

## THE INFLUENCE OF MAGNESIUM ON MECHANICAL PROPERTIES OF 5251 ALUMINIUM ALLOY COLD-ROLLED STRIPS

*Turczyn S.<sup>1</sup>, Rutecki P.<sup>2</sup>*

<sup>1</sup>*Akademia Górniczo-Hutnicza, al. Mickiewicza 30, 30-059 Kraków, Poland*

*turczyn@metal.agh.edu.pl*

<sup>2</sup>*Aluminium Konin – IMPEXMETAL S.A., ul. Hutnicza 1, 62-510 Konin, Poland*

*p-rutecki@aluminium-konin.com.pl*

## VPLYV HORČÍKA NA MECHANICKÉ VLASTNOSTI ZA STUDENA VALCOVANÉHO PÁSU Z HLINÍKOVEJ ZLIATINY 5251

*Turczyn S.<sup>1</sup>, Rutecki P.<sup>2</sup>*

<sup>1</sup>*AGH Krakow, Poľsko*

<sup>2</sup>*IMPEXMETAL S.A, Konin, Poľsko*

### Abstrakt

V článku je určený vplyv chemického zloženia hliníkovej zliatiny 5251 (Al-2Mg) na mechanické vlastnosti a štruktúru pásu valcovaného za studena. Boli sledované zliatiny s rôznym obsahom Mg. Finálne stavy produkcie za studena valcovaných pásov pozostávali zo vstupnej hrúbky 4,5 mm, finálnej hrúbky 1 mm, a rekryštalizačného žihania pre dosiahnutie čiastočného, alebo kompletného deformačného spevnenia. Vzorky odobraté z pásov s obsahom 1,8 % Mg a 2,2 % Mg, boli podrobené mechanickým skúškam, meraniu tvrdosti a kalíškovacej skúške, Na základe tvrdosti, medze sklzu a pevnosti, štruktúry materiálu bol stanovený vplyv obsahu Mg v zliatine 5251 na mechanické vlastnosti. Zvláštny dôraz bol položený na určenie parametrov žihania, ktoré umožňujú dosiahnuť finálny pás, zodpovedajúci iba jednému stavu deformačného spevnenia. Prijateľný proces tepelného spracovania sa preukázal pre zliatiny s rôznym chemickým zložením, umožňujúci dosiahnutie mechanických vlastností v určenej oblasti. Bolo zistené, že oblasť obsahu Mg v zliatine 5251 je príliš široká pre dosiahnutie mechanických vlastností, zodpovedajúcich rovnakému stavu deformačného spevnenia, vykonaného v identickom technologickom procese.

### Abstract

In this paper, the influence of chemical composition of aluminium alloy 5251 (Al-2Mg) on mechanical properties and structure of cold rolled strips was determined. Especially the alloys with different contents of magnesium were tested. Final stage of strips production consists of cold rolling from 4.5 mm initial thickness to 1.0 mm final thickness and recrystallization annealing, in order to partly or completely remove the strain hardening. The specimens taken from strips with magnesium content 1.8 % and 2.2 %, close to the limiting values, were subjected to mechanical testing, hardness measurements and cupping tests. On the base of hardness, yield and tensile strength measurements and material structure observation, the influence of magnesium content in aluminium alloy 5251 on mechanical properties was carried out. The special emphasis was put on the determination of annealing parameters, which allow to obtain the final strip corresponding with only one state of strain hardening. Finally, the suitable heat treatment process was established for alloys with different chemical composition, allowing

for obtaining mechanical properties in a given range. It was found, that the range of magnesium content in aluminium alloy 5251 is too wide to achieve mechanical properties, belonging to the same state of strain hardening, performing identical technological process.

**Key words:** aluminium alloy 5251, mechanical properties, cold rolled strips

## 1. Introduction

Rolling is one of the basic plastic working processes, considering steel products as well as non-ferrous metals, e.g. aluminium alloys, zinc alloys, copper alloys, etc. Design of the properties of a material after rolling consists in suitable selection of forming process parameters and heat treatment conditions, in order to obtain a product of required structure (grain size) and mechanical properties. Prediction of a material's structure is rather a difficult task, requiring the knowledge of many factors influencing the final grain size, and thus also the final material's properties. Considering the rolling process, special emphasis should be put on the selection of deformations, rolling temperature, idle times between deformations, etc. When planning the rolling schedule, the material's formability, its yield stress as well as chemical composition should also be taken into consideration. All these factors influence the rolling technology and the final mechanical properties of the strip after rolling [1,2,3].

