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DETERMINATION OF THE CRITICAL VALUE OF NORMALIZED COCROFT – LATHAM CRITERION DURING MULTI SLIGHT ROLLING BASED ON TENSILE TEST

OKREŚLANIE GRANICZNEJ WARTOŚCI ZNORMALIZOWANEGO KRYTERIUM COCROFTA – LATHAMA PODCZAS WALCOWANIA WIELOŻYŁOWEGO NA PODSTAWIE PRÓBY ROZCIĄGANIA

The Multi Slit Rolling technology is generally employed during ribbed wired rods rolling process. This technology enabled of the making two, three, four rods simultaneously from a single strip (a continuous casting or billet) during hot rolling process. To analysis of the slitting process during MSR the normalized Cockroft – Latham criterion was used. Limit values of the normalized Cocroft – Latham criterion for different values of temperature and strain rates may be determined by using the comparative method for the uniaxial tensile test of notched specimens. In multi slitting rolling process determination of the critical values is difficult, and could be made by using the inverse method. In this paper comparison of the critical values of the normalized Cockroft – Latham criterion estimated in tensile test and during multi slitting rolling process were presented. A relationship enabled determination of the critical value of the normalized Cockroft – Latham criterion during multi slit rolling process based on tensile test was appointed.
Keywords: multi slit rolling, normalized Cockroft – Latham criterion, crack

Technologia walcowania z wielokrotnym podziałem pasma znajduje zastosowanie w procesach wytwarzania prętów żebrowanych. Ideą tej technologii jest możliwość wytwarzania dwóch, trzech, czterech, a nawet pięciu prętów z jednego pasma wsadowego. Do analizy procesu rozdzielania żył zastosowano znormalizowane kryterium Cockrofta – Lathama. Zależność granicznych wartości znormalizowanego kryterium Cockrofta – Lathama od temperatury oraz prędkości odkształcenia określono stosując metodę porównawczą dla próby jednoosiowego rozciągania próbek z karbem. Wyznaczenie granicznej wartości znormalizowanego kryterium Cockrofta – Lathama, przy której następuje rozdzielenie pasma w procesie walcowania wielożyłowego jest zagadnieniem bardziej skomplikowanym, do jego realizacji zastosowano metodę odwrotną. W pracy przedstawiono porównanie granicznych wartości znormalizowanego kryterium Cockrofta – Lathama wyznaczonych w próbie rozciągania próbek z karbem oraz podczas procesu walcowania wielożyłowego z wzdłużnym podziałem pasma. Przedstawiono zależność umożliwiającą określenie granicznej wartości analizowanego kryterium podczas walcowania wielożyłowego na podstawie wartości wyznaczonych w próbie rozciągania.

1. Introduction

The Multi Slit Rolling technology is generally employed during ribbed wired rods rolling process [1, 2, 3]. This technology enabled of the making two, three, four rods simultaneously from a single strip (a continuous casting or billet) during hot rolling process. Rolling in multi-strand passes can be conducted on the existing rolling mills without having to incur any considerable investment outlays or install any special equipment. It allows a considerable increase in the production capacity of a rolling mill. The processes of rolling in multi-strand passes are characterized by a spatial state of strain and are difficult to be accurately described by mathematical models. Particularly difficult to define is the pattern of metal flow in the slitting pass and the strip slitting process itself [3]. In MSR technology special shape of the roll pass is the finishing rolls group: pre-slitting pass and slitting pass – is used. In pre – slitting pass the preliminary division of the material is made. In the slitting pass billet is formed to the single strips joined only by the thin bridges. Final division to the separated strips is made in the special guide box by the not propelled slitting rolls. Moving band impact against the separating rollers, setting the rollers in rotation. During moving of the band by the slitting rolls in the joining bridge are

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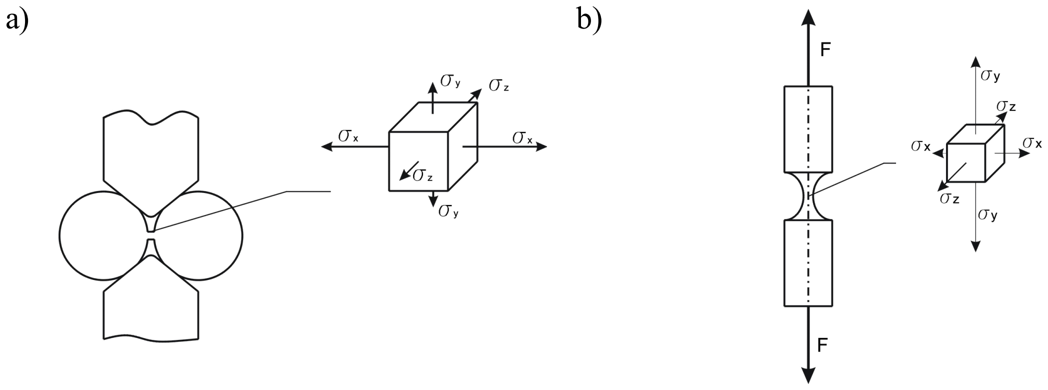

