

S. KUT^{*#}, P. MAJ^{**}, T. MRUGAŁA^{***}**EFFECT OF RELATIVE THICKNESS REDUCTION AND HEAT TREATMENT
ON AMS 5596 SHEET MECHANICAL PROPERTIES AFTER FLOW FORMING**

In the paper the results of experimental research of the process of flow forming of cylindrical drawpieces were presented. The drawpieces were made of the 3.1 mm thick AMS 5596 sheet by drawing process. Tests were performed on two-roller metal spinning machine of a vertical axis Leifeld SFC 800 V500.

The main purpose of this research was to determine the relationship between relative thickness reduction and the mechanical properties of tested material. Knowledge of these dependencies is especially useful in designing machines' components manufactured by flow forming, in the selection of parameters of realization of this technological process as well. Mechanical properties were determined on the basis of uniaxial tensile of the micro samples obtained from the drawpieces: (I) after cold flow forming, (II) after cold flow forming and in-process heat treatment. Obtained results were shown graphically in the diagrams and their analysis was carried out. In addition, the microstructure of the sheet material tested after drawing and flow forming is presented.

Keywords: metal spinning, AMS 5596 sheet, flow forming, heat treatment, yield strength

1. Introduction

Sheet metal components of machines and devices can be produced by various methods, including deep drawing. In case of axisymmetric drawpieces the alternative way is conventional spinning and shear spinning. These techniques are presented in the literature [1,2]. Their use is economically justified, especially in the production of individual or small series. Therefore, the use of spinning is often in the production of axisymmetric drawpieces e.g. in the aerospace industry.

Nickel alloys exhibit particular applications in construction of modern aircraft engines. They are very often used for the construction of combustion chambers, turbines and exhaust gases. These are places where heat-resistant materials are required, the properties of which allow transfer of high mechanical and thermal loads. Most commonly used materials are: Inconel, Nimonic, Udimet. For example, the weight share of the INCONEL 718 alloy components used for the Pratt & Whitney PW4000 airplane construction is equal to 22% [3]. The share of this alloy in the construction of the typical CF6 engine produced by GE Aircraft Engines is as high as 34% of its total weight, approximately 12% of which are components made of sheet metal [4].

Inconel 718 can be hardened by: cold working, age hardening, cold working followed by age hardening. As demonstrated in works [5,6], the forming method strongly influences the microstructure and precipitation process. The knowledge of the

influence of cold plastic working parameters and heat treatment on the mechanical and plastic properties of this steel is particularly useful during the structural design of the given part and the technological design as well. During structural design it allows to take into account the actual properties of the material the part is made of taking into account the influence of the technological process and the parameters of its realization e.g. relative thickness reduction after flow forming. Also, while designing the technological process for the part it allows to determine the possibility of forming a given part and in the most optimal way choose the parameters for the technological process. Knowledge in this area also enables to obtain the product with the most desirable properties by properly designing the technological process. For example, increasing the strength of the material of the given part as a result of the reinforcement obtained by the flow forming process can lead to a decrease in its mass, which is particularly important in the construction of flying objects.

The Flow forming is a modernized, improved advanced version of metal spinning, which is one of the oldest methods of chipless forming. Flow forming has spread widely since 1950. Flow forming is a cold metal forming process for the manufacture of rotationally symmetrical, hollow components. This forming technique offers significant advantages in comparison with conventional production techniques such as spinning, deep drawing, rounding circular bodies with subsequent welding etc.

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These advantages are particularly pronounced when components are to be produced in small or medium size batches due to relatively lower tooling costs than other process such as deep drawing. The other advantages are [7]: low production cost, very little wastage of material, excellent surface finishes, accurate components, improved strength properties, easy cold forming of high tensile strength alloys and production of high precision, thin walled seamless components.

A very important technological parameter that has a significant influence on both the course of the flow forming process and the mechanical properties of the material after flow forming is relative thickness reduction. Its percentage value can be calculated as:

$$Z = \frac{t_0 - t_1}{t_0} \cdot 100\% \quad (1)$$

where: t_0 – wall thickness before flow forming, t_1 – wall thickness after flow forming.

An important influence on the course of the flow forming process and consequently on the dimension and shape accuracy as well as surface quality of the product is the feed rate. To achieve suitable flow in flow forming and achieve the desired surface finish, a compromise has to be established between the feed rate, thickness of blank and roller profile [8]. If too low a feed rate was used for a particular blank thickness, the material would tend to flow in the radial direction, increasing the internal diameter of the blank. On the other hand, when high feed rates were employed, defects such as nonuniform thickness, reduction in diameter as well as a rough surface would result [8]. If the feed rate exceeds a certain limit, it would spoil the surface finish and produce thread-like serrations on the tube [9,10]. This is because with very large feed rates, the material would tend to flow underneath the roller in the opposite direction to the roller axial movement. The effects of feed rate on thickness strain, radial force, diameter accuracy and surface roughness for the flow forming of aluminium tube were investigated experimentally by Yao and Murata [11]. They concluded that the increase in feed rate would increase spinning force, thickness strain and surface roughness. In addition, diametral accuracy would decrease with the increment of feed rate.