Chemical composition of a given material significantly affects the mechanical properties of a final product [4]. Variations in chemical composition cause the necessity of changing rolling parameters and subsequent heat treatment of the strip, in order to obtain the product showing the same repeatable levels of properties. All aluminium alloys have a certain range of major alloying element's content. The wider this range is, the larger is the probability of obtaining diversified properties of final strips. The aluminium alloy grade designated as 5251 is one of the *aluminium-magnesium* series, and is often called *hydronalium*. It shows very high corrosion resistance, good formability, weldability, high fatigue strength and is easy to polish. Chemical composition of 5251 aluminium alloy, according to PN-EN 573-3 standard [5], is presented in Table 1. The alloys of aluminium with magnesium also contain the additions of Mn, Cr, Si and other metals. The small content of manganese (0.2÷0.6 %) or chromium (0.1-0.2 %) increases the tensile strength by 20÷25 MPa, while the alloy's structure does not change substantially. The additions of titanium or vanadium, even in small amounts, reduce the grain size in castings of these alloys [2,4]. However, the most important alloying element controlling the mechanical properties of an alloy, is magnesium, Fig.1.

Table 1. Chemical composition of aluminium alloy 5251 according to PN-EN 573-3 (wt-%).

| Mg        | Fe   | Cu   | Mn        | Si   | Cr   | Zn   | Ti   | Other      |          | Al   |
|-----------|------|------|-----------|------|------|------|------|------------|----------|------|
| Maximum   |      |      |           |      |      |      |      | separately | together |      |
| 1.70-2.40 | 0.50 | 0.15 | 0.10-0.50 | 0.40 | 0.15 | 0.15 | 0.15 | 0.05       | 0.15     | rest |

The main objective of this work was the attempt of evaluation of mechanical properties' variations of 5251 alloy cold-rolled strip, as a function of magnesium content. The results of these investigations were used to elaborate the technological recommendations to the production of strips showing required mechanical properties.

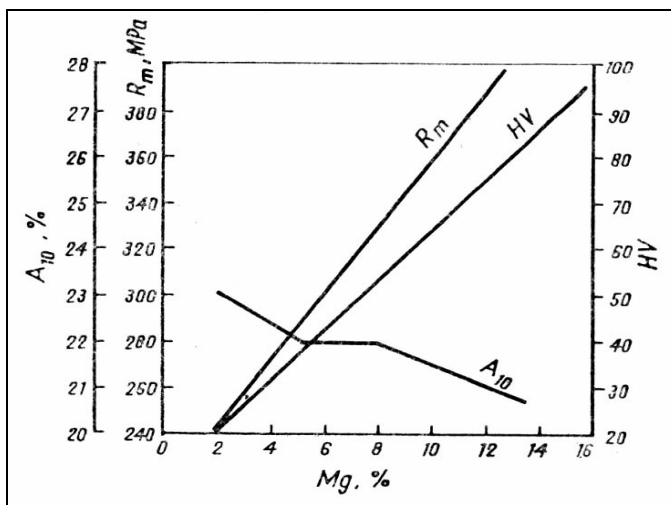


Fig.1 Influence of magnesium content on mechanical properties of aluminium alloy.

## 2. Experimental procedure

The character and scope of investigations resulted from the necessity of achieving the required mechanical properties of 5251 aluminium alloy strips. The final stage of production of these strips is cold rolling from 4.5 mm initial thickness to 1.0 mm final thickness. After rolling, the strip is subjected to annealing, in order to partly or completely remove the strain hardening. The strip is delivered to the buyer in different states of strain hardening, e.g. "O", "H22" or "H24", characterized by different mechanical properties, Table 2. This work was focused on the determination of annealing parameters, which allow to obtain the final strip corresponding with only one state of strain hardening. Two sorts of 5251 aluminium alloy, differing in major alloying element's content, were used in the experiments, Table 3.