Fig. 1. Stress schema during: a) slitting in multi slit rolling technology b) uniaxial tension of notched specimens

arise high tensile stress (square to the rolling direction). To the analysis of the slitting process the normalized Cockroft – Latham criterion was used [4] expressed as:

$$C = C_0 + \int_0^{\bar{\varepsilon}} \frac{\sigma_1}{\varepsilon_i} d\bar{\varepsilon} \tag{1}$$

where: C_0 – initial value of the normalized Cockroft – Latham criterion, $\bar{\varepsilon}$ – strain intensity,

σ_1 – 1^{st} main stress, σ_i – stress intesity.

On the fig. 1a the stress schema in cross plane to the rolling direction during initiation of the slitting was presented. As can be seen during the strand slitting to the separated strips stress in three directions (σ_x, σ_y, σ_z) are tensile. During uniaxial tension of notched specimens in the central zone of metal is comprehensive state of tension (Fig. 1). In addition to the tensile stress in the axis of the notched specimen, there, in the normal relative to its axis, are tensile stresses. In multi slit rolling process the bridge connecting the separated strips can be treated as a notched zone.

2. Material properties

The accuracy of calculations performed using a computer program is dependent on the accurate determination of the properties of materials used for tests. Undertaken experimental studies aimed at the determination of the effect of strain parameters on the magnitude of yield stress for steel BSt500S (according to the Polish standard). Plastometric tests were performed on a DIL 805 A/D dilatometer-plastometer possessed by the Institute of Modelling and Automation of Plastic Working Processes, using strain velocities of 0.1 s^{-1}, 1.0 s^{-1}, and 10.0 s^{-1}, respectively. Chemical composition of material used for tests is given in Table 1

TABLE 1

Chemical composition of materials used for tests [%]

C	Mn	V	Si	Cr	Ni	S	P	Cu
0.2	1.4	0.1÷0.15	0.4÷0.5	0.04	0.25	0.04	0.04	0.25

In order to obtain a mathematical relationship making the value of yield stress, σ_p, dependent on deformation parameters, (ε, $\dot{\varepsilon}$, T), the results of the performed tests were approximated with a functional relationship described with Equation (2). The yield stress σ_p dependence of strain intensity ε, strain rate $\dot{\varepsilon}$ and temperature T is approximated by Henzel-Spittel [5] formula expressed as:

$$\sigma_p = A_0 e^{m_1 T} \varepsilon^{m_2} \dot{\varepsilon}^{m_3} e^{m_4 \varepsilon} \tag{2}$$

Estimated coefficients A_0, m_1, m_2, m_3, m_4 of the BSt500S steel are given in Table 2. The mean square for this function was 0.1164.

TABLE 2

Parameters of function (2) for the BSt500S

A_0	m_1	m_2	m_3	m_4
16086.83	0.00387	0.434633	0.060926	0.99398

3. Determination limiting values of the normalized Cockroft – Latham criterion in uniaxial tension of notched specimens

To determine of the limiting values of normalized Cockroft – Latham criterion the comparative method was used. The limiting values of the nromalized Cockroft – Latham criterion could be determined in a basic tests such as: uniaxial tension, uniaxal compresion of the shape speciments, bending or torsion can be used. In this work to determine dependecy of the limiting values analyzed critefion to temperature and strain rate uniaxial tension of notched speciments was used. On the fig. 2 was shown shape and dimensions of the speciments used in uniaxial tension tests.

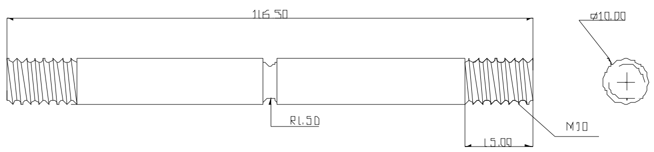

Fig. 2. Shape and dimension of notched speciment used to determination of the limit values of normalized Cockroft – Latham criterion

Uniaxial tension of notched specimens was performed on a multi-function metallurgical process simulator, Gleeble 3800, available at the Modelling and Automation of Plastic Working Processes of the Czestochowa University of Technology.

