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RESEARCH PAPER

INFLUENCE OF ROLLING SPEED ON THE TEMPERATURE FIELD DURING COLD ROLLING OF ALUMINIUM SHEETS

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ABSTRACT

One of the effects of plastic deformation is an increase in the temperature of the formed metal. Strip temperature is a critical control factor in the cold rolling process of aluminum sheets, as it affects the quality of the finished product (thickness distribution over the strip width) and the possibility of defects caused by the adhesion of the rolled metal to the surface of the rolls. The rolling pressure, friction stress, and contact state show different characteristics in different zones along the deformation zone, which causes the heat generation and transfer states to be different, so the strip temperature is subject to a complex change process. The paper presents the results of experimental temperature measurements at several points on the width of the rolled strip and on the surface of the working rolls depending on the rolling speed in the range of 0.5-4.0 m/s. The results obtained showed a clear dependence of both the strip temperature and the working roll temperature on the rolling speed, with the increase in strip temperature being more intense. At very high rolling speeds, the temperature of the rolled sheet may even exceed 100$^{\circ C}$, which is unfavourable due to the possibility of the formation of deposits on the surface of the rollers.

Keywords: cold rolling; aluminium strip; deformation heat; heat transfer

INTRODUCTION

In cold plastic deformation of metals, part of the energy from the deformation energy is converted into heat, which results in an increase in the temperature of both the deformed material and the shaping tools [1-5]. The mechanical energy generated during plastic and elastic deformation of the metal is partially converted into heat; the remaining part is stored as deformation energy. The stored deformation energy remains in the material after unloading in the form of internal defects, phase changes and other permanent microstructural changes [6-10], while the generated heat causes an increase in the material temperature [11]. In the rolling process, in addition to the heat generated during plastic deformation, there is also a heat flux resulting from the friction process that occurs in the contact area between the tool and the deformed material [12-15].

The results of the numerical modelling of the rolling process [12] indicate that the increase in the temperature of the rolled strip as a result of the heat released both due to plastic deformation and friction forces increases slowly at the front of the deformation zone and increases its intensity along the path of contact with the surface of the rolls. The increase in temperature from the entry of the deformation zone of the surface of the work rolls with the deformed band as a result of friction forces is more intense than the temperature increases due to plastic deformation. This may be due to the fact that the roughness of the strip surface at the entrance of the deformation zone is greater, and therefore the friction coefficient is greater [13]. The value of the friction coefficient also depends on the lubrication conditions - but in this case, it is difficult to formulate clear relationships [16, 17]. The maximum temperature increase due to friction forces may reach approximately 25% of the temperature increase caused by plastic deformation. The value of the strip temperature at the exit from the deformation zone is influenced by the strip entry temperature, rolling speed and reduction ratio - but the impact of the reduction ratio is not as strong as the first two [12, 15]. This phenomenon is more visible in the case of materials with good thermal conductivity - such as aluminium.

The increase in temperature of the rolled strip as a result of the plastic deformation of the material is partially reduced due to the transfer of heat to the work rolls. The results of numerical calculations [12] indicate that the gradual decrease in the temperature of the rolled strip as a result of the transfer of heat to the work rolls begins from the moment of transition from the back stick zone to the forward slip zone. The amount of temperature reduction resulting from this heat transfer depends on the rolling speed - as the rolling speed increases, the amount of heat transferred to the rolls decreases.

During rolling, not only the temperature of the rolled strip changes, but also the temperature on the surface of the work rolls (and, to a lesser extent, the backup rolls). The temperature of the surface of work roll in contact with the strip tends to increase rapidly and then decreases rapidly at the exit of the deformation zone [18-20] - such large temperature changes in the thin heat-conducting layer under the surface of the work roll can have a detrimental effect on the roll material and the possibility of the formation of thermal microcracks [21].

An excessive temperature increase in the rolling deformation zone may result in unfavourable phenomena, such as changing the profile of the work rolls (resulting in different thicknesses of the strip in width) and sticking of the rolled material to the surface of the strip. Therefore, in the process of cold rolling of thin aluminium sheets, it is necessary to use cooling-lubricating liquids, fed to the work rolls, backup rolls and the rolled strip.