Table 2 Mechanical properties of alloy 5251 (Al-2Mg) depending on the state of strain hardening.

| Strain hardening state | Thickness mm |     | $R_m$ MPa |     | $R_{0.2}$ , min MPa | Elongation, $A_{50}$ , min, % | Bending radius* |       | Hardness* HB |
|------------------------|--------------|-----|-----------|-----|---------------------|-------------------------------|-----------------|-------|--------------|
|                        | from         | to  | min       | max |                     |                               | 180°            | 90°   |              |
| O                      | 0.5          | 1.5 | 160       | 200 | 60                  | 14                            | 0 t             | 0 t   | 44           |
| H22                    | 0.5          | 1.5 | 190       | 230 | 120                 | 6                             | 1,5 t           | 1,0 t | 56           |
| H24                    | 0.5          | 1.5 | 210       | 250 | 140                 | 5                             | 2,0 t           | 1,5 t | 62           |

\* for information only

The alloys with magnesium content (1.8 % and 2.2 %), close to the limiting values were selected. In further part of this paper, the alloy with 1.8 % Mg content is designated as 5251/Mg<sub>min</sub>, while the one with 2.2 % magnesium content is denoted as 5251/Mg<sub>max</sub>. The content of other alloying elements remained on the same or similar level. In order to make the final properties of both alloys comparable, the whole experimental procedure was realized on identical specimens, taken from the same stage of cold rolling and annealing processes. The samples taken from the following stages were investigated: hot-rolled coils (feedstock for cold rolling), the strip after each cold-rolling pass and the material after annealing.

Table 3 Chemical composition of alloy 5251 used in experiment.

| Element | 5251/Mg min   | 5251/Mg max   |
|---------|---------------|---------------|
|         | content, wt-% | content, wt-% |
| Al      | 97.193        | 96.685        |
| Mg      | 1.805         | 2.200         |
| Si      | 0.178         | 0.202         |
| Cu      | 0.056         | 0.126         |
| Zn      | 0.034         | 0.077         |
| Ti      | 0.015         | 0.016         |
| Fe      | 0.451         | 0.459         |
| Mn      | 0.221         | 0.176         |
| Cr      | 0.018         | 0.027         |
| V       | 0.004         | 0.004         |
| Ni      | 0.004         | 0.008         |
| Sn      | 0.000         | 0.001         |
| Pb      | 0.008         | 0.016         |
| Be      | 0.001         | 0.001         |

The heat treatment was performed at three adequately selected temperatures: 240°C, 250°C and 260°C, which allowed to obtain the strip corresponding with the above mentioned ranges of properties. The specimens were taken out of the furnace every hour, and maximum annealing time amounted to six hours. Taking into account that the beginning stage of annealing (the first hour) caused the significant changes in mechanical properties of a material, the first specimen was taken out after half-an-hour period. The specimens were subjected to mechanical testing, hardness measurements and cupping tests. The obtained results of investigations made it possible to determine the properties' variations as a function of rolling and annealing parameters, i.e. the deformation during rolling and annealing time and temperature.

The macrostructure examination was also performed and resulted in the determination of grain size in the strip subjected to various annealing conditions (time and temperature). This examination was expected to confirm the fact that magnesium content does not considerably influence the grain size.

### 3. Results of investigations and their analysis

The main objective of realized research was the evaluation of the effect of Mg content on the mechanical properties of cold-rolled 5251 aluminium alloy strips subjected to subsequent recrystallization annealing. As mentioned above, a slight change of magnesium content in Al-Mg alloys results in significant increase in hardness and strength and decrease in ductility of a material. It is clearly visible in the obtained diagrams of tensile strength ( $R_m$ ) and yield strength ( $R_{p0.2}$ ) vs. rolling reduction. It can be observed in Fig.2 that the difference between  $R_m$  values amounts to approximately 20 MPa, which is caused by different magnesium content in the alloy. This difference stayed on the same level during the whole cold rolling process. Similar situation was observed in case of and yield strength ( $R_{0.2}$ ), Fig.3. The alloy with higher Mg content showed the hardness higher by about 5 HB, both before cold rolling and after that, while the elongation ( $A_{50}$ ) decreased rapidly during rolling, to the level of approximately 4 %, for both

alloy sorts, Fig.4. Diversification of mechanical properties of cold-rolled strips results in the necessity of precise selection of heat treatment parameters. Hence, the next stage of investigations was the evaluation of mechanical properties of strips subjected to recrystallization annealing.

