Roll Forming Technology for Manufacturing Axisymmetric Automotive Components

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Abstract

A unique roll forming technology that permits complex axisymmetric components, such as automotive wheels and turbine disks, to be formed in a single forming operation, has been developed by two Russian institutes, the Institute of Technical Physics of the Russian Federal Nuclear Center and the Institute for Metals Superplasticity Problems. This process was used to fabricate automobile wheels from a Russian AVT alloy, a 6010 aluminum alloy equivalent. The process included steps of isothermal compression of the initial blanks, isothermal forging of the blanks into preforms, and final isothermal roll forming of preforms into wheel shapes, all at 430°C for the AVT alloy. The microstructure and mechanical properties were evaluated at various locations in the finished wheels by optical metallography and tensile testing at elevated temperatures. Tensile properties were obtained by strain-rate change tests and tensile tests to failure at high strain rates. Microstructure and mechanical properties of the preforms and blanks were also evaluated. The results indicate that dynamically recovered microstructures were developed during the processing, which showed relatively high strain rate sensitivity and rendered sufficient plasticity at the elevated temperature for the wheel fabrication process.
Introduction

A unique roll forming technology that permits complex axisymmetric components, such as automotive wheels and turbine disks, to be formed in a single forming operation, has been developed by two Russian institutes, the Institute of Technical Physics of the Russian Federal Nuclear Center (VNIITF), and the Institute for Metals Superplasticity Problems (IMSP). Current technology for making such components outside Russia requires either casting parts (with inherently inferior mechanical properties) or forming several components followed by machining and welding operations. The roll-forming process offers the opportunity to manufacture a strong component in one continuous, economical operation\textsuperscript{[1]}. In addition, the process eliminates the need to manufacture the matched die sets that are required in conventional forging operations. Thus the cost of the dies and the time required to manufacture them can be eliminated. The resulting product could find acceptance in a high volume, highly competitive marketplace.

Automobile wheels were made by this process using 5083, Russian AVT (6010 equivalent), 6061, and 7000 aluminum alloys. Microstructures and mechanical properties at various locations on the wheels and preforms, and near the surface of blanks of the starting materials were evaluated at the Kaiser Aluminum & Chemical Corporation’s Center for Technology and Lawrence Livermore National Laboratory (LLNL). In the present report, the results for the Russian AVT alloy wheels are presented. The roll-forming process and the results of microstructure and mechanical property evaluation are described. The analyzed mechanical properties include the deformation behavior at elevated temperature.

Materials and Wheel Fabrication Processes

The starting materials were ingots of the Russian AVT alloy (a 6010 equivalent). The chemical composition of the AVT alloy together with the Aluminum Association’s limits of composition for the 6010 alloy are shown in Table 1. The AVT’s Mg content is lower than the minimum, and its Cu content is at the minimum required for the 6010 composition. The size of the ingot was 225 mm diameter and 1200 mm in length.

<table>
<thead>
<tr>
<th>Material</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVT wheel</td>
<td>0.99</td>
<td>0.23</td>
<td>0.16</td>
<td>0.31</td>
<td>0.51</td>
<td>--</td>
<td>0.02</td>
<td>0.06</td>
<td>Bal.</td>
</tr>
<tr>
<td>AA’s limits</td>
<td>Min.</td>
<td>0.8</td>
<td>--</td>
<td>0.15</td>
<td>0.2</td>
<td>0.6</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>for 6010</td>
<td>Max.</td>
<td>1.2</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td>0.1</td>
<td>0.25</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The wheel fabrication by the present technique requires essentially two main steps of operation: prior forging and subsequent roll-forming. The fabrication processes described below are for wheels intended for use in the Russian "Samara" VAZ-2108 model passenger automobiles. The fabrication process for manufacturing the wheels consisted of seven sequential steps:

1) *Slicing of ingots to blanks of 225 mm diameter and 91 mm thickness.*

2) *Homogenization annealing of the blanks.* Annealing was done in three sequential steps, (a) 450°C for 2 hours, (b) 490°C for 2 hours, and (c) 530°C for 8 hours.
3) *Isothermal compression of each blank from a thickness of 91 mm to 71 mm.* This deformation, done at 430°C and a strain rate of $10^3$ - $10^2$ s$^{-1}$, provided the necessary starting geometry and improved the microstructure.

