant material losses. Thus, in that case, it is very important to have the broadest possible knowledge on materials used in such structures, particularly on their strength properties.

Typical materials used for plating of plane and helicopter fuselage, tensioned wing parts, ribs subject to shear as well as any area where appropriate rigidity, high static and fatigue strength is required include aluminium alloy 2024-T3. That alloy may also be used in the area of engines, where high operating temperature occurs – which amounts up to 120°C in case of 2024-T3 alloy – (acc. to ALCOA Alloy 2024 TechSheet). Basic strength properties are determined using tensile test at elevated temperature in accordance with the standard PN EN 10002-5:2002 or ASTM E 21-05.

The aim of this paper is to determine effects of temperature on basic strength properties of aluminium alloy 2024-T3. Due to that aim, authors of this paper presented results of monotonous tensile tests of 0.16" thick standard samples made of non-clad plates of aluminium alloy 2024-T3. The tests were performed for eight different temperatures ranging from 25°C up to 200°C with the step of 25°C. Tests were performed for samples cut out from a sheet plate in two different directions: in the parallel and perpendicular direction to sheet plate rolling direction.

### 2. TEST STATION

The tests were performed in the Department Laboratory for Research on Materials and Structures (certified by the Polish Centre for Accreditation – PCA AB 372) of the Faculty of Mechanical Engineering at the University of Technology and Life Sciences

in Bydgoszcz, using the testing machine INSTRON 8502 (with the following parameters: maximum static force – 300 kN, maximum dynamic force – 250 kN, piston stroke:  $\pm 75$  mm) fitted with the control system 8500+, and equipped with the heating chamber (Fig. 1).



Fig. 1. The test sample and the extensometer installed inside the heating chamber (opened in the presented photo) of the Instron 8502 system

### 3. THE MATERIAL AND TEST CONDITIONS

Tests were performed using non-clad plates made of aluminium alloy 2024-T3 (AlCu4Mg1 – supersaturated, cold deformed

and naturally aged up to stable condition) in accordance to the American standard AMS-QQ-A-250/4.

The tests were performed in compliance with guidelines of Urząd Lotnictwa Cywilnego (Civil Aviation Office) based on the standard MIL-HDBK-5H (1998) as well as relevant ASTM standards referred to there. Monotonous properties of the alloy 2024-T3 in elevated temperatures were determined in accordance with the standard ASTM E 21-05 (2005).

Design features of the samples are shown in Fig. 2. Samples were cut from plate sheets in two perpendicular directions using *Water Jet* technology:

- parallel to the plate sheet rolling direction;
- perpendicular to the plate sheet rolling direction.

The analysed part of samples was subject to finishing in order to obtain required surface roughness.

Tests were performed at the temperature of 25°C, 50°C, 75°C, 100°C, 125°C, 150°C, 175°C and 200°C. The temperature was measured directly on samples which were heated until their temperature stabilized at the required level. The temperature was maintained at that level for at least 10 minutes before the test start.

During tests, samples were subject to uniaxial monotonously increasing tension up to their damage. During tests, the load force and the displacement of the test machine handle, together with the sample deformation, were recorded using high temperature extensometer with measurement base of 12.5 mm and the measuring range  $-1.25 \pm +2.5$  mm. The tests were performed with displacement rate of 0,05 mm/s in order to achieve constant sample deformation rate.

#### 4. TEST RESULTS

Selected tension charts obtained from the tests in the direction parallel to the plate rolling direction were provided in Fig. 3a, while for tests in the direction perpendicular to the plate rolling direction - in Fig. 3b.

Based on charts presented in Fig. 3, the authors determined average values of strength parameters:

- elastic (Young's) modulus  $E$ ;
- yield point  $R_{eL}$  or yield strength at non-proportional increment  $R_{p0.2}$ ;
- tensile strength  $R_m$ ;
- ultimate elongation  $A_t$ .

The determined parameters were presented in Tab. 1.

#### 5. ANALYSIS OF TEST RESULTS

##### 5.1. Effects of temperature on strength properties

Based on the obtained results, one can conclude that the tested plate is characterized by significant differences of strength properties depending on the rolling direction. Samples taken parallel to plate rolling direction, regardless of the temperature, are characterized by clear yield point and better strength-related properties (apart from the elongation) than samples taken perpendicular to the rolling direction.

Fig. 4 shows schematically the change of strength properties determined based on the monotonous tensile test of the studied plate depending on temperature.