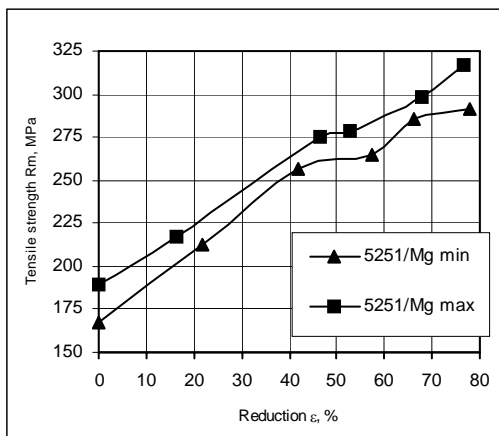


Fig.2 Tensile strength vs. rolling reduction.

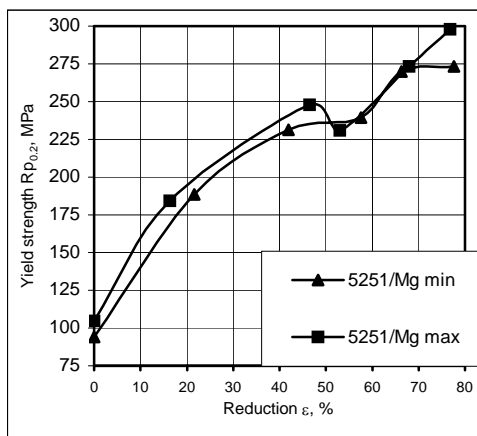


Fig.3 Yield strength vs. rolling reduction.

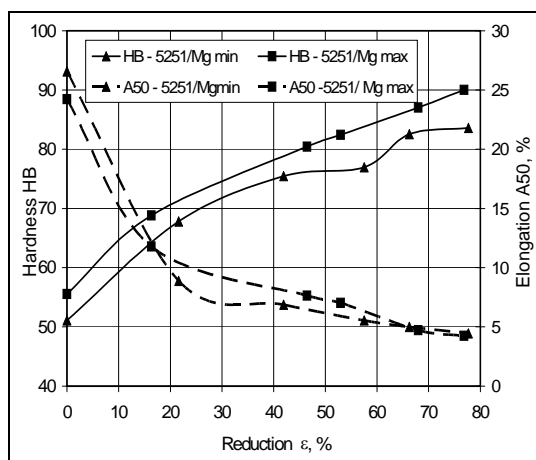


Fig.4 Hardness and elongation vs. reduction.

The analysis of the obtained diagrams of mechanical properties' variations as a function of annealing time and temperature leads to the observation that, as it was expected, increasing annealing time results in lower strength and higher ductility (Figs. 5-7). However, the character of these changes is different when related to the applied annealing temperature. The most rapid drop in strength and increase of ductility was observed at 260°C, while the least intensive changes occurred at 240°C.

The annealing temperature affects not only the intensity of strength decrease, but also the final level of mechanical properties. It is to be noticed that higher temperature (with constant

annealing time) resulted in lower strength properties and larger elongation. However, these values differ between 5251/Mg<sub>min</sub> and 5251/Mg<sub>max</sub> alloy sorts. It can be observed in Fig.5 and Fig.6 that there is a difference between yield and tensile strength values for both alloys. The alloy denoted as 5251/Mg<sub>max</sub> shows the tensile strength higher by 15÷20 MPa, when compared to that of 5251/Mg<sub>min</sub> alloy, during the whole annealing process. The yield strength ( $R_{0.2}$ ) shows the contrary tendency. During the annealing process, the difference between  $R_{0.2}$  values, which existed before heat treatment, fades out. After six hours period, this difference becomes very slight, Fig.5.

