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Research on the effect of temperature increase during flow forming without cooling on 6060 aluminum alloy

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This paper presents the results of flow forming tests for the 6060 aluminum alloy in the T5 heat treatment condition. The tests were conducted on a cylindrical mandrel using two forming rollers without the use of a cooling agent. The purpose of the study was to conduct two experiments. In both experiments, the final gap between the roller and the mandrel was designed to be the same. The impact of the deformation value on the change in the mechanical properties of the material with the simultaneous impact of the number of forming passes was determined. In addition, the effect of the elimination of a coolant on the process was analyzed. The material temperature rise caused by friction between a pair of working parts: the roller—and the workpiece—were examined with a thermal imaging camera.

This paper presents the results of microhardness tests and analyzes the impact of the forming parameters on the strength properties of the alloy. Because the forming process was done without cooling, the impact of the temperature prevailing during the deformation process on the change in the strength of the alloy was studied and analyzed. The deformation zone in which intensive grain deformation took place was determined.

Keywords: *flow forming, tube, aluminum alloy, hardness, plastic forming of metals*

1. Introduction

The impact of the elimination of coolant on the process was analyzed and how the increase in temperature affected the shaped material was examined. Flow-forming is a mechanical working process. It is used to make cylindrical or conical parts for the aerospace, automotive, and construction industries. Typical products made using this technology include parts of rockets, missiles, and lighting poles. By reducing the thickness of the tube wall, the process of elongation of the workpiece along the spindle axis is performed. The CAD model of the flow-forming process is presented in Figure 1.

Depending on the preset boundary conditions, the plasticized material can flow according to the feed of the forming rollers (forward flow forming) or in the opposite direction (backward flow forming) [1].

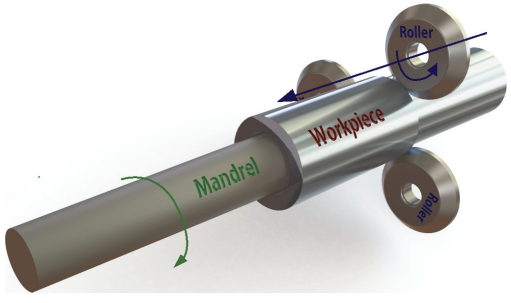


Fig. 1. Schematic of flow-forming process

The flow-forming technology enables high-dimensional tolerances and improves the strength properties of the processed material. The main advantage of this technology is the relatively low cost of the tooling used in production. An additional advantage of the tooling is the considerable versatility of the forming rollers, which can be used to make products that differ significantly in terms of their length, diameter, and material.

Publications on flow-forming of aluminum alloys analyze and prove the significant impact of

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temperature on the processed material. Most of the analyses, however, are focused on how the heat treatment process affects the strength properties of the processed material before forming [2–4]. The number of studies that analyze the effect of rising temperature at the interface of the formed surface is quite limited [5, 6] and those that do exist use a coolant in their analyses.

Flow-forming can be used to form tubes from a variety of metals: aluminum, steel, nickel, and copper. A number of publications on the flow-forming of aluminum alloys have been analyzed, but only a limited number of publications have been identified that accurately analyze the increase in temperature caused by the friction between the roller and the material being formed [5]. The researchers used cooling during the flow-forming and validated their numerical studies with physical tests.

Literature reviews [1, 7] are directly related to the issue of the flow-forming of tubes and discuss research results for the following factors: the way aluminum is aged, the geometry of the forming rollers, the maximum wall thickness reduction in a single pass, the minimum wall reduction, the material flow, and the resulting changes in the dimensions of the formed workpieces. Using the results of the tests [8–10], a roller geometry was designed with the working edge angle $\alpha = 20^{\circ}$.

The authors of the publication [3] examined the maximum deformation of tubes made of two grades of aluminum, 2024 and 7075, in the annealed state. Using macroscopic and microscopic observations, the authors determined the maximum deformation for the grades of aluminum studied. The authors then performed 40% deformation tests for each of the grades; both grades were heat-treated at 490°C and 465°C for 80 and 150 minutes, respectively. The heat-treated material was evaluated for the maximum deformation value using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) microscopy. The tests showed that the maximum degree of deformation for grade 7075 in the delivery condition/grade 7075 heat-treated, grade 2024 in the delivery condition/grade 2024 heat-treated were 40%, 40%, 50%, and 40%, respectively. The use of higher deformation values led to the formation of microcracks and micro-cavities formed in the outer layer and the core. Vickers HV microhardness tests for all grades indicated that the outer part of the tube, which was in contact with the roller, had a higher hardness than the material closer to the mandrel.