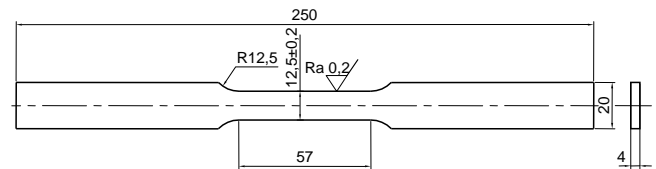


Fig. 2. Sample for monotonous properties tests

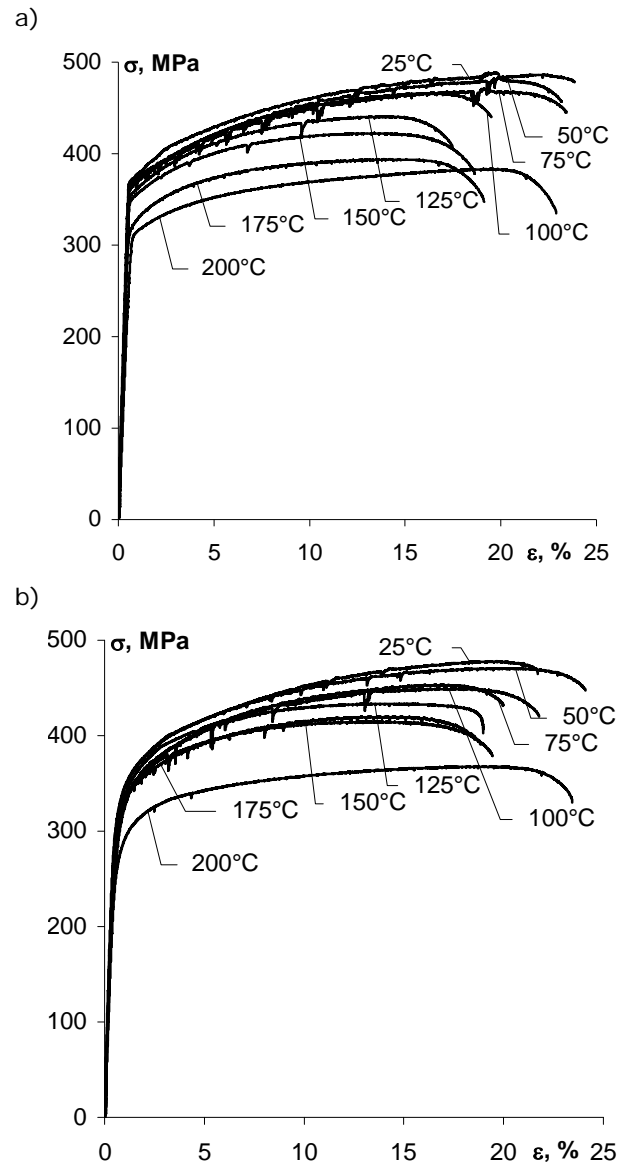


Fig. 3. Charts of monotonous tensile tests of samples made of aluminium alloy 2024-T3 cut parallel (a) to the plate rolling direction and perpendicular (b) to the plate rolling direction for different temperatures

The nature of strength properties change depending on the temperature, presented in Fig. 4, is qualitatively similar for both sampling directions. Either the tensile strength value  $R_m$ , as well as yield point  $R_{eL}$  (parallel to rolling direction) or the yield strength at non-proportional increment  $R_{p0.2}$  (perpendicular to rolling direction) decrease as the temperature rises. The tensile strength in the temperature range from 25°C to 125°C decreases by about 10%, while at the temperature of 200°C it achieves about 75% of  $R_m$  value obtained for the temperature 25°C. The decrease is lower for  $R_{eL}$  ( $R_{p0.2}$ ), i.e.: at the temperature of 125°C, it drops by about 5%, while at 200°C, by about 15%

as compared to the temperature of 25°C.

Whereas the elastic (Young's) modulus  $E$  slightly increases as the temperature rises and achieves the maximum value at about 75°C, and then gradually decreases. For sampling direction parallel to the plate rolling direction, that decrease is significantly higher than for perpendicular direction. At the temperature of 200°C, the modulus drops to about 2/3 of its value at the temperature of 25°C in the former case, and to about 85% in the latter case.