Figure 1 shows the roller profiles most commonly used in the flow forming process of axially symmetric sheet metal parts. Type of rollers (a) (b) and (c) are most commonly used in spinning process of the drawpieces with both rectilinear and curvilinear profiles. In many cases, these rolls are also used for flow forming, especially drawpieces with curvilinear profiles. Typical rollers for flow forming are rollers (d) and (e). However, in spite of their high efficiency, they can only be used properly for flow forming of the drawpieces with rectilinear profiles.

Flow forming offers a remarkable increase in tensile properties due to strain hardening. Molladavoudi and Djavanroodi [12] the effects of thickness reduction on the mechanical properties and spinning accuracy were experimentally investigated on 7075-O aluminum tube. In the studies they showed, that yield and tensile strength increment are 64% and 14% for 60% rela-

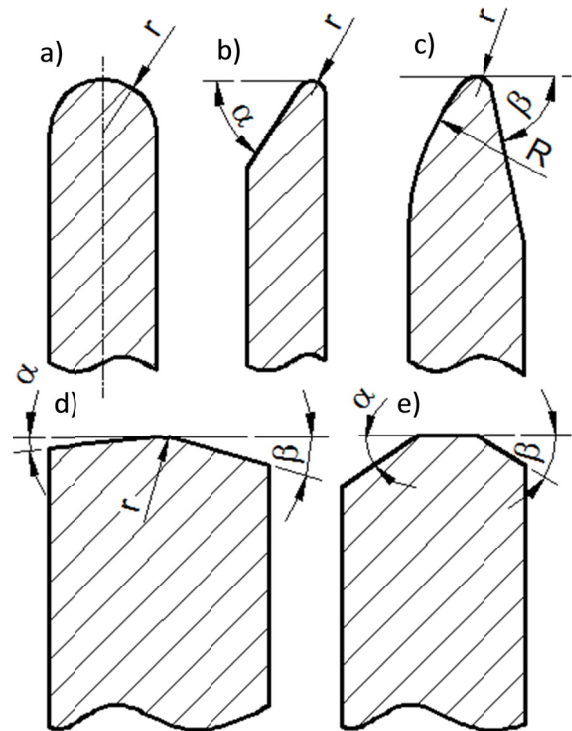


Fig. 1. Sample rollers profile for flow forming

tive thickness reduction. And percentage elongation decreased up to 71%, for 60% relative thickness reduction. Haghshenas and Klassen [13] investigated of mechanical properties of flow formed FCC alloys. For this purpose, flow forming operation with relative thickness reduction of 70% was performed on 5052 and 6061 aluminum alloys, 70/30 brass, and pure copper. The mechanical response of starting materials and flow formed parts, i.e. tensile strength, yield strength, elongation were discussed for each material separately and the results were compared.

Knowledge of the impact of relative thickness reduction on the mechanical properties of the material after flow forming is very useful during structural design of machine elements manufactured by flow forming, and also during the selection of parameters for the implementation of the technological process. Unfortunately, knowledge in this field is insufficient, as it is limited to a narrow group of materials. Therefore, the paper presents the results of experimental investigations of the flow forming process of a AMS 5596 drawpiece and the dependencies determined on their basis, between the relative thickness reduction and the strength properties of the material of the tested sheet after flow forming as well as after flow forming and heat treatment.

2. Experimental research

The study was carried out using the AMS 5596 sheet with the thickness of $t_0 = 3.1$ mm made from the Inconel 718 superalloy. The chemical composition of the sheet material is given in Table 1. The mechanical properties of the tested sheet in the initial state from the manufacturer are shown in Table 2.

TABLE 1

Chemical composition of AMS 5596 sheet

Element	Chemical composition (% of wt.)	
	Min	Max
Ni	50	55
Cr	17	21
Nb	4.75	5.5
Mo	2.8	3.3
Ti	0.65	1.15
Al	0.2	0.8
Co	1	—
Mn	0.35	—
Si	0.35	—
Cu	0.3	—
C	0.08	—
P	0.015	—
S	0.015	—
Ta	0.05	—
B	0.006	—
Fe	balance	—

TABLE 2

Mechanical properties of the tested sheet in the initial condition from the manufacturer

Angle to the rolling direction [deg.]	Yield strength [MPa]	Tensile strength [MPa]	Elongation at break [%]
0	412	905	45
45	373	934	37
90	395	916	39

The main aim of the research was to determine the relationship between the relative thickness reduction value during flow forming and the mechanical properties of the tested material.