An analysis of papers [3, 10–12] made it possible to estimate the mutual impact of the parameters of the flow forming of the tubes. The authors selected a range of process parameters: relative thickness reduction/deformation between 30 and 45% [13–15], feed rate 50–100 mm/min [13, 16], and a rotational speed of 60–100 RPM [15, 17] in order to minimize groove formation. An analysis of the literature has shown that the maximum thickness reduction of the wall of aluminum from the 6xxx group can be carried out up to 40%. A thickness reduction of more than 40%, may cause the formation of micro-cracks and micro-cavities in the outer surface of the formed tube [3].

An FEM analysis of the thermo-mechanical process of flow forming provided information on the forces generated and the temperatures produced due to the friction at the contact surface between the roller and the processed material. The study indicates that after moving the rollers by a distance of 13.75 mm, the temperature can increase up to a range of 186°C to 255°C. The authors note that the temperature peak on the outer surface of the workpiece reaches up to 400°C. According to the authors, despite the fact that the process is carried out cold, the effect of a reduction of the hardness of the processed material due to an increase in temperature should not be excluded. Comparison of details from real tests with FEM test results showed an error of 2.3% [5].

2. Research methodology/design of the experiment

The flow-forming tests were carried out on 500-mm long tubes made of the 6060 T5 alloy. The diameter of each tube was in the range of $\phi 76^{+0.14}_{+0.06}$ mm, while the thickness was 7.6 ± 0.1 mm. The chemical composition of the alloys studied is shown in Table 1. The tubes for the flow-forming tests were obtained by hot extrusion.

Table 1. The chemical composition of the AA 6060 tested

Element	Si	Mg	Fe	Mn	Cr	Ti	Cu	Zn
Wt%	0.55 ± 0.03	0.381 ± 0.01	0.088 ± 0.02	0.063 ± 0.04	0.014 ± 0.00	>0.010 ± 0.00	0.002 ± 0.00	0.001 ± 0.00

The authors of the study, on the basis of their many years of research experience in the plastic forming of aluminum alloys of the 6xxx series [18] and their ongoing work in the field of flow forming [19], adopted the following research method.

The flow-forming tests were carried out on an MZWH-600 flow-forming machine for the feed/revolution parameter equal to 0.4 mm/rev. The tests were conducted to determine the impact of the number of flow-forming passes on the behavior of the material during the plastic forming process and to analyze the impact of the heat generated during the forming on the deformed material. The flow-forming tests were carried out without the use of a cooling agent.

The tests were conducted using one pass and three passes of rollers. A roller was used with a working edge angle of $\alpha = 20^\circ$ and a calibration edge angle of 5° (Fig. 1).

In the flow-forming tests, the constant factors were the forming speed and the total deformation value. The variable factor, on the other hand, was the number of flow-forming passes (1 and 3), assuming that the gap between the mandrel and the forming roller in the third forming pass is the same as during the forming in only one pass.

The tests were conducted for the forming speed of 0.4 mm/rev, assuming a roll feed rate of 200 mm/min. Aluminum tubes with a length of 500 mm were formed over a section of 200 mm. No cooling was used during the flow-forming process. A diagram of the forming process is shown in Figure 2.

The objectives of the tests were:

- to determine the impact of temperature on the forming process;
- to determine the impact of the number of forming passes on the geometry of the final product and the strength properties of the aluminum alloy; and

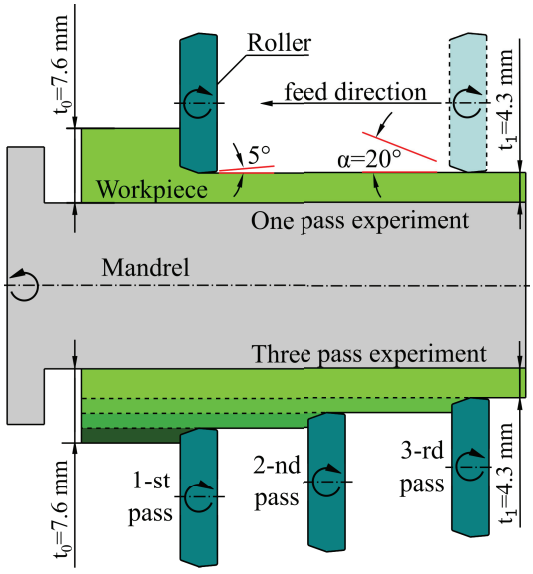


Fig. 2. Diagram of the flow forming process. The top half of the figure shows the trajectory of the rollers in one pass, while the bottom half of the figure shows the trajectory for 3-pass experiment

- to determine the impact of the number of forming passes on the grain size.