It should be noted that  $R_m$ ,  $R_{eL}$ ,  $R_{p0.2}$  and  $E$  charts presented in Fig. 4 are highly correlated with the results of the experiments. As regards the elongation  $A_t$ , charts presented in Fig. 4 show only qualitative nature of the change of its value depending on the temperature. The elongation slightly decreases as the temperature rises and its achieves the minimum value for 125-150°C, and then gradually rises.

Based on presented research results, one can conclude that main strength properties of the plate made of the alloy 2024-T3 may drop by up to 10% for the operating temperature range recommended by the manufacturer (max. 120°C).

### 5.2. The Portevin - Le Châtelier effect

The analysis of charts obtained from the research (Fig. 5) shows abrupt stress change during tensile test, which is characteristic for the Portevin-Le Châtelier effect (so called PLC effect).

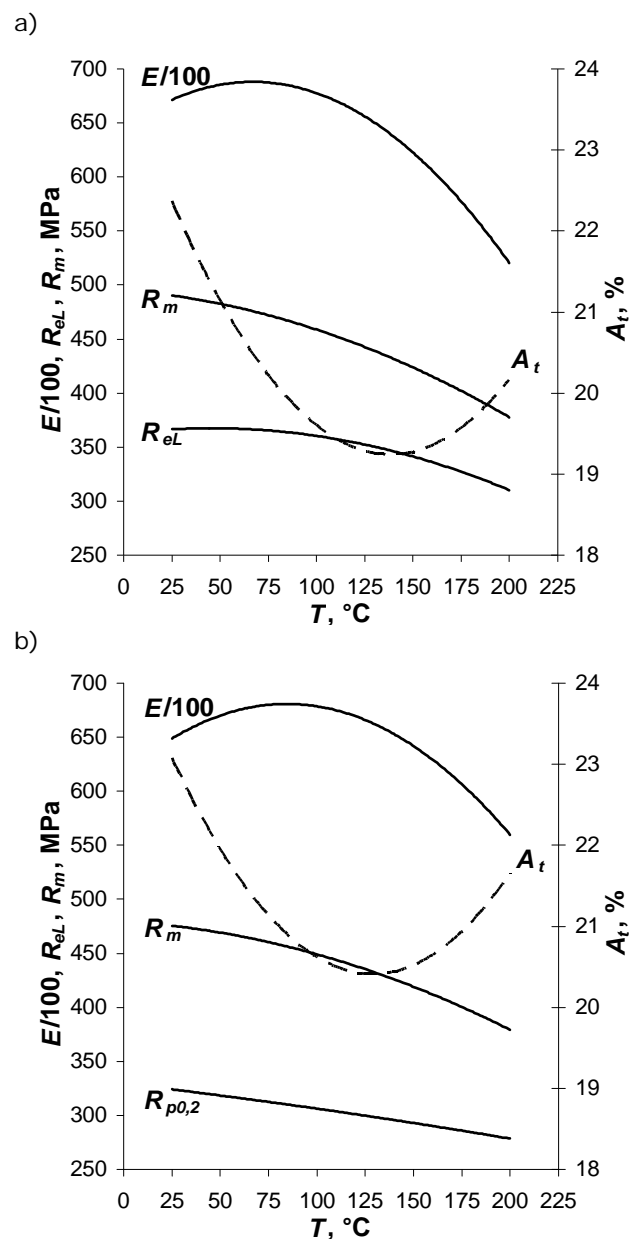
For better image of those changes, Fig. 5 shows selected tension charts for samples cut parallel to the plate rolling direction tested at different temperatures. Those charts were limited only to the range where significant plastic strain occurs. Fig. 6 shows analogous charts obtained for samples cut perpendicular to the plate rolling direction.

**Tab. 1.** Strength properties determined based on monotonous tensile tests of 0,16" thick samples made of non-clad plates of aluminium alloy 2024-T3

Direction	Temperature	$E$	$R_{eL}$	$R_{p0.2}$	$R_m$	$A_t$
	°C	MPa				%
Parallel to the plate rolling direction	25	68 563	367.5	-	488.8	23.9
	50	66 879	367.5	-	483.0	23.2
	75	70 403	361.8	-	471.1	23.4
	100	65 564	360.3	-	466.2	18.4
	125	62 863	354.0	-	440.7	16.5
	150	62 082	348.3	-	422.5	17.7
	175	66 814	318.2	-	394.2	19.1
	200	46 624	312.9	-	383.2	22.2
Perpendicular to the plate rolling direction	25	64 456	-	323.6	478.0	21.7
	50	65 674	-	320.4	470.9	24.1
	75	72 926	-	314.4	453.3	20.0
	100	65 965	-	307.4	449.3	21.8
	125	64 721	-	279.8	433.6	21.1
	150	60 858	-	305.7	414.9	19.4
	175	66 886	-	306.7	420.2	18.8
	200	53 675	-	270.0	367.7	23.4