Achieving the research goal required the elaboration of an experimental research plan. Schematically, the research plan is shown in Figure 2. In the first place, discs were cut by a laser. A series of drawpieces for tests was obtained by deep drawing. The drawing method as well as the shape and dimensions of the drawpiece were selected to achieve the highest dimensional and shape reproducibility and the smallest thin-wall ratio on the cylindrical surface of the drawpiece. The shape and dimensions of the tested drawpiece are shown in Figure 3. After completion all drawpieces were subjected to heat treatment consisting of annealing at (900-1000)°C. Then drawpieces were marked and the measurements of the geometrical parameters were made, with particular regard to the wall thickness in the cylindrical part. The arithmetic mean of wall thickness measured on the length of the cylindrical surface for all the tested drawpieces was in the range of 3.24 to 3.3 mm.

Experimental research was carried out on a two-roller industrial spinner of a vertical axis Leifeld SFC 800 V500 which is owned by Pratt & Whitney Rzeszow. The working station for spinning tests with a visible arrangement of forming tools was shown in Fig. 4. For the research the station was equipped with the following tools: a) a mandrel (1) with a diameter

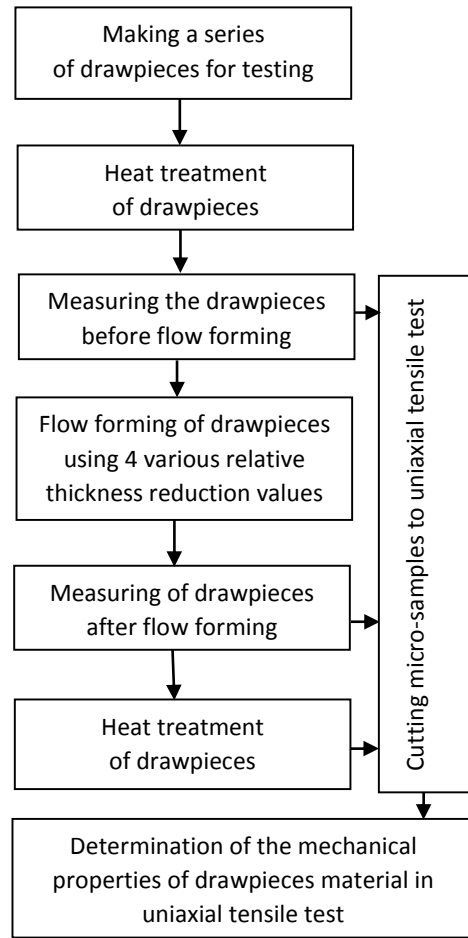


Fig. 2. The simplified algorithm of research

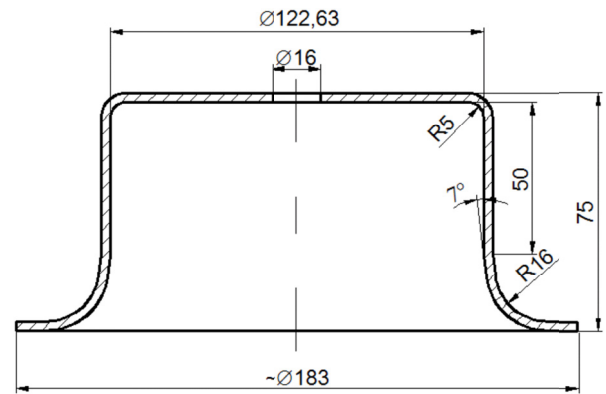


Fig. 3. Drawpiece (sample) for flow forming

$d = 122.5$ mm and a maximum working height $h_{max} = 190$ mm, b) two sets of forming rollers (2) of outer diameter $D_r = 320$ mm and fillet radius $r = 12$ mm. In relation to the mandrel axis the forming rollers are inclined at a constant angle of 45°.

Roller profile as shown in Figure 1 (c) was used in the study of flow forming. This choice was dictated by the possibility of performing the process of sheet metal parts flow forming with curvilinear profile. These types of tin parts are much more common (e.g. in aviation) than metal parts with rectilinear profile. On the other hand, as already mentioned, typical rollers for flow forming (Fig. 1d and Fig. 1e) are used for flow forming the part

with rectilinear profile. The CNC spinning machine allows to control the movement of tools while spinning from the program or manually. It is also possible to generate a control program based on manual control and then play it.

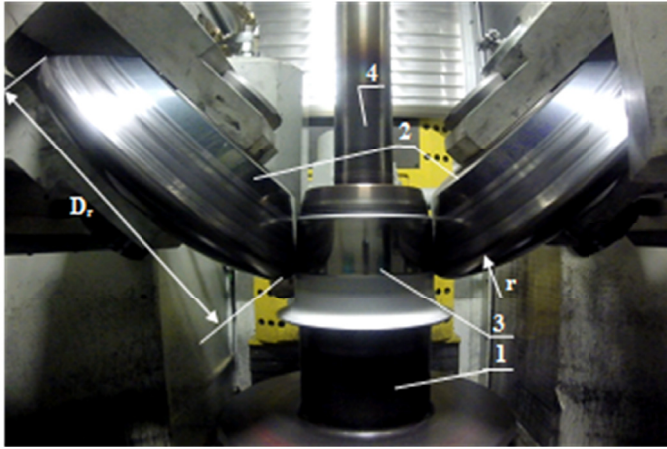


Fig. 4. Test stand: 1 – mandrel, 2 – rolls shaping, 3 – drawpiece, 4 – tail-stock (Pratt & Whitney Rzeszów S. A. proprietary)