The gap between the forming rollers and the mandrel for the specimens formed in one pass was the same as the gap in the last pass for the specimens formed in 3 passes. In both of these cases, it was equal to approximately 4.3 mm, $\varepsilon_t = (43.4\%)$.

For the forming in 1 pass, the total value of deformation calculated from equation (1) was 43% mm, and for the forming in 3 passes, the value of deformation of each pass was equal to one-third of the value of the total deformation, i.e., first pass $\varepsilon_1 = 14.5\%$, second $\varepsilon_2 = 16.9\%$, third $\varepsilon_3 = 20.4\%$.

Because the forming process was carried out in an unconventional manner, that is, without cooling, an analysis of the temperature change during the forming process was conducted using a VarioCAM® high-resolution thermal imaging camera.

The factors studied were the following:

- **relative deformation** (deformation value) expressed by the change in wall thickness using equation (1):

$$\varepsilon_t = \frac{t_0 - t_1}{t_0} \cdot 100\% \tag{1}$$

where:

t_o – initial wall thickness;

t_1 – wall thickness after the forming pass.

- **microhardness HV0.1** (Vickers Micromet 2104 hardness tester);
- **mechanical properties $R_{p0.2}$, R_m, A_{50}, Z** (Instron 4483 series H1907); and
- **grain size** (Zeiss Axio Observer 7 optical microscope).

An Insize micrometer with a measurement accuracy of 0.01 mm was used to measure the wall thickness of the material formed.

3. Tests

3.1. Test results for the material in delivery condition

Before the flow-forming tests, the strength parameters (Table 2) and the microhardness of AA 6060 were determined in the "as delivered" condition (see Fig. 9).

Table 2. The mechanical properties determined in the static tensile test

Tensile speed [mm/min]	**$R_{p0.2} \pm U_{Rp0.2}$ [MPa]**	**$R_m \pm U_{Rm}$ [MPa]**	**$A_{50\ mm} \pm UA_{50\ mm}$ [%]**	**$Z \pm U_Z$ [%]**
0.5	137 ± 12	176 ± 12	20.1 ± 1.0	64.8 ± 2.5
5	137 ± 12	179 ± 12	19.4 ± 1.9	61.7 ± 4.4
50	135 ± 12	177 ± 12	20.9 ± 2.5	61.9 ± 6.5
500	141 ± 12	182 ± 12	16.6 ± 5.7	57.0 ± 3.7

Δt – calculated according to formula 1; $R_{p0.2}$ – offset yield stress; R_m – ultimate tensile strength; $A_{50\ mm}$ – reduction of area in cross-section of sample; Z – elongation of sample; HV – hardness vickers.

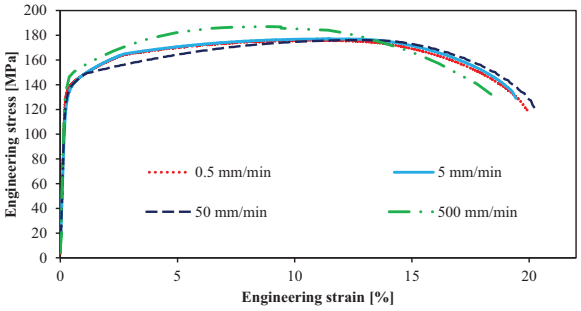


Fig. 3. The tensile curve for specimens deformed at the speed of v = 0.5–500 mm/min

The static tensile test was carried out at 21.1°C on 12 standardized specimens taken longitudinally from a tube with an outside diameter of $D_o = 76$ mm. The test was conducted for four traverse movement speeds: 0.5, 5, 50, and 500 mm/min.

The results of the static tensile test are shown in Table 2, and the mean values of the determined quantities are also given, along with the values of the expanded uncertainty U for the confidence interval of 95% and the expansion coefficient of k = 2. The initial measurement length was $L_o = 50$ mm. Figure 3 shows the results of the tests.

