RESEARCH ON THE INTERNAL STRESSES IN ROUND WIRES OBTAINED FROM AlMgSi ALLOY

Paweł STRZĘPEK, Andrzej MAMALA, Beata SMYRAK, Wojciech ŚCIĘŻOR,
Małgorzata ZASADZIŃSKA

AGH University of Science and Technology, Faculty of Non-Ferrous Metals, Department of Metal Working and Physical Metallurgy of Non-Ferrous Metals, Cracow, Poland, EU
strzepek@agh.edu.pl

Abstract

The research problem focuses on the wires made of aluminum alloys acquired in the wire drawing process of the wire rod obtained using the Continuus Properzi method. The nature of the drawing process generates a heterogeneity of strain on the wire cross-section, which results in the formation of internal stresses. The result of drawing round wires is a parabolically shaped internal stress distribution: tensile stresses around the surface and compressive stresses around the axis of the wire.

The aim of the work was to empirically determine the distribution of internal stresses in the wires made of aluminum alloy EN AW 6101 (AlMgSi) obtained in various conditions. The internal stresses were determined through the surface treatment method. In order to achieve that, after proper preparation of the wire samples, their surface was pickled using a 50 % NaOH solution. After stabilization of the thermal state, changes in length were investigated. Parallel to the internal stress tests, the macroscopic properties were characterized in a uniaxial static tensile test.

Keywords: Internal stresses, residual stresses, wires, AlMgSi alloy, EN AW 6101

1. INTRODUCTION

Technological solutions in mechanics often assume the so called natural state of material which means the material is theoretically free of any kind of stresses until the external load is imposed. Such assumption is not always correct as most processed materials are not free of stresses formed during the previous working process, heat treatment, surface treatment or even assembly. Stresses occur within even if the material is unloaded and such phenomena is called internal stress or own stress [1].

Significant part of the aluminum manufactured products obtained during mechanical working are wire rods, wires and wire based products. After the cold drawing process is finished the wires usually are not free of internal stresses which may reach surprisingly high values. These stresses cause initial effort of metal even before any external load is imposed. One must take that into consideration when calculating the resultant value of the stress, especially if the internal stress and the external load both have the same mathematical sign. When discussing wires one must know that the tensile stresses which occur at the surface have the plus sign and must be summed with the external load, however, the compression stresses which occur at the centre of the wire have a minus sign and therefore reduce the resultant value of the stress. The combination of the internal tensile stresses and fatigue of the overhead cables may cause cracking due to the static tension and the dynamic bending caused by aeolian vibration [2].

Figure 1 presents the classification of the internal stresses formulated by Lebedev. This work focuses on the internal stresses that occur as a result of mechanical working when the elastic limit of the processed material is exceeded which Lebedev defines as residual ductile stress [1]. Currently there are no studies connected to the internal stresses related to EN AW 6101 aluminum alloy wires dedicated for power cables. Such wires may be subjected to artificial aging after or before drawing. Considering the latter case, the residual stresses are of much significance from the point of view of the functional properties of the wires. An example of the application of the Heyn's method designed to estimate the residual stresses in cold drawn wires and their correlation with fatigue can be found, among others in [3].

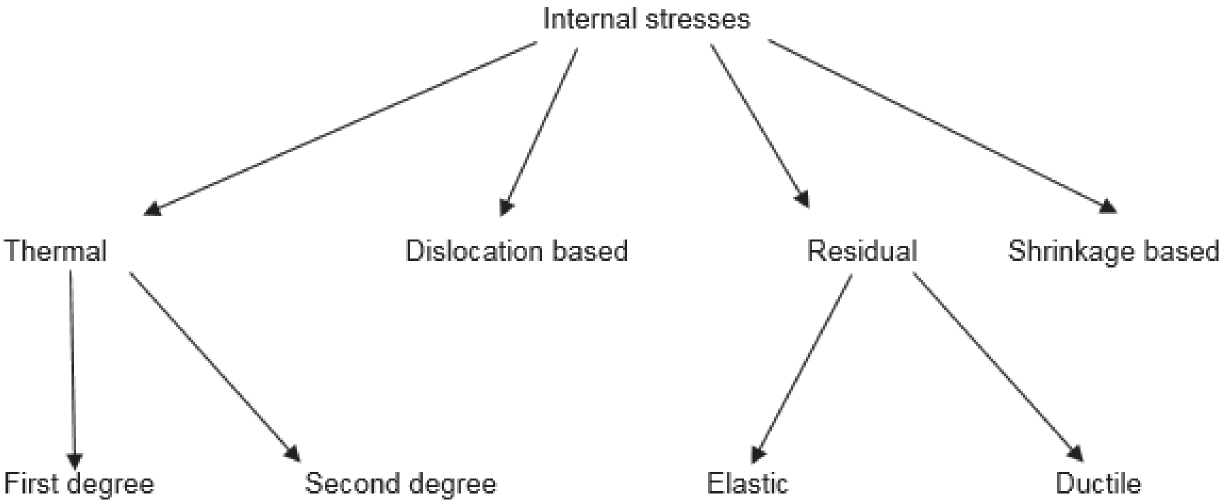

Figure 1 The classification of the internal stresses formulated by Lebedev [4]