Drawpieces with the flange were formed only on cylindrical surface of approximately 50 mm length (Fig. 3). Flow forming was performed in one pass of shaping rollers using a constant feed rate of 30 mm/min and a constant rotational speed of 500 rpm. After flow forming, the wall thickness of the individual drawpiece was measured. Based on the results of the average wall thickness measurement of the drawpiece before and after flow forming, the actual relative thickness reduction from the dependence (1) was calculated. In this way four relative thickness reduction were obtained: $Z_1 = 10\%$, $Z_2 = 19\%$, $Z_3 = 53\%$ and $Z_4 = 87\%$.

Samples for uniaxial tensile test were taken according to the research plan (Fig. 2). In the first place, the samples were taken from the drawpiece before flow forming process (Fig. 5a). Three samples were taken in the circumferential direction every 120 degrees at an equal distance from the bottom ($a = 30$ mm). In the same manner samples from every drawpiece after flow forming were taken (Fig. 5b). Then all the drawpieces from which the samples were taken were subjected to a heat treatment consisting of annealing at $(900-1000)^\circ\text{C}/1\text{h}$ in a vacuum. From each drawpiece after flow forming and heat treatment three more samples were taken every 120 degrees in the circumferential direction and at the same distance from the bottom as before. As a consequence, 6 samples were taken from every drawpiece after flow forming (every 60 degrees) for uniaxial tensile test, i.e. 3 after flow forming and 3 after flow forming and heat treatment. The use of a constant distance $a = 30$ mm during samples were taken is very important, because after drawing, the circumferential strain of the sheet material increase along with the height. For this reason the distance has been chosen in such a way that the circumferential strains represent the average value at the height of the drawpiece before flow forming process.

Samples were taken in the circumferential direction as they have much more uniform distribution of thickness compared to

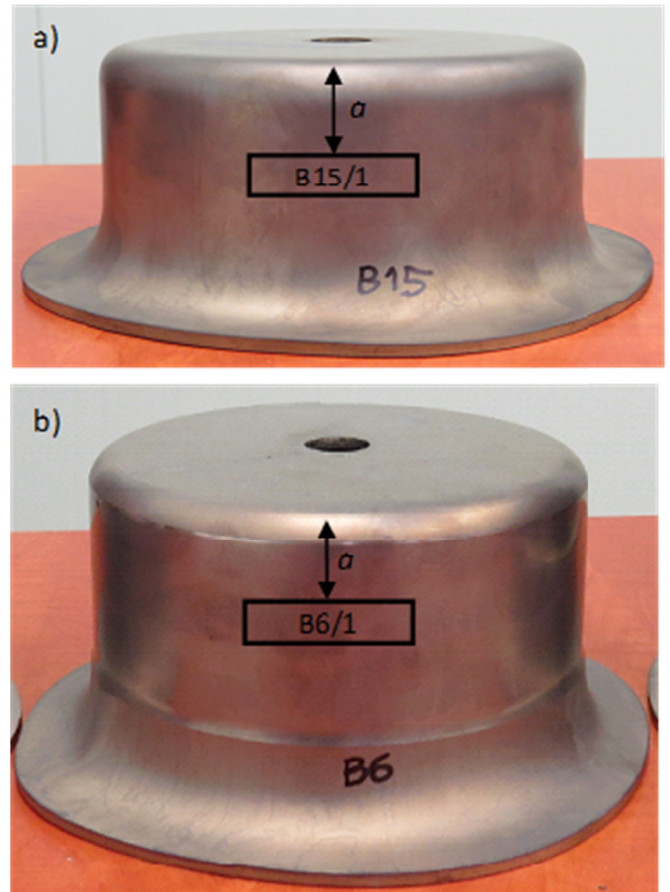


Fig. 5. View of the drawpieces with marked sampling point: a) before flow forming, b) after flow forming ($Z_2 = 19\%$), $a = 30$ mm

the axial direction samples and uniform mechanical properties of the material over their entire length. All samples were cut by laser from a drawpiece and had rectangular shape with dimension 6.5×39 mm. After laser cutting, the samples required a slight straightening. The samples were then packaged in several pieces and processed on a milling machine. The application of mechanical processing of samples allowed to eliminate the influence of the heat zone occurring after laser cutting. The final shape and dimensions of the micro-specimens for tensile test are shown in Figure 6.

