In order to produce pipe that is more competitive in the global marketplace—for instance, compressor pipe and lining pipe for oil wells—we need to improve the electrowelding systems employed, with the introduction of resource-saving production processes that ensure satisfactory strength (including strength of the weld seam).

The quality of continuous pipe electrowelding may be judged on the basis of the total margin in the width of the initial blank for shaping, welding, and subsequent rolling, which is generally selected by the designer of the production system (Table 1). If we were to employ considerable reduction (up to 7.5%) of the pipe blank in closed shaping cells, taking account of the transverse and longitudinal bending and the rolling in open grooves, we could not expect improvement in the electrowelded pipe; on the contrary, the likely outcome would be excessive energy consumption and load in the equipment, roller wear, residual stress in the final pipe, and accompanying loss of plasticity and local cold hardening.

According to Table 1, the same margin is specified for all types of pipe, regardless of the ratio of the diameter and wall thickness, the mechanical properties of the pipe material, and the thickness of the metal. The margin in shaping, welding, and subsequent rolling may only be minimized by measures aimed at reducing the longitudinal strain and the work of shape change.

### Table 1. Characteristics of pipe-electrowelding systems and the associated tolerances on the width

<table>
<thead>
<tr>
<th>Mill, product range, plant</th>
<th>Number of driven cells (O + C + G + B)*</th>
<th>Rolling diameter $D_0$, mm</th>
<th>Total motor power $N$, kW</th>
<th>Gear ratio $i$</th>
<th>Total rated torque $M_{rat}$, kN m</th>
<th>Total margin $\Delta$, mm</th>
<th>Total reduction, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGA, 150–450 × 4–8, OAO Tagment</td>
<td>6 + 2 + 3</td>
<td>300</td>
<td>500 (750)</td>
<td>14</td>
<td>70 (105)</td>
<td>8–10</td>
<td>1–2.3</td>
</tr>
<tr>
<td>TESA, 73–219 × 3–8, OAO STZ</td>
<td>7 + 3 + 3</td>
<td>440</td>
<td>875</td>
<td>30</td>
<td>260</td>
<td>6–7</td>
<td>0.85–2.3</td>
</tr>
<tr>
<td>TESA, 168–530 × 4–13, ZAO TMK–KPV</td>
<td>2 + 3 + 4 + 1</td>
<td>430</td>
<td>360</td>
<td>80</td>
<td>290</td>
<td>21–22</td>
<td>1.3–4.2</td>
</tr>
<tr>
<td>TESA, 203–530 × 4–10, OAO VMZ</td>
<td>5 + 3 + 4 + 2</td>
<td>600</td>
<td>1120</td>
<td>20</td>
<td>224</td>
<td>42–44</td>
<td>2.6–6.5</td>
</tr>
<tr>
<td>TESA, 50–159 × 2–8, OAO Uraltrubmash</td>
<td>2 + 2 + 2</td>
<td>250</td>
<td>150</td>
<td>40</td>
<td>60</td>
<td>5–8</td>
<td>1.2–2.3</td>
</tr>
</tbody>
</table>

* O, C, G, B, open, closed, grooving, and bending cells.
as well as the parasitic frictional forces and the negative torques on the rollers.

Pipes characterized by moderate diameter, with dimensions in the range $140-530 \times 4-12 \text{ mm}$ ($D/s \geq 30-100$), may be regarded as thin-walled. In shaping, there will be considerable and nonuniform (over the perimeter) residual longitudinal stress on account of the unfavorable conditions of strip deformation. In that case, as a rule, the ends of the pipe will be oval after cutting into measured lengths. In terms of the minimum deformation necessary and sufficient for stable shaping, welding, and subsequent rolling, the total margin for moderate-diameter pipe (wall thickness $4-10 \text{ mm}$) is no more than $5-8 \text{ mm}$, as confirmed by the production of high-quality pipe on TESA 73-219, TESA 50-159, and PGA 150-450 systems, respectively (Table 1).

We know that the useful work required to convert a strip to a cylinder (0–300°), in cells with open grooves, is 5–10% of the total work of the mill [1]. At the same time, the forces in each such cell and on its drive are generally comparable with, and sometimes exceed, the load in cells with closed grooves that are responsible for the basic final shaping, with $360^\circ$ deformation at the perimeter, welding, rolling in grooves, and straightening. Most operational mills contain 4–7 cells with open grooves, for preliminary rough shaping. The rollers are characterized by maximum width, diameter, and cut depth, and the wear of the grooves is nonuniform on account of the difference in relative speeds in the lead and lag zones, when the frictional forces are large. Matching of the speeds and hence optimal loading over all the cells of the mill cannot be ensured by the traditional adoption of the lower roller’s diameter $D_0$ over the tip (floor) of the groove as the rolling diameter in the design of the shaping tool, with an increment of 0.5–2 mm in this diameter on moving from cell to cell.

In closed grooves (Fig. 1a), the rolling diameter ($D_t$) is less than the ideal diameter ($D_i$) but consider-

ably greater than the roller diameter $D_0$ over the tip of the groove. We know that [2]

$$D_t = D_i - \lambda d_g = D_0 + (1 - \lambda) d_g,$$

where $d_g$ is the diameter of the groove; $\lambda$, is the velocity coefficient, which takes values between 0.65 and $\pi/2$, depending on the groove geometry. In general, for a groove of any shape, the calculation of $D_t$ entails determining the position of the center of gravity of the metal’s contact arc within the roller groove

$$D_t = D_i - 2r_i \frac{\sin \alpha}{\alpha} = D_0 + 2r_i \left(1 - \frac{\sin \alpha}{\alpha}\right),$$

where $2\alpha$ is the angle of the contact arc. On the basis of this formula, we may determine, with sufficient accuracy, the actual rolling diameter and velocity parameters of any roller in closed grooves, where the pressure and frictional forces are uniformly distributed over the groove perimeter. Attempts to create methods of calculating the rolling diameter so as to ensure reliable velocity matching in cells with open grooves have proven unsuccessful.

The kinematics of shaping in open grooves (Figs. 1b and 1d) is much more complex and depends on numerous factors, some of which are random. For example, it is impossible, in principle, to ensure that the strip is adjacent to the groove of the lower roller and, in particular, that the reduction due to the pressure of the upper roller is uniform over the perimeter, since the difference in the groove radii exceeds, or is equal to, the maximum wall thickness in the mill range: $R_{ex} - R_{in} \geq S_{max}$. As a rule, the strip is adjacent to the groove in narrow local sections.

In shaping with a gap over the bottom of the groove (Fig. 1b), the edges of the strip are in contact with the lower roller at the rim, where the speed is higher but the bending force and the frictional forces are small, as for shaping in roller guides. Therefore, the rollers have no significant influence on the speed of the strip. With extreme pressure on the rollers, the rolling diameter

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**Fig. 1.** Kinematics of rolling in circular grooves: (a) closed groove; (b) open groove; (c, d) plots of azimuthal ($V$) and relative ($v$) velocities; CM, center of mass.