Slight changes in the mechanical properties of the material were observed for a tensile speed of 500 mm/min. Since the changes in the results are small, when determining the feed rate a decision was made not to consider the effect of the forming speed as a significant factor.

The HV0.1 microhardness was measured on the cross-section of the specimen at 0.3 mm intervals. The microhardness range was 54.1 to 67.1 HV, and the average value of microhardness measurement HV0.1 was 61.7, with the standard deviation of 3.1.

3.2. Test results after the flow-forming process

Since no cooling was used during the forming, the entire process was analyzed with a thermal imaging camera. It was observed that heat was released during the flow-forming process as a result of the deformation of the material, and that the heat depends on the size of the deformed material (Fig. 4).

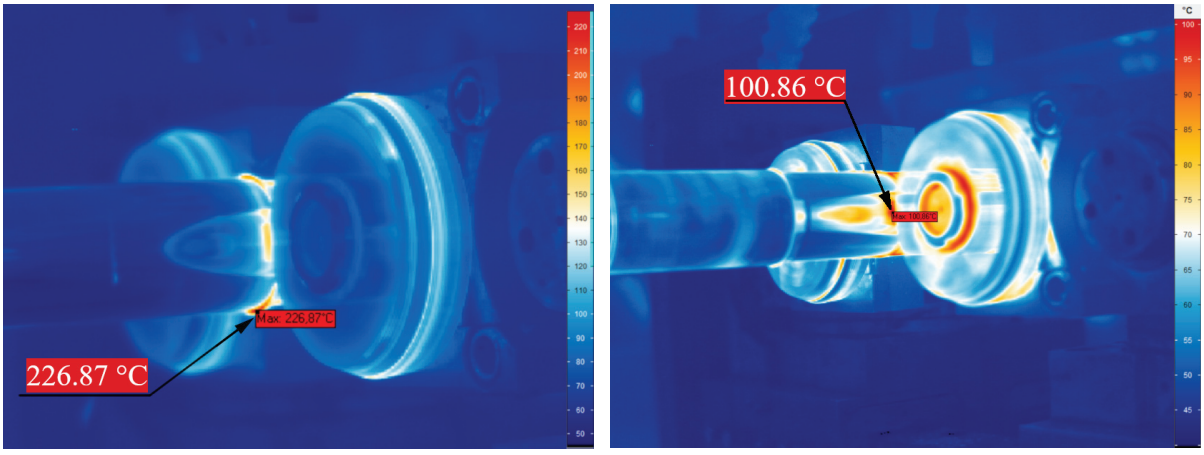


Fig. 4. Temperature distribution (°C) during the forming in 1 pass (left) and in the first pass of 3 passes experiment (right)

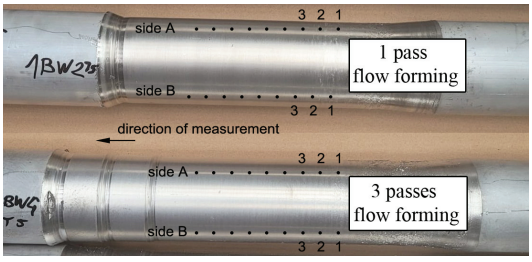


Fig. 5. The AA 6060 material after flow forming

As the material is formed, the temperature gradually rises; in the case of the forming in 1 pass (wall thickness reduction of 3.3 mm), a maximum temperature of 226°C was reached, while in the case of the forming in 3 passes (wall thickness reduction of 1.1 mm per pass), the maximum temperature reached 100°C. It was observed that the increase in temperature is directly influenced by the value of the deformation of the material, which is confirmed by the results of the tests presented in paper [5]. In the ongoing process, the temperature has a tendency to increase by an additional 30°C and stabilize after around 45 s.

After the forming process (Fig. 5), the specimens were subjected to further testing, i.e., geometry analysis, microhardness tests over the thickness of the specimen, grain analysis, and static tensile testing.

The slight peeling of the material on the right side of the specimens (Fig. 5) did not affect the test results. Specimens for further analysis were taken from an area where peeling was not present. The results of the flow-forming tests that were performed at feed of 0.4 mm/revolution speed are presented in Table 3.