Static uniaxial tensile tests were performed on a Zwick / Roell Z030 machine according to ISO 6892-1 standard. The gage length was 10 mm. The rate of increase in the tensile stress

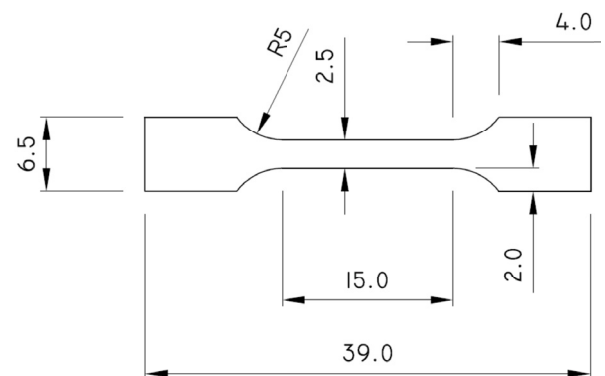


Fig. 6. Shape and dimensions of micro-sample for uniaxial tensile test

in the range of elastic deformations was 30 MPa/s. Velocity in the range of plastic deformations was 0.00025 1/s. Based on the tests that were carried out, the following parameters which were analyzed later in the article were determined: yield strength, tensile strength and relative elongation percentage. In addition, the microstructure of the sheet material tested after drawing and flow forming is presented.

3. Research results and their analysis

The obtained results are presented in the graphs (Fig. 7÷9). Position of the points on the graphs corresponds to the arithmetic mean of the parameter's value calculated from the three experiments. Error bars in the graphs show the dispersion of values of the determined parameters. The length of individual error bars corresponds to the difference between the maximum and minimum numerical value of the parameter under consideration from among the three determined experimentally. The first parameter that was analyzed was the yield strength value of the tested material, depending on the thickness reduction after flow forming and after both flow forming and heat treatment. The average value of the yield strength of the drawpiece's material prior to flow forming was 483 MPa (Fig. 7). Using only 10% of the relative thickness reduction during flow forming caused an increase in yield strength of up to 836 MPa. Along with the relative thickness reduction the yield strength increases significantly. The use of a relative thickness reduction of 87% results in an almost twice greater yield strength than with a relative thickness reduction of 10%. By contrast, compared to the yield strength of untreated drawpiece, this increase is almost 3.5 times. During cold flow forming, the yield strength increases with the relative thickness reduction. Within the scope of the tests, this dependence can be described by the linear equation:

$$R_{0,2}(I) = 10.172 \cdot Z + 761.72 \quad (2)$$

where: $R_{0,2}(I)$ – yield strength [MPa] after flow forming, Z – relative thickness reduction according equation (1).

Performing heat treatment on drawpieces after flow forming results in a significant decrease in the yield strength over the entire range of tested thickness reduction. The greater the thickness reduction value, the lower the value of the yield strength at the same time. For example, for relative thickness reduction $Z = 10\%$ yield strength decreases more than one and half times. In the case of $Z = 87\%$, the yield strength decreased more than twice times compared to the value obtained after flow forming. Within the scope of the tests, the relationship between the yield strength and the thickness reduction after flow forming and heat treatment can be described by a linear equation in the form:

$$R_{0,2}(II) = 3.431 \cdot Z + 472.79 \quad (3)$$

where: $R_{0,2}(II)$ – yield strength [MPa] after flow forming and heat treatment, Z – relative thickness reduction according equation (1).

As with the yield strength, the higher thickness reduction value, the greater tensile strength of the material. However,

this increase with low thickness reduction value is less intense (Fig. 8). Within the scope of the tests, the relationship between the tensile strength and the relative thickness reduction can be described by a linear equation in the form:

$$R_m(I) = 6.869 \cdot Z + 1080.5 \quad (4)$$

where: $R_m(I)$ – tensile strength after flow forming [MPa], Z – relative thickness reduction according equation (1).

The mean tensile strength of the drawpiece's material prior to flow forming was 955 MPa. A small 10% relative thickness reduction after flow forming resulted in an increase in tensile strength of 157 MPa. Also, there is a significant increase in tensile strength along with increased thickness reduction in the area of the examined thickness reduction values. Increasing the thickness reduction value from 10% to 87% results in nearly 1.5 times higher tensile strength of the sheet metal after flow forming. In contrast to the tensile strength of the untreated material, the average tensile strength (for $Z = 87\%$) increased by 708 MPa.

As a result of the heat treatment, the tensile strength of the drawpiece's material has decreased throughout the range of the tested relative thickness reduction values. At a maximum of relative thickness reduction value ($Z = 87\%$) the tensile strength decreased by 552 MPa. On the other hand, with a minimum of relative thickness reduction value ($Z = 10\%$), the tensile strength on average decreased by 140 MPa. The relationship between the relative thickness reduction value and the tensile strength of the tested sheet material after flow forming and heat treatment can be described by the equation:

$$R_m(II) = 1.891 \cdot Z + 950.6 \quad (5)$$

where: $R_m(II)$ – tensile strength after flow forming and heat treatment [MPa], Z – relative thickness reduction according equation (1).

Depending on the size of the relative thickness reduction used in the flow forming process, the mechanical properties of the material change. The material becomes more durable, as evidenced by the increase in the yield strength. At the same time, its ductility decreases. Along with the relative thickness reduction, the ductility of the material decreases, and thus its ability to plastic working during technological processes. Together with thickness reduction, the work hardening ability of the material is reduced. In practice, strengthening of the material during cold forming is all the greater, the greater the difference between its tensile strength and the yield strength.