The Portevin-Le Châtelier effect is characteristic, among others, for non-ferrous metal alloys (e.g. brass and aluminium alloys) as well as for iron at elevated temperatures. It manifests

on the tensile chart with multiple repeating jumps which result from the fact that atoms of impurities are intercepted by moving dislocations, which are immobilized and then abruptly released. Stopping dislocation movement results in stress increase, while release of dislocation in stress reduction. As a result, dislocation movement speed changes between extreme values. At low speed, the strain progress caused by stress increase is slow and once it achieves sufficient value for dislocation release, the fast plastic flow phase starts, causing stress decrease. Released dislocations intercept atoms of impurities on their way again, which results in dislocation slowing down and that cycle repeats again (Przybyłowicz (1999, 2002)). It should be noted that PLC effect occurs only within a certain limited strain speed range. If the strain rate is sufficiently high, the flow stress is always higher than the dislocation release stress and, as a result, the abrupt strain change is unnoticeable (Courtney (2000)).



**Fig. 4.** Changes of strength properties determined based on monotonous tensile tests of samples made of aluminium alloy 2024-T3 cut parallel (a) to the plate rolling direction and perpendicular (b) to the plate rolling direction, depending on the test temperature

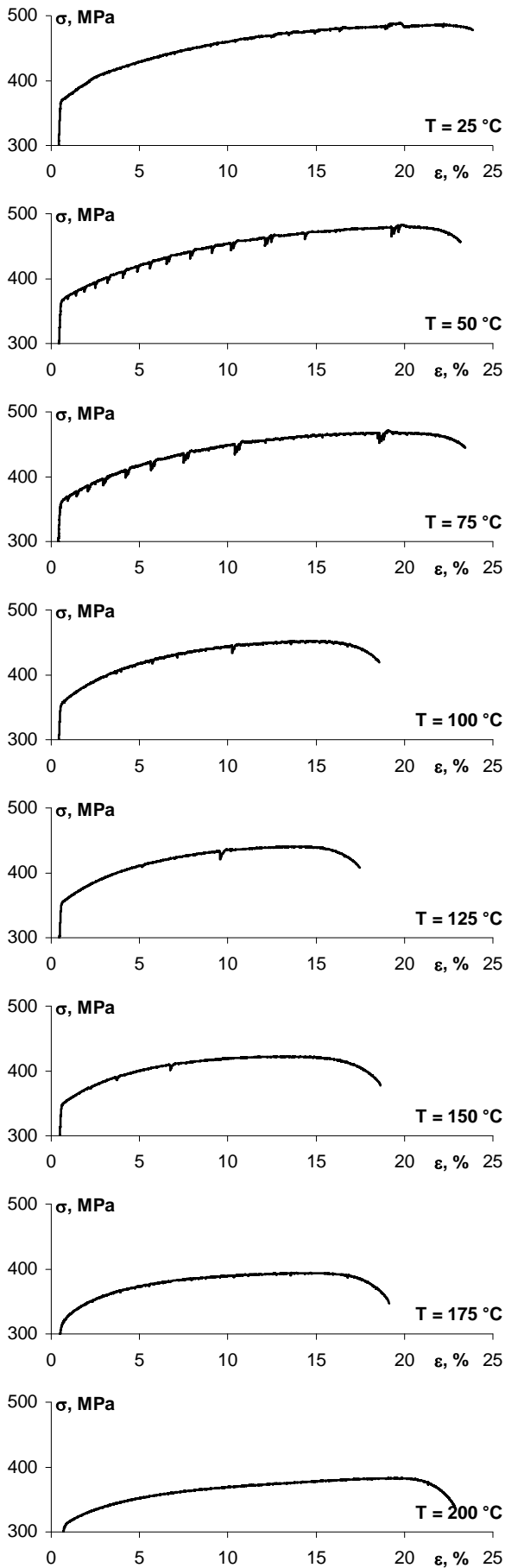


Fig. 5. Tensile tests charts for samples made of aluminium alloy 2024-T3 cut parallel to the plate rolling direction for different temperature values