The first to apply the mechanical method for measuring the residual stress of cylindrical objects were Martens and Heyn in 1912. It was Heyn's method that was the first to determine the residual stresses using the cutting method. It involved the mechanical removal of subsequent outer layers of the wire and measurements of changes in diameter and length. This method assumes that if after cutting of the layer, the rod has lengthened in relation to the raw wire rod then there were tensile forces formed from the residual stresses in the removed layer [1].

2. OBJECTIVE, PROGRAM, RESEARCH METHODOLOGY

The aim of the research was to answer the question: what is the degree and distribution of internal residual stresses in wires obtained from EN AW 6101 aluminum alloy and how the geometrical parameters of the dies applied in the last production sequence influence the amount of the residual stresses.

During research 4 different dies were used and their geometrical parameters are presented in the **Table 1**. It allowed the author to determine the influence of the die angle and the bearing length on the amount of residual stresses in the wires after the drawing process. For this purpose, 4 different wire types with a diameter of 3.013 mm were obtained from the EN AW 6101 wire rod under laboratory conditions using a drawing machine. All dies along with their diameters and elongation coefficients for each draw are presented in **Table 2.**

Table 1 Geometrical parameters of dies used during research

Die number	Die angle	Bearing length (mm)	Diameter (mm)
1	12°	0.9	3.013
2	20°	0.9	3.013
3	20°	0.6	3.013
4	20°	1.21	3.013

Table 2 Initial diameters (d_o), diameter of the dies (d_1) used during research and elongation coefficient (λ_j) for each draw

d_o (mm)	9.5	8.7	8	7.5	6.65	6.05	5.5	4.55	3.8	3.5
d_1 (mm)	8.7	8	7.5	6.65	6.05	5.5	4.55	3.8	3.5	3.013
λ_j	1.19	1.18	1.14	1.27	1.21	1.21	1.21	1.19	1.18	1.35

After the drawing process 200 mm samples were cut from each wire and 25 mm from each end was covered with a protective layer of paint to form 150 mm measuring base. The protection was set to prevent the wire from being pickled along its length. Separate samples were prepared for the static tensile test which was carried out using the testing machine at the speed of 10 mm/min and measuring base of 100 mm.

The pickling of samples was carried out using 50 % solution of NaOH and its aim was to remove the perimeter layer of the wire along the measuring base, which allowed the author to calculate the residual stresses of wire samples using equations (1) and (2). The pickling process lasted 15 minutes, after which the wire was pulled out from the solution and rinsed under cold water to stabilize its temperature, then its diameter was measured using micrometer with an accuracy of 0.001 mm and its length was measured using especially designed equipment with an accuracy of 0.0005 mm. After measurements the wire was put back into the solution tank. The cycles were repeated 10 times for each wire which means each wire was pickled for 150 minutes. Residual stresses were calculated using the equations proposed by Heyn:

$$\sigma_1 = E \frac{c_p}{c_u} \frac{l_n - l_o}{l_o} \tag{1}$$

in which:

σ_1 - stress after the first pickling

E - Young's modulus (68 GPa)

c_p - surface area which was not removed after the first pickling

c_u - surface area which was removed after the first pickling

l_n - length of the wire after n pickles

l_o - initial length of the wire

$$\sigma_n = \frac{E}{l_o} \frac{c_{p_n}(l_n - l_o) - c_{p_{n-1}}(l_{n-1} - l_o)}{c_{un}} \tag{2}$$

in which:

σ_n - stress after n pickles

c_{pn} - surface area which was not removed after n pickles

c_{un} - surface area which was removed after n pickles

3. STUDY RESULTS AND THEIR ANALYSIS

Analysis of the values of residual stresses shows the classical nature of their distribution in the wire, which is tensile stress in the outer layers and compressive stress in the inner layers of the wire. It is worth noting that there was a strong decrease in tensile stresses in a relatively thin subsurface layer.