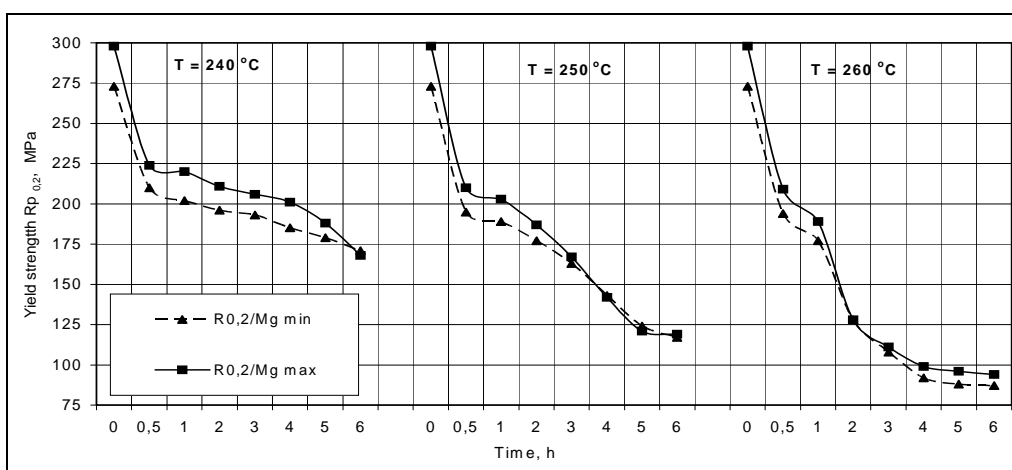


Fig.5 Yield strength  $R_{p0.2}$  vs. time of annealing.

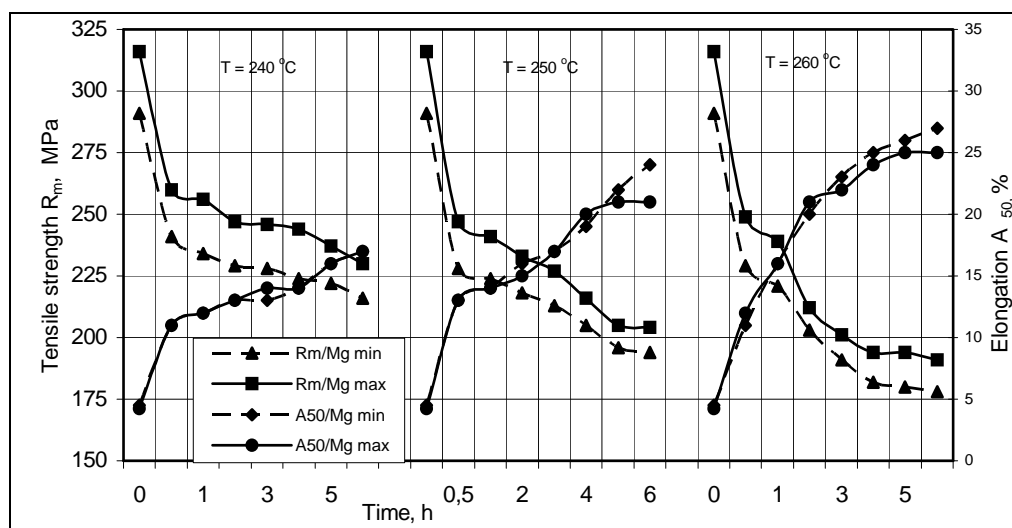


Fig.6 Tensile strength  $R_m$  and elongation  $A_{50}$  vs. time of annealing.

The magnesium content in 5251 aluminium alloys does not substantially influence the elongation ( $A_{50}$ ) value, Fig.6. Practically, for all investigated annealing variants, the difference between  $A_{50}$  values for both alloys is small. The annealing also results in significant decrease in

hardness of the investigated alloys. Regardless of the applied temperature, the difference between hardness levels of 5251/Mg<sub>min</sub> and 5251/Mg<sub>max</sub> alloys is visible during the whole heat treatment process, Fig.7. At the temperatures of 250 °C and 260 °C the slight decrease of this difference occurs in time, while at 240 °C it remains almost constant during entire annealing.