In case of drawpiece's material before flow forming ($R_m - R_{0,2}$) = 472 MPa, whereas after using $Z = 10\%$ this difference is ($R_m - R_{0,2}$) = 261 MPa.

The measure of suitability of a given material for shaping in cold plastic working processes may be the elongation of the sample in uniaxial tensile test. Due to the fact that during tensile test in many cases the material separation took place outside the measuring area of the extensometer, not total elongation A_t but elongation at maximum stretching force A_g was analyzed. The average values of the elongation, depending on thickness reduction used and the heat treatment after flow forming, are shown in

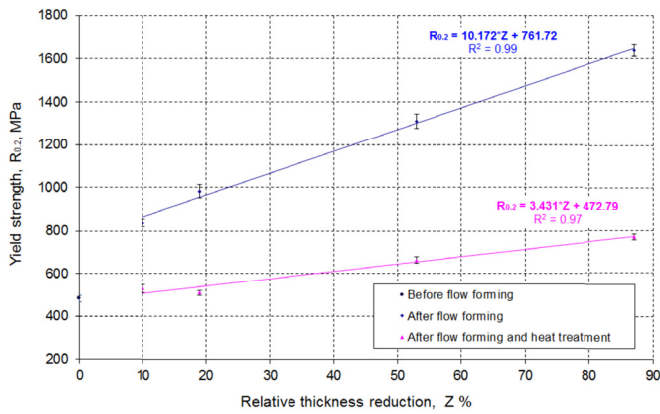


Fig. 7. Impact of the relative thickness reduction on the yield strength of the AMS 5596 sheet material: after flow forming (blue line), after flow forming and heat treatment (pink line)

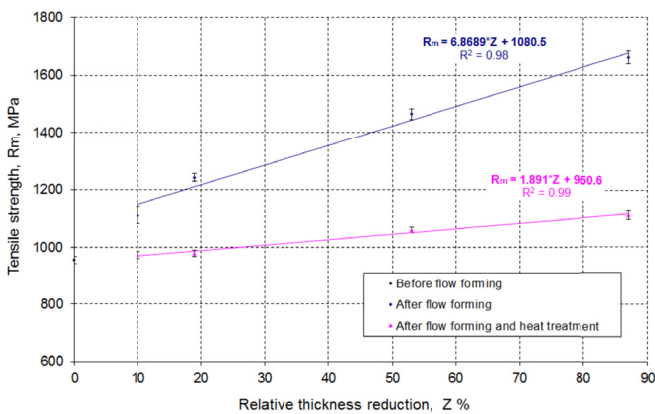


Fig. 8. An impact of the relative thickness reduction on the tensile strength of the AMS 5596 sheet material: after flow forming (blue line), after flow forming and heat treatment (pink line)

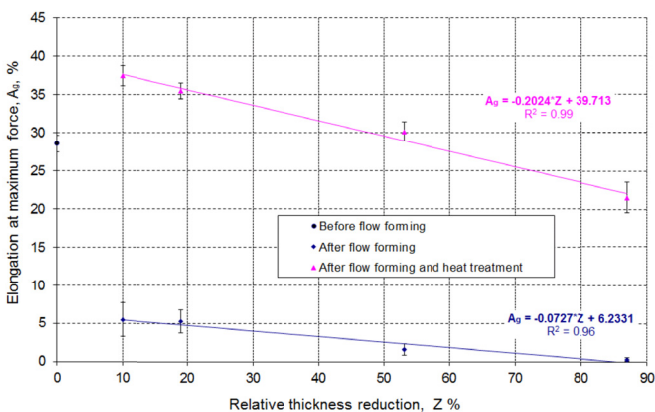


Fig. 9. Influence of the relative thickness reduction on the elongation using the highest force for the material AMS 5596: after flow forming (blue line), after flow forming and heat treatment (pink line)

the Figure 9. The average value of elongation of the drawpiece’s material prior to flow forming was almost 29%. The application of $Z = 10\%$ has resulted in reduction, by five times, in elongation to approximately 6%. A further increase of thickness reduction in the tested range caused a much smaller decrease in elongation. However, with a maximum value $Z = 87\%$, the maximum

elongation was approximately 0.5 %. In the tested area of the thickness reduction values, the relationship between elongation and the relative thickness reduction after flow forming can be described by a linear equation in the form:

$$A_g(I) = -0.0727 \cdot Z + 6.2331 \quad (6)$$

where: $A_g(I)$ – elongation at maximum stretching force, Z – relative thickness reduction according equation (1).