Although in the last pass the gap between the rollers and the mandrel was the same for all the specimens tested, a different relative deformation value was obtained for specimens formed in one and three passes. The reason for this was the springing of the material, which was much greater in one pass than in three consecutive forming passes. The magnitude of the springing was determined as the difference between the preset and obtained deformations. For one pass, the magnitude of the springing was 9.1% (0.7 mm), and for three passes it averaged 3.3% (0.2 mm). The smaller magnitude of springing is due to the strengthening of the material in previous forming passes and a smaller deformation zone in one pass.

Figure 6 shows the distribution of the material thickness obtained in the flow-forming process.

In the most extreme cases, the wall thickness measurements on the opposite sides (thickness A and B) differed by 0.2 mm. The difference was due to the manufacturing accuracy of the tube, whose wall thicknesses on opposite sides differed by about 0.25 mm. The number of forming passes had little effect on offsetting the inaccuracy of the wall made before the forming process.

Table 3. A summary of the results of the flow forming of aluminum alloy 6060

No.	Type of experiment	t_0 (mm)	t_1 (mm)	$\Delta t = t_0 - t_1$ (mm)	Average Δt (mm)	ε_t (%)	Average ε_t(%)
1	1 pass	7.55	4.98	2.57	2.62	34%	35%
2	1 pass	7.7	4.96	2.74		36%	
3	1 pass	7.6	5.04	2.56		34%	
4	3 passes	7.55	4.54	3.01	3.04	40%	40%
5	3 passes	7.65	4.72	2.93		38%	
6	3 passes	7.55	4.37	3.18		42%	

Table 4. Strength properties of specimens after the forming

Number of forming passes	Δt (mm)	$R_{p0,2}$ (MPa)	R_m (MPa)	$A_{50\ mm}$ (%)	Z (%)	HV
1	2.62	199–207	216–224	10.2–12.7	45.7–53.4	73.0
3	3.04	211–226	220–239	7.1–12.1	50.4–60.8	78.7

Δt – calculated according to formula 1; $R_{p0,2}$ – offset yield stress; R_m – ultimate tensile strength; $A_{50\ mm}$ – Reduction of area in cross-section of sample; Z – elongation of sample; HV – hardness vickers

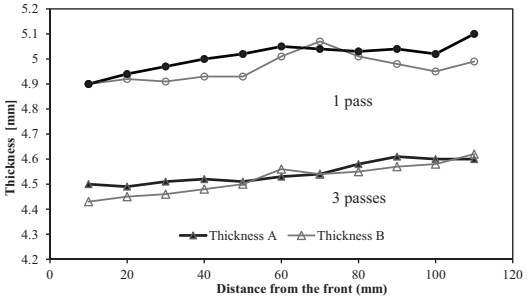


Fig. 6. The wall thickness distribution measured after 1-pass and 3-pass flow forming

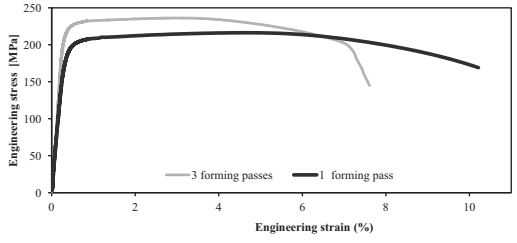


Fig. 7. A diagram showing the results of tensile testing of the specimens after 1-pass and 3-pass flow forming

Table 4 summarizes the results of the strength tests performed on the specimens after the flow forming, and Figure 7 shows the graphs obtained on the basis of the tests.

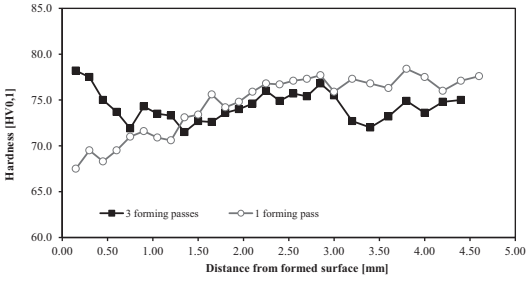


Fig. 8. Results of microhardness measurements on the pipe cross-section after the flow-forming process in 1 pass and 3 passes

An analysis of the results shown in Table 4 and Figure 7 indicates the impact of the number of flow-forming passes on material strengthening. Since the strengthening of the material is directly related to hardness, the impact of the number of forming passes on the hardness of the product was analyzed in detail. The results are shown in Figure 8.