4) *Isothermal forging of the blanks into preforms.* Forging was done with a 1600 ton capacity hydraulic press at 430°C and a strain rate of $10^3$ - $10^2$ s$^{-1}$. The time required for this isothermal forging step did not exceed 10 minutes.

5) *Isothermal roll-forming of wheel.* Roll forming was done at 430°C and a strain rate of $10^0$ to $10^1$ s$^{-1}$ using a computer-controlled Leifeld PNC-600-4/2 roll forming machine shown in Fig. 1. This roll-forming technology was developed at IMSP in collaboration with VNIITF. The time for the isothermal roll-forming did not exceed 10 minutes.

6) *Heat treatment.* The as-formed wheels were heat treated to T6 temper by heating to 530°C for one hour, quenching in water, and then aging at 165°C for 10 hours.

7) *Surface machining and drilling to finished wheel specifications.*

Fig. 2 shows the three stages of the fabrication, (i) compressed blank, (ii) preform after isothermal forging, and (iii) roll formed wheel. Figure 3 shows an example of the finished wheels. It was demonstrated at IMSP that the workability and deformation forces for 6061 alloy were almost identical to those of the AVT alloy. The difference did not exceed the accuracy of measurements, indicating that wheels can be manufactured from the 6061 alloy using the identical process.

![Fig. 1. Isothermal roll forming machine.](image-url)
Evaluation of Microstructures and Mechanical Properties

Microstructure Analysis:

A thin slice of about 1 cm thickness was cut out of a finished wheel, ground, polished, and macroetched so that the entire macrostructure on a radial section of the wheel could be examined, as shown in Fig. 4. The rim section of the wheel in the photomacrograph shows a stronger contrast after etching than the hub section, indicating that the recrystallized grains were large in the rim section.
Metallographic samples were prepared from the blank and the rim section of the preform. The microstructures on the cross-section parallel to the rotational axis are shown in Figs. 5 (a) and (b). Microstructures show a strong columnar structure of coarse grains in the blank, Fig. 5(a), and a similar pattern but of finer grains in the rim section of the preform, Fig. 5(b). Fig. 5(b) indicates that the isothermal forging of a preform from a compressed blank refined the microstructure but still retained the elongated feature of the cast ingot microstructure.

Additional metallographic samples were cut out from several locations in the hub and rim sections of the finished wheel. Microstructures at the locations marked “A”, “B”, and “C” in Fig. 4 are shown in Figs. 5(c), 5(d), and 6. Microstructures are much coarser in the rim section, Fig. 5(c), than in the hub section, Fig. 5(d), where equiaxed subgrains of as small as 5-10 μm are visible. During the final roll forming step, the rim section was worked at a very high strain rate of $10^0$ to $10^3$ s$^{-1}$ reducing its thickness to 1/5 of the original thickness. This rapid and heavy hot working must have generated local adiabatic heating and abundant strain energy, which triggered in-situ dynamic recovery. Thus a fine-subgrained microstructure was produced at the end of the forming step. During subsequent T6 heat treatment significant static recrystallization and grain growth occurred which produced a large, recrystallized grain structure as shown in Fig. 5(c).

Most of the hub section, on the other hand, was heavily worked at a lower strain rate of $10^3$ to $10^2$ s$^{-1}$ during the preform forging, but virtually unworked during the final roll forming and T6 heat treatment. Thus, the hub section might have recovered and stabilized its subgrain structure, but have not experienced significant recrystallization and grain growth during the roll forming. A study on a 3000 series alloy showed that static recrystallization and grain growth would not