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As mentioned above in the rolling deformation zone, part of the energy expended is revealed in the form of heat, which causes the formation of heat flows. The heat balance of the cold rolling process, shown schematically in **Fig. 1**, can be represented by the following equations:
(i) Heat balance in the plastic deformation (rolling deformation zone):

$$Q_{pr} - 2Q_r = \Delta Q_t \tag{1.}$$

where: Q_{pr} - the amount of heat released rolling deformation zone,
Q_r - the amount of heat transferred to the work roll through the contact surface,
ΔQ_t - the amount of heat carried away by the tape with the rolling deformation zone.
(ii) Heat balance of the roll work:

$$Q_r - Q_{emr} - Q_{op} - Q_{ot} = \Delta Q_r \tag{2.}$$

where: Q_{emr} - the amount of heat taken up by the cooling-lubricating liquid (emulsion),
Q_{op} - the amount of heat transferred to the backup roll,
Q_{ot} - the amount of heat transferred to the environment,
ΔQ_r - the amount of heat that changes the work roll temperature field.
(iii) Heat balance of the backup roll:

$$Q_{op} - Q_{emop} - Q_{ot} = \Delta Q_{op} \tag{3.}$$

Under quasi-stationary thermal conditions can be assumed $\Delta Qr = \Delta Qop = 0$.
The amount of heat released rolling deformation zone can be approximately determined from the relationship:

$$Q_{pr} = \eta_w a_{pr} V \tag{4.}$$

where: η_w - thermal coefficient of plastic deformation - for aluminium $\eta_w = 0.93$,
a_{pr} - work of plastic deformation related to a unit of volume - determined practically or theoretically,
V - the volume of the rolled strip passing between the rolls in time $\Delta\tau$.

$$V = 3600 h_s \Delta L v_k \Delta\tau \tag{5.}$$

where: h_s - strip thickness,
ΔL - width of the rolled strip,
v_k - average rolling speed over time $\Delta\tau$.
The amount of heat transferred to the work roll through the contact surface with the rolled strip can be determined from the relationship:

$$Q_r = \alpha_{sr} F_{sr} (T_s - T_r) \Delta\tau \tag{6.}$$

where: α_{sr} - heat transfer coefficient between the strip and the work roll,
F_{sr} - contact surface between strip and work roll,
T_s and Tr, strip and work roll temperature, respectively.
The amount of heat transferred to the working roll to the backup roll can be determined from the following relationship:

$$Q_{op} = \alpha_{rop} F_{rop} (T_r - T_{op}) \Delta\tau \tag{7.}$$

where: F_{rop} - the contact surface of the backup roll with the work roll.
In an analogous way, the amount of heat taken up by the cooling lubricant can be calculated. The amount of heat released to the environment Q_{ot} can be omitted due to the low value of the heat exchange coefficient.

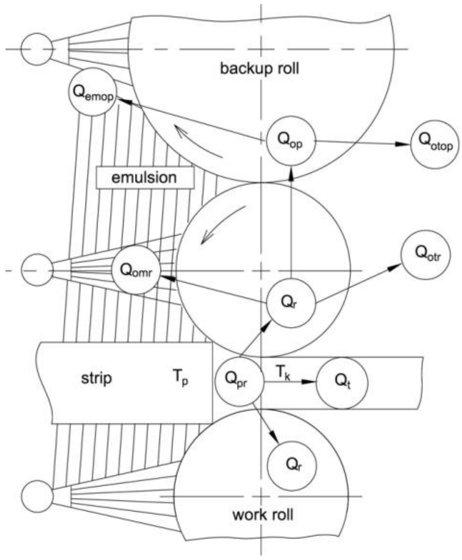

Fig. 1 General diagram of the heat balance of cold rolling on a four-roll mill

The aim of the experimental investigation was to determine the effect of rolling speed on the thermal effect of the cold rolling process of aluminium sheet - specifically, measurements were made of the surface temperature of the rolled strip, the surface of the working rolls and the temperature of the cooling-lubricating liquid. The linear velocity of points on the surface of the working rolls was taken as a measure of the rolling speed.