On the basis of the conducted research the influence of the die angle and the bearing length on the residual stresses was determined. The former comparison is shown in **Figure 2** and the latter in **Figure 3**. The stress - strain curves of wires not subjected to pickling process were also analysed in order to determine their mechanical properties depending on the die used in the last sequence.

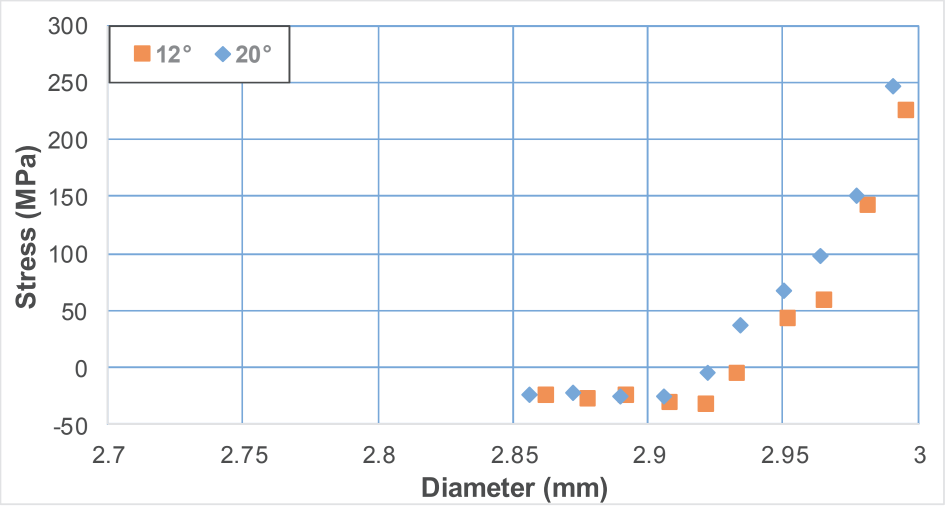

Figure 2 The comparison of drawing dies with the same bearing length but different die angle

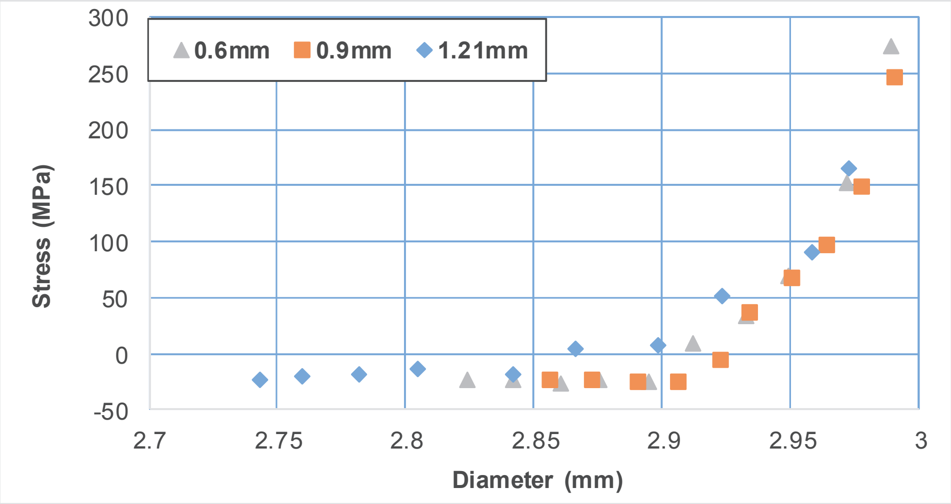

Figure 3 The comparison of drawing dies with different bearing length and the same die angle

Using **Figure 2** it is easy to see that the influence of the die angle is negligible in terms of residual stresses, as the difference does not exceed 10 %. In the case of the bearing length the differences are clearly visible. From **Figure 3** it can be easily read that the values in some cases differ by more than 40 %. The results of the research were summarized in **Table 3**. After the residual stresses went from tensile to compressive they began to stabilize which allowed their extrapolation and development of their symmetrical image to the y axis presented in **Figure 4**, illustrating the whole stress course for each of the wires used during research.