The use of heat treatment restores the plastic properties of the material. The graph (Fig. 9) shows that the elongation of the specimen after flow forming and heat treatment is all the greater, the lower the relative thickness reduction value in the flow forming process. Elongation of the heat treated drawpiece’s material (with $Z = 10\%$) has increased almost 7 times compared to the no heat treated drawpiece’s material. On the other hand, with a maximum value of thickness reduction $Z = 87\%$, the average elongation of the drawpiece’s material after the heat treatment is no more than 1% but 21%. Within the scope of the tests, the relationship between elongation and the relative thickness reduction after flow forming can be described by a linear equation in the form:

$$A_g(II) = -0.2024 \cdot Z + 39.713 \quad (7)$$

where: $A_g(II)$ – elongation at maximum stretching force, Z – relative thickness reduction according equation (1).

From the defined dependencies (2) to (7), the yield strength, tensile strength and elongation can be calculated for the tested material, depending on the relative thickness reduction value and the heat treatment in the range of Z of the tested thickness reduction values, i.e. from 10% to 87%.

Observation microstructure of the AMS 5596 sheet material were performed for the initial material from the manufacturer. As can be seen in Fig. 10a equiaxed grains of γ can be seen in the whole volume of the material. Additional there are some primary carbides and annealing twins. No additional phases were detected. Similar phase composition is expected in all cold formed samples. The differences in the figures is a result of etching processes. Areas strongly deformed and grain boundaries are susceptible to pitting which makes it difficult to get clear micrographs. On the other hand, differences in the size and texture of grain boundaries are easily distinguishable in all tested states. The drawpiece wall before flow forming Fig. 10b, and after the flow forming Fig. 10c and d shows its distinct variation depending on the relative thickness reduction applied. The morphological texture and banding increase gradually along with the deformation in the direction of the movement of the forming rolls, which increases the strength of the material. From the point of view of technology, it is best to obtain a homogeneous structure in the entire volume of material. The large variation in the value of thickness reduction in the volume of the shaped product affects the heterogeneous microstructure, which consequently results in the diversification of mechanical properties in individual of drawpiece areas shaped by the flow forming.

With the thickness reduction the materials tend to form a band structure with strongly orientated grains. Based on the

Fig. 10 it is apparent that the roller movement strongly affects the microstructure this increases with thickness reduction which in turn forces the material to accommodate higher stress and strain at the micro level. In the Fig. 10a almost parallel grain boundaries can be seen in comparison to Fig. 10b whereas the same features have a ribbon-like shape. Bearing in mind Hall-Petch equation the material with the highest reduction should possess higher strength. On the other hand, higher defect concentration should exhibit lower ductility.

When analyzing the material after heat treatment Fig. 11 it should be noted that the overall grain shape and size are preserved. However due to the annealing in the severely deformed areas, mostly grain boundaries small acicular δ precipitates can be seen. The material is also more homogeneous which is associated in much smaller pit concentration as a result of etching process. Just like in the cold deformed material higher thickness reduction resulted in a finer structure and slightly higher tensile strength.