MATERIAL AND METHODS

Experimental tests were carried out for the process of rolling the aluminium sheet with an initial thickness of 10.0 mm and a width of 1260 mm, in a four-roll rolling mill (commonly known as a quarto rolling mill) - the diameter of the work rolls was 600 mm and of the backup rolls was 1500 mm. The cooling-lubricating liquid was supplied to each work roll and backup roll separately. Rolling processes were carried out for five different values of the rolling speed: 0.5; 1.0; 1.5; 3.0 and 4.0 m/s. Measurements of the temperature of the strip and upper work roll were made at several points, four for the work roll and three for the strip (**Fig. 2**) - this arrangement of measurement points was chosen on the assumption of a symmetrical temperature distribution with respect to the vertical axis of symmetry. Temperature measurements of the surface of the strip and work roll were made using a thermistor with a measurement range of 10-120$^{\circ C}$ - the accuracy of the measurements was within the range of ±0.1°C.

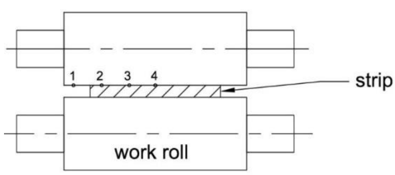

Fig. 2 Location of temperature measurement points

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These measurements were carried out for the stabilised phase of the rolling process, i.e. after rolling a minimum of 20 m of the strip, i.e. when temperature fluctuations did not exceed several degrees. The average value of the measurements carried out over a period of a few seconds was taken as the final result. The temperature of the cooling-lubricating liquid was measured in containers placed before and after the rolling stand using a mercury thermometer with an accuracy of ±0.1°C.

To avoid excessive heat transfer from the rolled strip to the work rolls, the rolls were heated to a temperature of approximately 30°C before the rolling process began.

RESULTS AND DISCUSSION

The results of temperature measurements performed near the exit of the strip from the deformation zone showed that, as expected, the temperature in the centre of the work roll (**Fig. 3**) and the temperature in the centre of the rolled strip (**Fig. 4**) are higher than at the edges. In the case of a rolled strip, this happens because of heat exchange with the environment at the edge of the strip (point no. 2 in **Fig. 2**) and as a result of more intense heat exchange with the less heated material of the work rolls. Lack of contact of the work rolls with the deformed material in point no. 1 (**Fig. 2**) results in a significantly lower temperature at this point. For almost all rolling speeds, the temperature at the edge of the rolled strip is lower than at the other two measurement points. Only for rolling speed v = 4.0 m/s were the temperature differences at individual points insignificant. The highest temperature and its even distribution over the strip width prove that at this rolling speed, the smallest portion of the heat generated in the deformation zone Q_{pr} (**Fig. 1**) is transferred to the work rolls and the surroundings (in this case to the cooling-lubricating liquid).

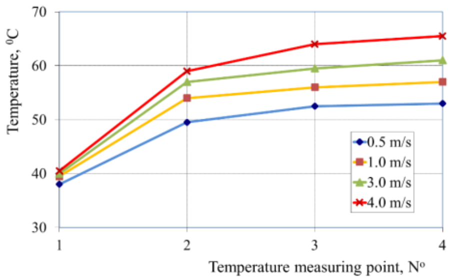

Fig. 3 Temperature distribution over the width of the work roll for different rolling speeds

In the middle of the rolled strip, i.e. for measurement point number 4, the difference in temperature measured for the lowest and highest rolling speed was 38.0°C. In the case of the work roll, the corresponding temperature difference was 10.5°C. Therefore, the temperature difference on the surface of the rolled strip was 3.62 times greater than the temperature difference measured on the surface of the working roll. This may indicate that as the rolling speed increases, the intensity of the heat generated in the rolled material in the deformation zone Q_{pr} absorbed by the work rolls Q_r decreases.