![Fig. 4. Photomacrograph of a radial cross-section of the Russian AVT alloy wheel. Microstructures at the locations marked “microstructure” are shown in Figs. 5 and 6. The locations marked “tensile” show the areas from which tensile test samples were taken.](image)
occur if hot working at an elevated temperature was followed by annealing at the same or lower temperature. The hub section experienced some static recrystallization and grain growth during the T6 treatment. However, the extent of recrystallization and grain growth was limited since much of the strain energy introduced during the forging step was lost during roll forming. Thus, the driving force for recrystallization and grain growth would have come only from the thermodynamic potential provided by the temperature difference between the roll forming (430˚C) and the solution treatment (530˚C) for the T6 temper. The driving force provided by the temperature difference would need to be sufficient to overcome the stabilized subgrain structure and initiate recrystallization and grain growth. Therefore the fine subgrain microstructure shown in Fig. 5(d) must have been developed from the fine columnar grain structure of the forged preform shown in Fig. 5(b). This microstructure would have been developed mostly through recovery and subgrain stabilization during the roll forming step with less influence from recrystallization and grain growth by T6 treatment.

The area marked “C” in Fig. 4 where the rim and hub sections meet shows an interesting dark and light contrast on the rim side and a light contrast on the hub side. Such contrasts indicate that the roll forming operation could deform the microstructure locally to a certain depth but not necessarily across the entire thickness. The area “C” was examined for the microstructural transition from the rim side to the hub side as shown in Fig. 6. Fig. 6(a) is a low magnification photomicrograph of the “C” area. Fig. 6(b) shows a well-developed, recrystallized large-grain structure of the rim side in the upper part of Fig. 6(a), whereas Fig. 6(d) shows a fine equiaxed subgrain structure of the hub side in the bottom part of Fig. 6(a). Fig. 6(c) represents the
transitional area between the rim and hub sides with a mixture of fine equiaxed subgrains and long elongated grains, i.e., partially recrystallized structure. The microstructural features in Fig. 6 support the observations made from Figs. 4 and 5 that the coarse grained and highly textured structure in the rim section was created by the final roll-forming and subsequent T6 treatment.

Metallography of the wheels in the as-roll formed condition prior to the T6 temper treatment need to be done to fully understand the microstructural development during the roll forming process. Especially TEM work and measurements of grain/subgrain boundary misorientation angles would help clarify the nature and mechanisms of the microstructure refinement.

Fig. 6. Photomicrographs from the area marked “C” in Fig. 4 of the finished wheel manufactured from the Russian AVT alloy. The low magnification micrograph (a) shows the structure of the area where the rim and hub sections conjoin. Micrographs (b), (c) and (d) were taken from the upper, middle, and lower third areas shown in (a). Notice (b) was taken at a lower magnification than (c) and (d).

Mechanical Properties:

Room temperature properties: Small tensile test samples were prepared from the same finished wheel from which the metallographic samples were taken. Areas where the tensile samples were taken are marked “tensile” in Fig. 4. The temperature of testing is indicated as “room temp.” or “elevated temp.”. Tensile samples were taken from the areas where sufficient material volume was available. The tensile axis was selected to be either parallel to the axis of rotation for the
wheel, blank, or preform, or parallel to the circumferential direction. Two samples from each of two selected areas were tested at room temperature at a strain rate of $10^{-4} \text{ s}^{-1}$ and their results and average values are listed in Table 2. These results, when compared with the known properties of the 6010 alloy\cite{4}, show that the wheel was indeed in the T6 heat treated condition.

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Table 2. Tensile properties at room temperature.

<table>
<thead>
<tr>
<th>Specimen location, orientation, and dimensions of gage section*</th>
<th>Tensile strength MPa</th>
<th>Yield strength MPa</th>
<th>Elongation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle of rim, tensile axis parallel to the axis of the wheel, L=25mm, T=5mm, W=6.4mm</td>
<td>319</td>
<td>267</td>
<td>14.0</td>
</tr>
<tr>
<td></td>
<td>321</td>
<td>255</td>
<td>15.7</td>
</tr>
<tr>
<td>Average</td>
<td>320</td>
<td>261</td>
<td>14.8</td>
</tr>
<tr>
<td>Intersection of the rim and hub, tensile axis parallel to the wheel circumferential direction, L=20mm, D=6.4mm</td>
<td>348</td>
<td>297</td>
<td>16.7</td>
</tr>
<tr>
<td></td>
<td>357</td>
<td>307</td>
<td>17.5</td>
</tr>
<tr>
<td>Average</td>
<td>352</td>
<td>302</td>
<td>17.1</td>
</tr>
</tbody>
</table>