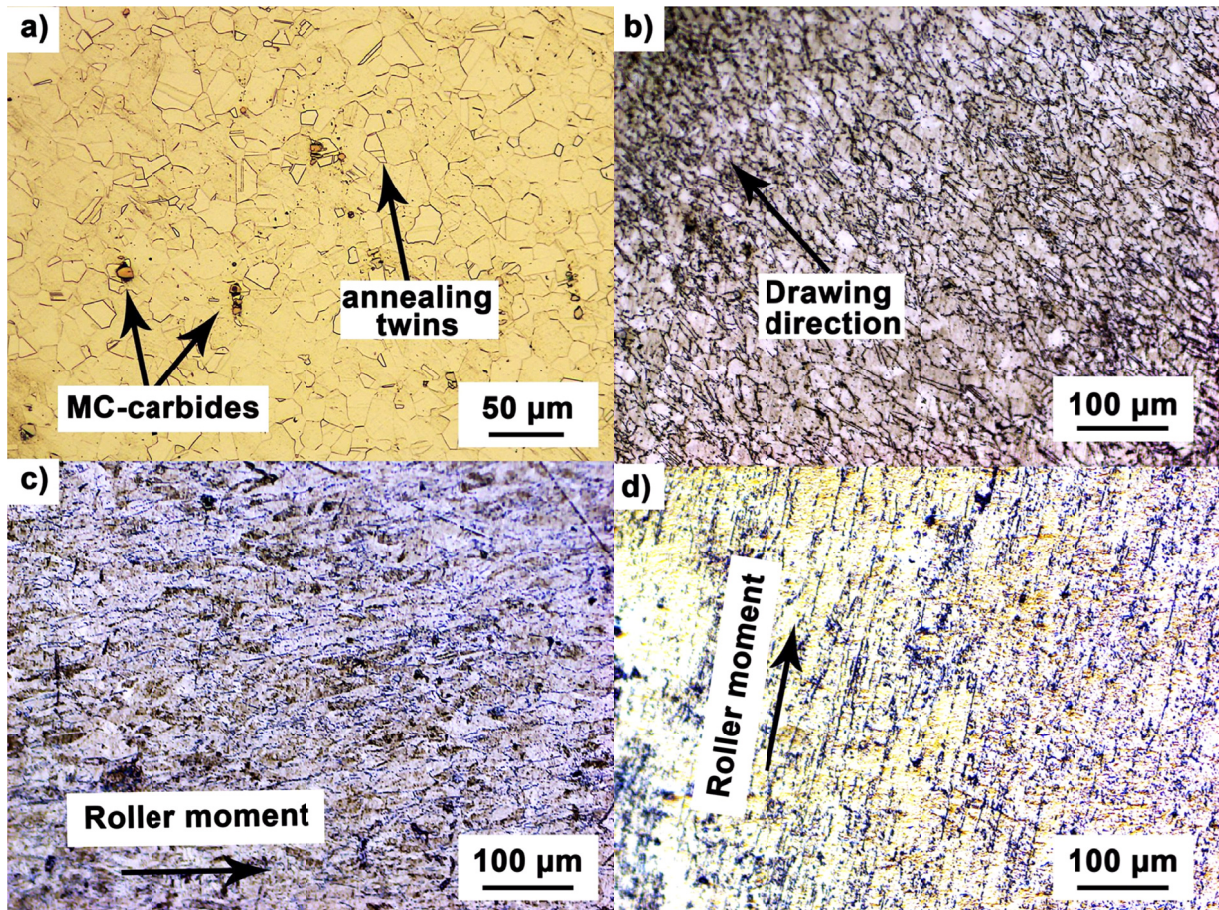


Fig. 10. Microstructure of the sheet material metal AMS 5596: a) in the initial state b) after drawing, c) after flow forming $Z = 54\%$, d) after flow forming $Z = 87\%$

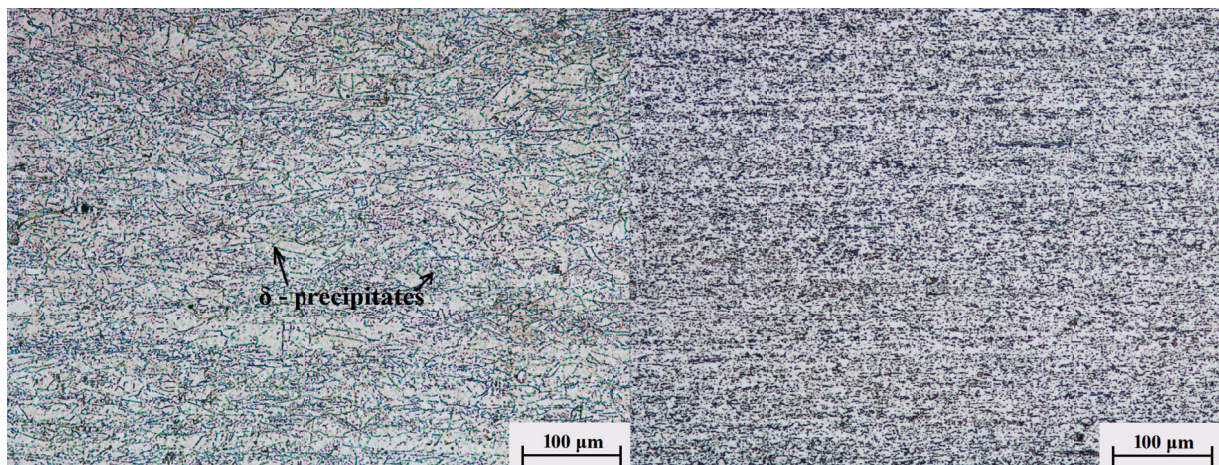


Fig. 11. Microstructure of AMS 5596 cylinders after heat treatment a) $Z = 54\%$ and b) $Z = 87\%$

4. Conclusions

Based on the survey, the following conclusions can be drawn:

1. During flow forming, as the thickness reduction increases, the significant increase in the yield strength and the tensile strength of the sheet material is observed due to work hardening. This increase is most intense in the range of small relative thickness reduction values, i.e. from 0% to 10%. However, the increase in tensile strength is less intense than the increase in yield strength. By using 87% of the thickness reduction an increase in the strength parameters of the drawpiece's material by a factor of 3.5 (yield strength) and almost 1.7 (tensile strength) was obtained compared to the untreated drawpiece's material. Within the test range of relative thickness reduction from 10% to 87%, the increase of the yield strength and the tensile strength can be practically described by linear equations (2) and (4).
2. The largest drop in elongation values during tensile tests was recorded with an increase in the relative thickness reduction from 0% to 10%. At that time, the elongation with the greatest force decreased from 29% to just 6%. Within the test range of relative thickness reduction from 10% to 87%, the decrease in elongation was much less intense. Practically, its course can be described by a linear equation (6).
3. With the parameters of the heat treatment used, the values of the parameters analyzed were dependent on the thickness reduction value. The higher the thickness reduction value, the higher the values of the tested strength parameters and, at the same time, the lower elongation values. The change of these parameters together with the thickness reduction can also be practically described by linear equations, i.e.: (3) for the yield strength, (5) for the tensile strength, and (7) for the elongation.

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