Microhardness measurement from the surface to the bottom of the tube in the case of the experiment using 1 pass of the forming roll indicates that the hardness at the surface is low (67.5 HV) and increases with increasing depth from the surface into the bottom of the material (75.2 HV). The opposite situation is in the

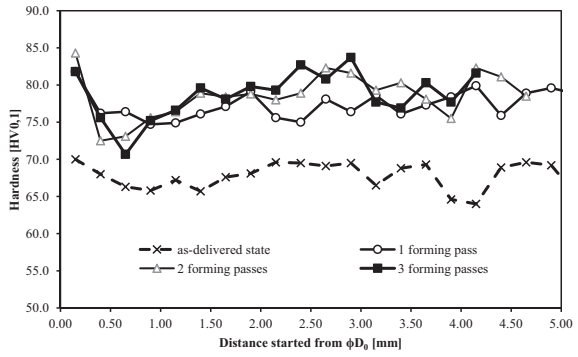


Fig. 9. The microhardness distribution over the thickness of the material formed

case of forming to this thickness in 3 passes. The graph showing the hardness distribution from the surface to the bottom of the workpiece after 3 passes indicates a higher hardness at the surface (78.2 HV), which decreases as you move away from the surface towards the bottom of the workpiece (74.0 HV). Since this phenomenon was reflected in many specimens, a decision was made to analyze in detail the change in microhardness that occurred in specimens formed in 3 passes. The hypothesis was posed that the change in hardness near the surface is due to the impact of the temperature generated during the forming pass.

In order to see how individual forming passes affect microhardness, microhardness changes were analyzed for successive, consecutive forming passes. Examples of the results for a specimen formed in three passes are shown in Figure 9.

Each of the three forming passes was characterized by a slight increase in hardness near the surface of the specimen; however, the hardness did not change with the number of passes but remained at a similar level.

In order to confirm and explain the phenomenon of material strengthening just below the surface, the microstructure of the specimens obtained was analyzed. Figure 10 shows the results of the tests.

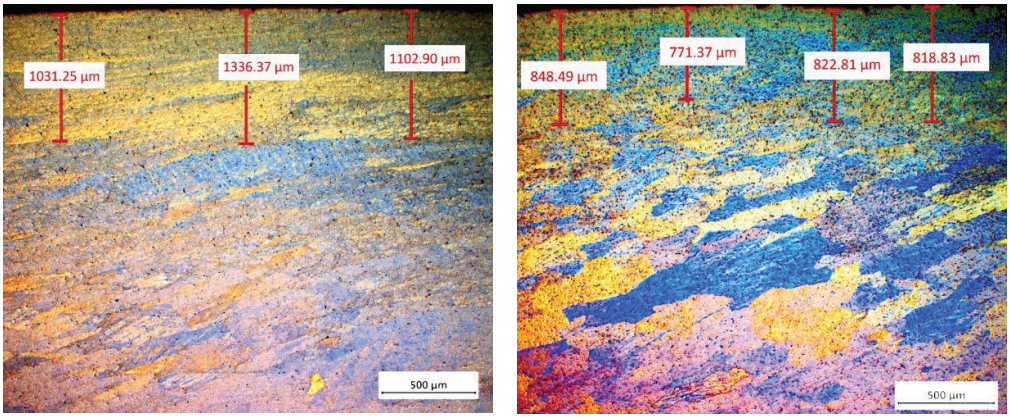
The gap between the roller and the mandrel in both experiments was set so that it resulted in $\Delta t = 3.3$ mm. However, the relative deformation $\Delta\varepsilon_{1\text{-pass}} = 34.3\%$ for one forming pass is less than that for three forming passes, which is equal to $\Delta\varepsilon_{3\text{-passes}} = 40.1\%$. Nevertheless, the height of the deformation zone on the grain size is greater after the 1-pass experiment than in the case of the 3-pass experiment. In order to more easily illustrate this phenomenon, the unit of the deformation value was changed from percent to millimeters. For 1-pass forming, the forming height was 2.7 mm, while for 3-pass forming, the forming height for each pass was an average value of around 1.01 mm, as shown in Figure 10. Examinations of the structure in the 1-pass experiment (Fig. 10a) indicate significant grain fragmentation, which can be observed down to a depth of about 1.2 mm. For three forming passes, it was equal to only 0.8 mm (Fig. 10b).