*L: gage length; T: thickness; W: width; D: diameter

**Elevated temperature properties:** Flat tensile samples of 25.4 mm gage length and 5 mm gage width were prepared for the elevated temperature tests and tested using a computer controlled, Instron testing machine equipped with an infrared-heating furnace. Strain rate change tests were conducted by varying the true strain rate from $10^{-4}$ to $2 \times 10^{-2} \text{ s}^{-1}$ in a prescribed manner. Before changing the strain rate, samples were prestrained by ~5% at a strain rate of $3 \times 10^{-3} \text{ s}^{-1}$. The samples were tested at 430°C (the same temperature used to fabricate the wheels) and 500°C. The results of the strain rate change tests are listed in Table 3.

The strain rate sensitivity exponent, $m$, was calculated from the slope ($ \frac{\partial \log \sigma}{\partial \log \dot{\varepsilon}}$) of a log-\sigma-log-\dot{\varepsilon} plot, where $\sigma$ is the flow stress and $\dot{\varepsilon}$ is the true strain rate. The $m$ values listed in Table 3 were the values for the lower strain rates used in the tests. The values were higher at lower strain rates and decreased as strain rates increased, an example of which is shown for the case of the preform circumferential samples in Fig. 7. On some samples, the $m$ values could not be obtained because the sample failed at a low strain (less than 20%) before the strain rate changes could be made.

The total engineering strain to failure, $e_f$, listed in Table 3 should not be confused with the total elongation obtained in a tensile test. The value of $e_f$ is the total sum of strains attained in individual constant true strain rate segments during a strain rate change test. Since no constant strain rate tensile tests were performed at low strain rates to obtain total failure elongations, $e_f$ values were collected as an alternative measure of the total ductility attained in each strain rate change test.
Two interesting observations can be made from the results listed in Table 3. First, higher $m$ values were obtained when the wheel circumferential, preform axial and circumferential samples were tested at 500˚C than at 430˚C, whereas the opposite results were obtained for the blank axial samples. The former group of samples had much finer microstructures than the latter group of samples. During the prestraining and subsequent deformation at changing strain rates, some dynamic microstructural refinement is likely to have occurred resulting in higher strain rate sensitive. The higher $m$ values at 500˚C for the former group of samples seem to indicate that they developed finer microstructures during the tests at 500˚C than at 430˚C and hence showed higher strain rate sensitivity. The blank axial samples, on the other hand, started out with a coarse hot-worked ingot microstructure and showed lower strain rate sensitivity at 500˚C than at 430˚C.

The second observation is that the $e_f$ values of the samples tested at 500˚C were generally lower than those of the samples tested at 430˚C regardless of the source and orientation of the samples. (The one exception is the wheel axial samples. The $e_f$ values of the wheel axial samples were identical at the two temperatures.) Samples tested at 500˚C showed less necking than the samples tested at 430˚C. Failure in these samples results from the initiation, growth and interlinkage of cavities. Particles responsible for cavity formation were abundantly observed in the material as can be seen in Figs. 5 and 6. These results can be explained by higher nucleation and growth rates for cavities that are typically found at a higher temperature. Microstructural studies of the tensile tested samples are under way in order to fully understand the difference in $m$ and $e_f$ values between various samples tested at the two temperatures.

With the exception of two cases, the $m$ values for the $10^{-4}$ to $10^{-3}$ s$^{-1}$ strain rate range as listed in Table 3, was 1/3 to 1/4, indicating that the plastic flow was rate-controlled by dislocation glide or climb controlled creep mechanisms$^{[5]}$. Only one sample, taken from preform in the axial orientation showed $m = 0.48$, indicating a superplastic flow behavior by grain boundary sliding mechanisms. However, its $e_f$ value was only about 35%. The sample failed prematurely probably due to some large constituent particles and inclusions as mentioned above.