In the case of a work roll, the temperature at its edge (point No. 1) practically does not change as the rolling speed increases (**Fig. 5**). In the case of other measurement points, a greater increase in temperature can be observed at greater distances from its edge. This means that heat exchange occurs not only between the material of the work roll and the material of the rolled strip but also with the heat flow from the centre of the roll to its outer segments. For higher rolling speeds, the intensity of this exchange (or rather the amount of heat flow) is lower, hence the higher temperature on the surface of the rolls (**Fig. 5**).

The characteristics showing changes in the temperature of the rolled strip depending on the rolling speed are similar (**Fig. 6**). For lower rolling speeds, in the range of 0.5-1.5 m/s, the increase in strip temperature is more intense than for higher rolling speeds. The dependence of the temperature of the rolled strip on the rolling speed for points 3 and 4 (in **Fig. 2**) is remarkably similar. The slightly different course of this characteristic for point number 2 is partly due to the contact of the rolled strip material with the environment.

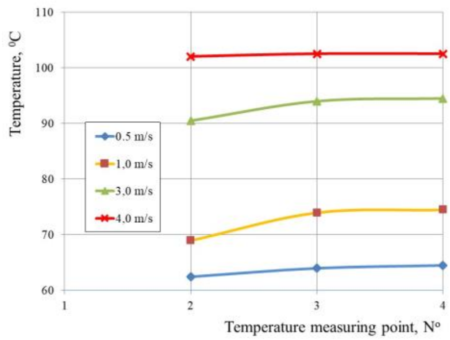

Fig. 4 Distribution of temperature over the width of the strip for different rolling speeds

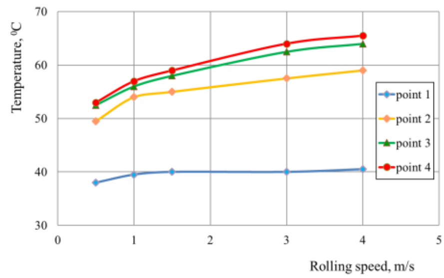

Fig. 5 Dependence of the temperature at different points on the surface of the working roll on the rolling speed

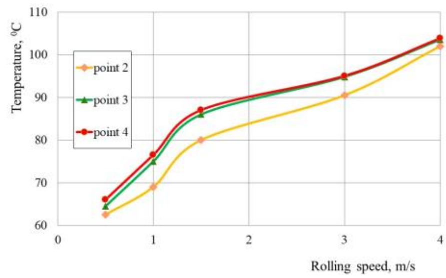

Fig. 6 Dependence of the temperature at different points on the surface of the strip on the rolling speed

Temperature measurements of the cooling and lubricating liquid performed in containers before and after the rolling stand did not show visible differences depending on the rolling speed. The temperature differences at the input and output were 11°C.

The results obtained from the temperature measurement may be useful in designing the profile of work rolls. Due to large temperature differences at the edge and in the centre of the work roll

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and too high strip temperature at higher rolling speeds, increasing the cooling intensity of the work rolls should be considered, especially in their central part, to avoid possible sticking of the rolled material to the surface of the work rolls.

CONCLUSIONS

Based on the results of experimental tests, the influence of rolling speed on the surface temperature of the rolled AW-1050 aluminum strip and the surface temperature of the work rolls near the exit of the rolled metal strip from the rolling mill was determined. The measurement results allow the following observations to be formulated.
- With an increase in rolling speed, both the temperature of the rolled strip and the temperature of the work rolls increase, and the range of changes in the temperature of the rolled strip is larger than the range of changes in the temperature of the work rolls. This is due to the fact that, as the rolling speed increases, the amount of heat transferred from the strip to the work rolls decreases due to the shorter contact time (heat transfer).
- For the rolling speed range of 0.5-3.0 m/s, the temperature at the edge of the rolled strip was lower than at the other measurement points. This is the result of contact of the strip edge with the surroundings and with the cooler segment of the work rolls.
- For a rolling speed of 4.0 m/s, the temperature differences for individual measurement points along the strip width are very small, because for this rolling speed the heat losses generated in the deformation zone are the smallest.
- The temperature of the work roll at a point outside the contact with the rolled strip is almost independent of the rolling speed, while for the remaining measurement points the temperature of the work roll increases with the increase in rolling speed, most intensely in the middle of the rolled strip.

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