For the 3-pass experiment, the preset forming height was on the level of 1.1 mm, while the deformation height obtained after spring back was equal to 0.98 mm. The area of the forming zone where the material was formed in the first pass was fully formed in the second pass and then in the third pass. The depths at which significant grain fragmentation occurred in the first pass did not result in a systematic increase in subsequent passes. As a result, the strengthening, as well as the forming zone created in the previous pass, was fully formed in the next pass (Fig. 11).

This is confirmed by the measurements of microhardness (see Fig. 9) and grain size in individual forming passes (Fig. 12). Based on the above observations, it was concluded that grain deformation is directly influenced by the value of deformation set in a given flow-forming pass, rather than the total value of deformation.

Both the microhardness measurement (Fig. 9) and the metallographic analysis show that the deformation zone obtained in the first flow-forming pass remains at a similar level of about 800 μm in the following two passes, as shown in Figure 12. Microstructure images with hardness measurements confirm the research results of the article [20] indicating that the distribution of equivalent plastic strain in the cross-section of the tube processed in the flow-forming process is not linear, but the highest concentration is in the top layer, while the middle and bottom layers show much lower strengthening due to plastic deformation.

Significant grain refinement, both after 1-pass and 3-pass flow forming, makes it impossible to



(a) 1–pass experiment (b) 3–pass experiment

Fig. 10. The microstructure of the specimen after flow forming: (a) 1-pass experiment, (b) 3-pass experiment

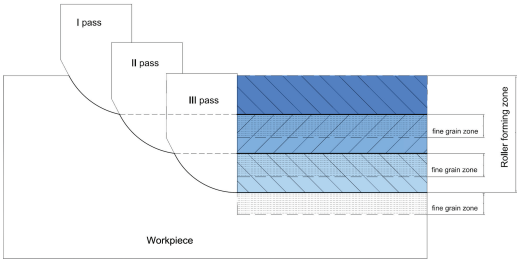


Fig. 11. Diagram of sample's microstructure individual flow forming pass

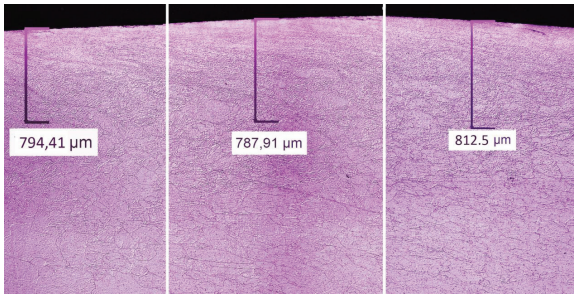


Fig. 12. The microstructure of the product after individual flow-forming passes

measure its size and interpret the change in microhardness on this basis. Therefore, to determine the influence of temperature during the flow-forming process without a cooling agent on the microhardness of the material at the deformed surface, a deeper analysis of this issue was carried out. First, the results of microhardness at a depth of up to 1 mm were compared for the process without and with a cooling agent. In the first case, the temperature in the contact zone of the processed material with the forming roll increased to 226°C. In the second case, the temperature did not exceed 85°C. In the case in which a cooling agent was used, the microhardness throughout the entire thickness of the sample was very stable and ranged from 73.4 HV to 74.6 HV. In the case where the flow-forming process was carried out without a cooling agent, the microhardness measured 0.2 mm from the surface was 78.2 HV, and at a depth of about 1 mm, the tendency to stabilize the hardness value was measured at about 74.3 HV, as shown in Table 5. Although the difference is small, it is repeatable under the conditions given and was observed on many samples.

Table 5. Hardness properties of specimens after the flow forming

Distance from surface (mm)	With cooling agent (HV)	Without cooling agent (HV)
0.2	73.5	78.2
0.4	73.4	77.5
0.6	74.6	75.0
0.8	74.5	74.7
1.0	74.6	74.3

HV, hardness Vickers.