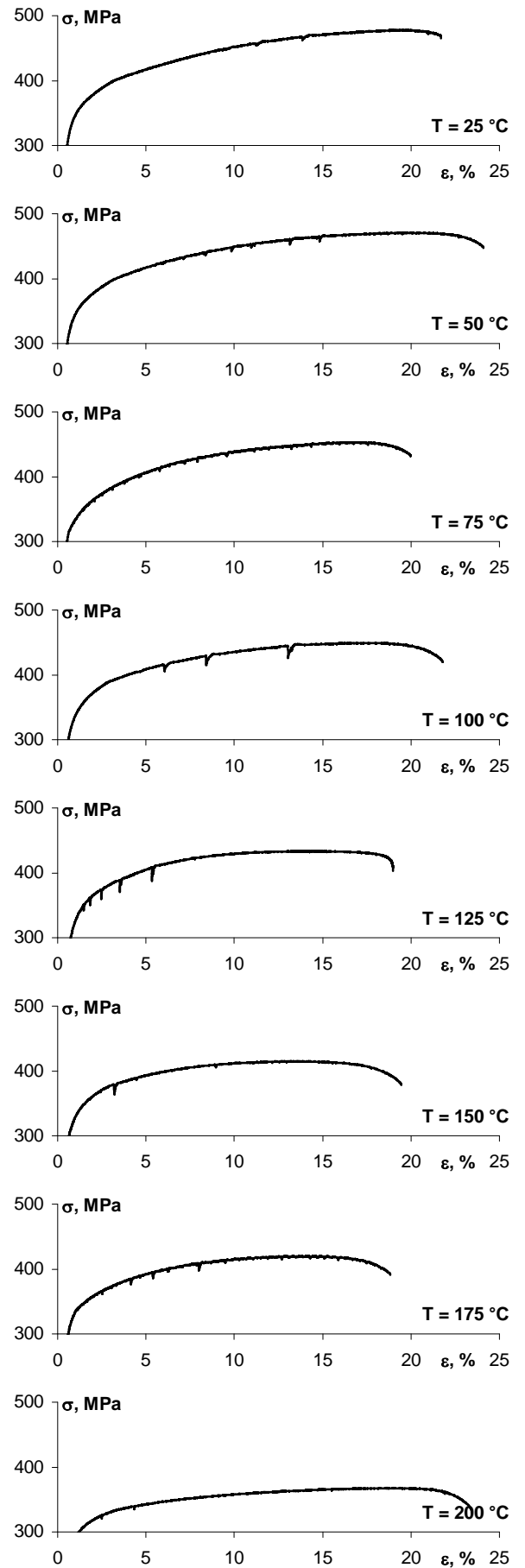


Fig. 6. Tensile tests charts for samples made of aluminium alloy 2024-T3 cut perpendicular to the plate rolling direction for different temperature values

There are also more mechanisms of PLC effect presented in professional literature, other than the aforementioned one. Other descriptions of the effect can be found, e.g. in the papers by Courtney (2000), Bharathi et al. (2003), by Huifeng et al. (2007) and by Ho (2000) and Klose (2004).

In case of the discussed tests results obtained for samples made of aluminium alloy 2024-T3, one can notice, that PLC effect is more intense for samples cut parallel to the plate rolling direction (Fig. 5). The amplitude and frequency of those noticeable stress jumps are higher than in case of samples cut perpendicular to the rolling direction (Fig. 6).

PLC effect was noticeable even at such low temperature as 25°C. Stress fluctuations were most intense within the temperature range from 50 to 75°C. In case of samples cut parallel to rolling direction, those fluctuations gradually fade out as the temperature rises and they are virtually unnoticeable at the temperature of 200°C. While for samples cut perpendicular to the rolling direction, stress jumps become less intense as the temperature rises, however their value increases.

## 6. SUMMARY

Plates made of aluminium alloy 2024-T3, which is the successor of duralumin, belong to the group of materials widely used in aircraft industry. Due to their functional properties, they may operate in elevated temperatures up to 120°C.

The research results presented in this paper indicate to orthotropic strength properties of the plate associated with the plate rolling direction and to gradual reduction of mechanical properties for the temperature increase from 25°C to 125°C.

The PLC effect occurring at the conditions of the performed tensile tests, depends on the temperature and the direction of sampling with respect to the plate rolling direction. The effect occurs even at such low temperature as 25°C, and is most intense in the temperature range 50-75°C, and then it gradually decreases as the temperature rises. The PLC effect is more distinct in case of sampling parallel to the plate sheet rolling direction.

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