Table 3 The results of the research and conducted calculations for each wire

Die number	Bearing length (mm)	Die angle (°)	Maximum tensile stress (MPa)	Average compressive stress (MPa)	Tensile stress minus compressive stress (MPa)
1	0.9	12	226	-26	252
2	0.9	20	246	-23	269
3	0.6	20	275	-25	299
4	1.21	20	165	-19	183

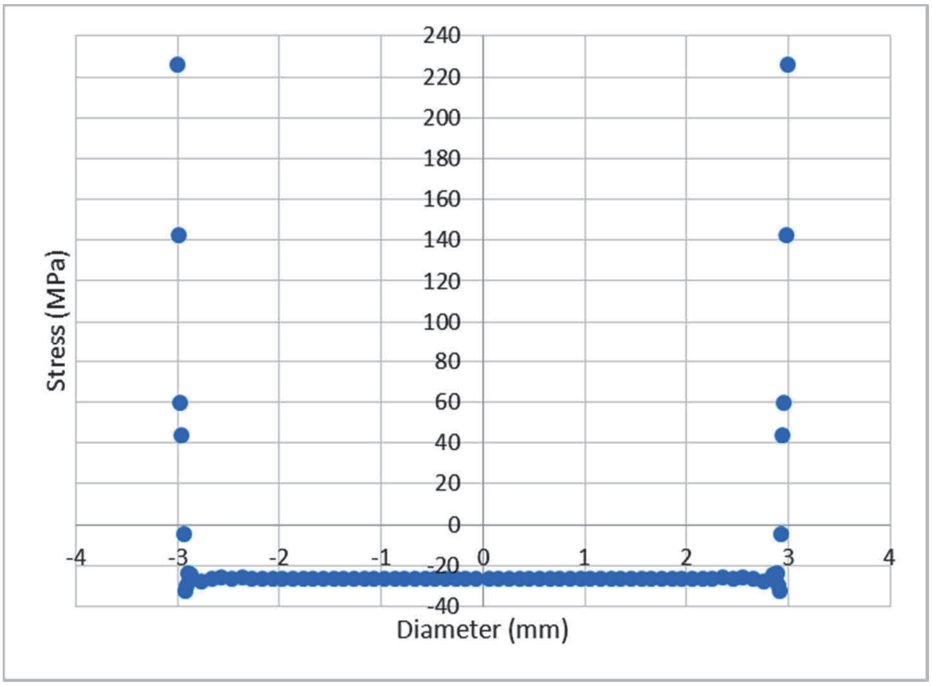

Figure 4 The distribution of residual stresses in the wires used during research (one diagram representing all wires)

Using the previously prepared wires which were not subjected to pickling process a static tensile test was carried out to determine mechanical properties of each wire. The results of the uniaxial tensile tests were summarized in **Table 4**.

Table 4 The results obtained from the stress - strain curves of each of the wires

Die number	UTS (MPa)	YS (MPa)	Elongation (%)
1	380	369	4.0
2	375	361	4.4
3	362	351	3.8
4	377	363	4.3

From the results presented in **Table 4** it is clear that the influence of the die's type on the mechanical properties is negligible, the differences in ultimate tensile strength (UTS) and yield strength (YS) do not exceed 5 %. The lowest values were obtained for the wire which was drawn through the die number 3 with an angle of 20° and bearing length of 0.6 mm which was also the wire that during research had the highest values of residual tensile stresses. The maximum tensile stresses occurring at the surface of the wire reach almost 80 % of the yield strength value. This is a very high and meaningful value from the operational point of view.

4. CONCLUSION

Based on the results of the experimental studies, it can be stated that:

1) The influence of the angle of the die on the residual ductile stresses both tensile and compressive is negligible, the differences in values are at the level of 10 %.

2) The influence of the bearing length of the dies on the residual ductile stresses is clear and easy to determine as increasing the bearing length from 0.6 mm to 1.21 mm reduced the stress value by more than 40 %.
3) Changing the dies angle or bearing length has no significant effect on the mechanical properties.

REFERENCES

[1] KŁOSSAK, C. *Internal stresses.* Main Institute of Metallurgy and Foundry*, Cracow, 1949.* (In original language: KŁOSSAK, C. *Naprężenia własne.* Główny Instytut Metalurgii I Odlewnictwa. Kraków, 1949.)

[2] KNAP, F. *Internal stresses in drawn wires and wire products,* Publishers of Technical University of Częstochowa, 1991. (In original language: KNAP, F. *Naprężenia własne w ciągnionych drutach I wyrobach z drutu.* Wydawnictwo Politechniki Częstochowskiej, Częstochowa, 1991.)

[3] KATAGIRI, T., SATO K., KASABA S., SASAKI H. and TASHIRO, S. Effects of post-drawing treatments on the fatigue strength of eutectoid steel wires. *Fatigue & Fracture of Engineering Materials & Structures.* 2003. no. 22, pp. 753-760.

[4] LEBEDEV, P. *Thermal stresses in theory of elasticity,* O.N.T.I., Moscow, 1937. (In original language: LEBEDEV, P. *Tiempieraturnyje napiażenia w teorji uprugosti.* O.N.T.I., Moskva, 1937.