Additionally, in order to explain the phenomenon of hardness change at the depth of up

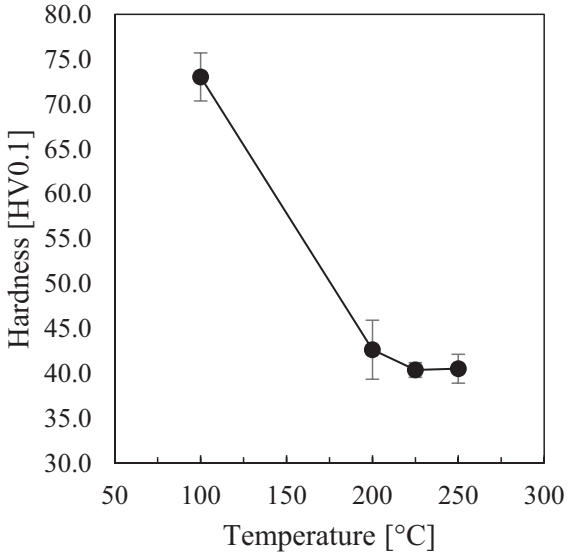


Fig. 13. The impact of temperatures 100, 200, 225, and 250°C on the microhardness of aluminum alloy 6060

to 1 mm from the deformed surface, a decision was made to investigate whether the heat generated during the process has a direct impact on the deformed material.

It was presumed that the change in hardness between the specimens seen in the area from the formed surface to a depth of about 1 mm was caused by the heat released during the forming process, which had a direct impact on the change in hardness of the material at the formed surface. Additional testing of the aluminum was conducted after the forming to validate the results. Specimens measuring 20 × 30 mm, which were cut from specimen no. 2 (Table 3), were prepared and heated with a furnace to a temperature in the range of 100°C to 250 °C. Figure 13 shows the results of the tests.

Analysis of the sample hardened by the flow-forming process was subjected to a temperature of 100°C, at which no change in microhardness was observed. However, it was observed that temperatures of 200°C and above resulted in a significant decrease in microhardness. As a result, it was found that the temperature arising during the three-pass forming process (approximately 100°C, Fig. 4) has no effect on changes in the microhardness of the material formed.

The tests carried out at higher temperatures make it clear that a temperature of 200°C has a significant impact on the microhardness of the specimen. Observations with a thermal imaging camera during the forming of aluminum 6060 in the one-pass experiment at $\Delta t = 2.62$ mm confirm that the temperature during the forming increased to 225°C. Based on this, it was confirmed that the increase in temperature caused the decrease in hardness of the material in the deformation zone.

The results of temperature measurements using a thermal imaging camera during the flow-forming process that have been presented indicate that the temperature of the processed material can be increased up to 225°C. The microhardness measurements performed indicate that increasing the temperature at the contact between the roller and the processed material leads to a decrease in the hardness of the material. The results presented in this article are consistent with the FEM [5] research results and the research results of technological trials in the article [21] in which the authors used a heated roller. Moreover, annealing studies [22] indicate that heating an aluminum alloy to a temperature in range of 200°C to 250°C led to a decrease in hardness and slight increase of plastic properties such as elongation; the authors also indicated that the alloy they tested showed greater susceptibility to the temperature value than to the heating time.

4. Conclusions

1. It is possible to form with flow-forming aluminum alloy 6060 without cooling agent.
2. As the deformation increases, the magnitude of the material's springing increases. To achieve the same deformation with less springing, more flow-forming passes must be performed.
3. At a deformation ε_t in range: 14.5%, 16.9%, and 20.4% for a three-pass experiment, there were no changes in the microhardness of the material, while at a deformation of 40% for one-pass experiment, the high temperature

caused changes in the microhardness at the surface of the deformed material.

4. A wall thickness reduction of 3.3 mm results in significant grain deformation to a depth of up to about 1.2 μm, while a wall thickness reduction of about 1.1 mm results in grain deformation to a depth of up to 0.8 μm, whereby no increase in the grain deformation depth was observed when performing successive forming passes at a wall thickness reduction level of 1.1 mm.
5. As the value of deformation increases, the temperature during the forming increases and at a level above 200°C affects the strength properties of the material formed.
6. Increasing the temperature to about 100°C during the forming process does not affect the microhardness of the deformed material.
7. Eliminating the cooling agent from the flow-forming process changes the microhardness of the product shaped at a depth of up to 0.75 mm. An increase in deformation in one operation causes an increase in temperature during the flow forming, which reduces microhardness. If the flow-forming operation is divided into multiple roller passes, the microhardness increases to a depth of 0.75 mm.
8. In the case of shaping in one pass, the fine grain zone is larger than in the case of shaping in three passes.

Conflicts of interests

The authors declare that they have no conflicts of interest.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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