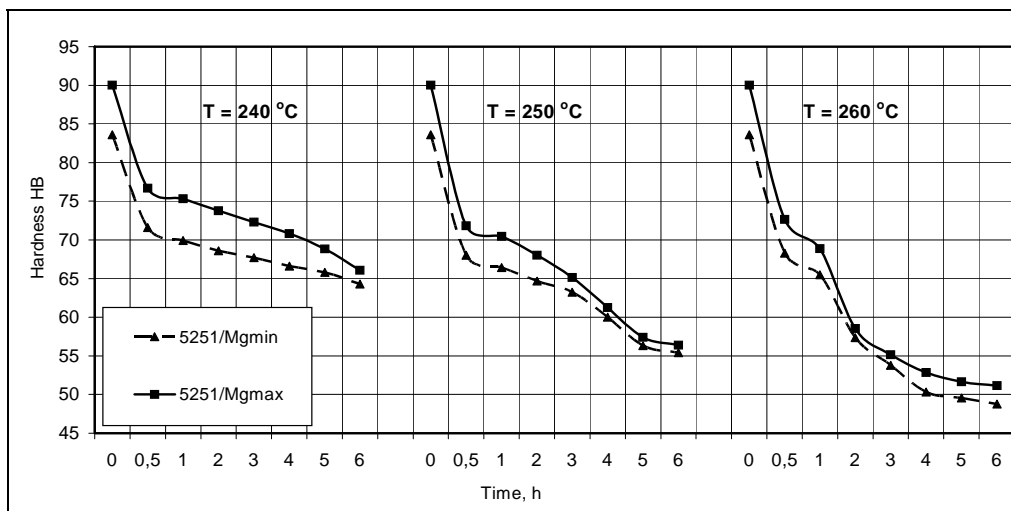


Fig.7 Hardness HB vs. time of annealing.

As it was mentioned above, magnesium does not influence the rate of grain formation and grain size. The grain size after annealing was the same in case of both 5251/Mg<sub>min</sub> and 5251/Mg<sub>max</sub> alloys. This was observed in all annealing variants, regardless of the temperature and time of heat treatment.

#### 4. Technological recommendations

Taking advantage of experimental results, the most favourable annealing variants were selected, which will allow to obtain 5251 aluminium alloy strips showing mechanical properties corresponding with the required states of strain hardening: “0”, “H22” or “H24”. The example of 5251/Mg<sub>min</sub> and 5251/Mg<sub>max</sub> alloys leads to the observation that there are many time-temperature variants of heat treatment, which make it possible to manufacture the strip showing required mechanical properties. Practically, for each 5251 alloy (with varying magnesium content) there are several possible heat treatment procedures resulting in obtaining the given state of strain hardening. The experiments show that each of the alloys will be characterized by different mechanical properties after cold rolling, resulting in the selection of different annealing parameters. The investigation of every 5251 alloy, showing various Mg contents (within wide range 1.7-2.4 %, according to standard [5]), would be very time-consuming and expensive. Furthermore, the exact meeting of the prescribed alloy’s chemical composition during melting and casting of ingots is impossible in industrial conditions. Therefore, this work was focused on the investigations of 5251 alloy sorts showing magnesium contents close to the limiting values.

Basing on the realized research, the proper annealing parameters (time and temperature) were proposed, which will allow to obtain the strip of both 5251/Mg<sub>min</sub> and

5251/Mg<sub>max</sub> alloys, in the prescribed state of strain hardening, Table 4. PN-EN 485-2 standard permits to manufacture the strips showing the properties corresponding with the requirements of one or two states of strain hardening. Taking this fact into consideration, many more annealing variants than those given in Table 4, may be selected. However, in this work the annealing conditions were determined, which allow to obtain only one state of strain hardening. The yield strength ( $R_{0.2}$ ) was the reason, as the standards do not specify its upper limiting value. The strip showing too high yield strength might not meet other requirements, e.g. the bend radius.

Table 4 Proposed annealing parameters for cold rolled strips from aluminium alloy 5251.

| State      | Time, h | Temperature, °C |
|------------|---------|-----------------|
| <b>H24</b> | 6       | 240             |
|            | 2.5 – 3 | 250             |
| <b>H22</b> | 4.5 – 5 | 250             |
|            | 2       | 260             |
| <b>0</b>   | 4 – 6   | 260             |

## 5. Summary

- 1) The range of magnesium content in 5251 aluminium alloy, admissible according to standards, is too wide. This leads to the distinct diversification of strength properties of strips ( $R_m$ ,  $R_{0.2}$ , HB) after cold rolling, thus resulting in the necessity of individual selection of annealing time and temperature, in order to obtain the product showing required mechanical properties.
- 2) The effect of magnesium on ductility (elongation, drawability) of 5251 aluminium alloy is slight. Also, the grain size in final strip is not affected by Mg content.
- 3) It is recommended to narrow down the range of magnesium content in 5251 aluminium alloy, which is quite difficult to realize in industrial practice. Lesser diversification of feedstock in respect of Mg content allows to select the heat treatment parameters more easily, for this selection is then made from larger set of time-temperature variants of the process.
- 4) The parameters of heat treatment should guarantee obtaining the strip showing mechanical properties corresponding with only one state of strain hardening. The yield strength ( $R_{0.2}$ ) is the reason, as the standards do not specify its upper limiting value. The strip showing too high yield strength might not meet other requirements, e.g. the bend radius.

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