Table 3. Results of strain rate change tests at 500˚C and 430˚C.

<table>
<thead>
<tr>
<th>Sample source &amp; orientation</th>
<th>Test temperature</th>
<th>Strain rate sensitivity exponent*, $m$</th>
<th>Total engineering strain to failure, $e_f$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial</td>
<td>430˚C</td>
<td>0.27</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>500˚C</td>
<td>0.15</td>
<td>75</td>
</tr>
<tr>
<td>Circumferential</td>
<td>500˚C</td>
<td>0.27</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>430˚C</td>
<td>0.15</td>
<td>75</td>
</tr>
<tr>
<td>Preform</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial</td>
<td>500˚C</td>
<td>0.48</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>430˚C</td>
<td>0.30</td>
<td>46</td>
</tr>
<tr>
<td>Circumferential</td>
<td>500˚C</td>
<td>0.30</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>430˚C</td>
<td>0.26</td>
<td>95</td>
</tr>
<tr>
<td>Blanks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Axial</td>
<td>500˚C</td>
<td>0.25</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>430˚C</td>
<td>0.33</td>
<td>55</td>
</tr>
<tr>
<td>Circumferential</td>
<td>500˚C</td>
<td>0.27</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>430˚C</td>
<td>0.33</td>
<td>95</td>
</tr>
</tbody>
</table>

*Only values for low strain rate range of $10^{-4}$ to $10^{-3}$ s$^{-1}$ were listed.

Additional round tensile samples of 5 mm gage length and 2.5 mm gage diameter were prepared from the wheel and preform in the axial and circumferential orientations and tensile tested to
failure at high true strain rates of $10^0$ and $10^1$ s$^{-1}$ at 430°C. All samples failed with the same elongation of about 80% regardless of orientation, source of samples or strain rate. But samples from the preform showed 5-10% higher flow stresses than those from the wheel for the same orientation and strain rate. For a given orientation and sample source, samples tested at the strain rate of $10^1$ s$^{-1}$ showed a 20-25% higher flow stress than those tested at the $10^0$ s$^{-1}$ strain rate. When these high strain rate test results for the preform circumferential samples were plotted on the log-$\sigma$-log-$\dot{\varepsilon}$ plot with the results of the earlier lower strain rate change tests, the two data sets coincided as shown in Fig. 7.

The above-described results (of both strain rate change tests at low strain rates of $10^{-4}$ to $10^{-2}$ s$^{-1}$ and tensile tests at high strain rates of $10^0$ and $10^1$ s$^{-1}$) show that the microstructures developed during the wheel fabrication process did not result in large plastic flow at the processing temperature. Nonetheless, the plasticity associated with the developed microstructures was sufficient for the practical application of the fabrication process. There were signs that microstructure conducive to enhanced plasticity at low strain rates in the range of $10^{-4}$ to $10^{-3}$ s$^{-1}$ might have been developed in the isothermally forged preforms as indicated by the test results shown in Table 3.

**Summary and Conclusions**

An incremental roll forming process for manufacturing axisymmetric automotive components was described. Microstructure, mechanical properties and plastic flow behavior of the Russian AVT alloy wheels, preforms and blanks processed using the technology were analyzed, and the following conclusions were obtained.

1. The isothermal forging of preform refined the coarse extruded microstructure in the blanks.

2. The isothermal roll forming of wheel developed a highly elongated coarse-grain structure in the rim area, and an equiaxed fine subgrain structure in the hub area.

3. Values of the strain rate sensitivity exponent, $m$, and total strain to failure, $\varepsilon_t$, measured through strain rate change tests showed that the microstructure developed during the fabrication process was not superplastic but had sufficient plasticity to enable the roll forming process.

4. The results of high strain rate tensile tests at 430°C was consistent with the results of the strain rate change tests.
Acknowledgments

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References