The specimens were deformed at a constant strain rate until their breaking. During the tensile tests, a constant temperature was maintained by continuously heating up the specimens. The specimens were fixed horizontally between the simulator's jaws to prevent the stack effect from occurring. During vertical fixing of specimens, the upper specimen end has a higher temperature due to convection heat. During the tensile test, the working anvils of the simulator moved at a constant linear velocity, which resulted in the deformation of the specimen in the notch area. At the moment of reaching the limiting fracture criterion value, micro-cracks started to form in the specimen, then the plastic fracture propagation proceeded until complete breaking of the specimen. The specimen length after breaking – $\underline{l}$, and the notch diameter at the breaking point – *ds*, were measured with an electronic slide calliper. Based on the obtained results, the mean values of l_{av} and ds_{av} were determined. Then, the specimen elongation – Δl, was determined.

In order to determine the actual values of the normalized Cockroft – Latham criterion, theoretical studies of the notched specimen tension process were. The theoretical notched specimen tension studies were carried out for conditions analogous to those used in the laboratory tests. As the notched specimen tension process is an axially symmetrical process, the numerical studies were conducted only for a section making up the ¼ of the actual specimen volume by introducing two planes of symmetry. To preserve the geometrical specimen shape in the notch region during deformation, the length of finite grid element sides were locally reduced. Additionally, symmetric transient zones were introduced, whose elements had the mean length, which made it possible to eliminate the errors occurring in the case, where the sizes of adjacent grid-generating elements significantly differed in length. During generation of the finite-element grid for the working tools, a grid with a fixed length of finite element sides was used. The conditions of friction between the material and the tools were assumed to be "bilateral", which corresponds to the specimens being fixed in jaws in the actual tension process. It was assumed that the speed of the working tools results from the preset strain rate. The modelling covered only the specimen tension stage, therefore it was necessary to introduce the initial temperature distribution that forms as a result of heating up to the preset temperature at which the specimen would be tensioned.

To establish the limiting values of the normalized Cockroft-Latham criterion, the obtained theoretical study results were compared with the results of the experimental tests at the moment of specimen breaking. For the analysis, the assumption was made that the critical elongations (the ones for which specimen breaking occurs) obtained in the laboratory tests correspond to the moment of specimen breaking in the theoretical studies.

The obtained results do not allow one to determine definitely the limiting normalized Cockroft-Latham criterion value, for which the specimen breaking occurred. In order to determine the limiting value, the normalized Cockroft-Latham criterion values were summed for the finite elements existing in the notch axis, while preserving appropriate weights [6]. The weights represented the dimension of the grid element for given fracture criterion values, as related to the total specimen radius measured in the notch axis. Thus determined limiting values of the normalized Cockroft-Latham criterion are given in Table 3.

TABLE 3

Limiting values of normalized Cockroft-Latham criterion determined in uniaxial tension of notched specimens

T [°C] \ $\dot{\varepsilon}$	0.1	1.0	10.0
900	0.23	0.42	0.56
1000	0.32	0.52	0.76
1100	0.40	0.78	0.97

Based on the determined limiting values of the normalized Cockroft – Latham criterion it can be stated that with increasing strain rate, the limiting criterion value sat which specimen breaking occurs during the tension test, also increase (Fig. 3). For specimens tensioned at a strain rate of 0.1÷1.0 s^{-1}, this increase is larger than for specimens tensioned at a strain rate of 1.0÷10.0 s^{-1}. The analysis of the effect of temperature reveals that with the increase in temperature, for the same strain rates, the limiting normalized Cockroft – Latham criterion values, for which the material failure occurs, also increase.

Figure 4 shows, on the other hand, the dependence of the determined limiting normalized Cockroft-Latham criterion values as a function of $\log(\dot{\varepsilon})$. Then, the obtained results were approximated with the linear approximation method (the approximation results are denoted with broken lines in Fig. 4). When analyzing the obtained results it can be assumed that, for the strain rate range under examination, a linear relationship can be assumed to exist between the limiting values of the criterion analyzed and $\log(\dot{\varepsilon})$. The use of such a reference system enables easier determination of the effect of strain rate on the limiting normalized Cockroft-Latham criterion values determined from the uniaxial notched specimen tension test.

On the basis of the test results presented on Fig. 3, 4 it can be stated that the limiting normalized Cockroft-Latham criterion value at which the loss of metal cohesion occurs, is strongly influenced both by the temperature of the test specimens and by strain rates applied during the tests. Based on the obtained test results, a relationship has been developed, which describes variation in the limiting normalized Cockroft-Latham criterion value as dependent on the strain rate and temperature of the deformed BSt500S steel test specimen:

$$C = 1.66 + 0.2233 \cdot \log\dot{\varepsilon} - 0.333 \cdot (\log\dot{\varepsilon})^2 - 0.0038 \cdot T + \\ +0.000003 \cdot (T)^2 \quad (3)$$

where: C – limit value of the Cockroft – Latam criterion, T – temperature, $\dot{\varepsilon}$ – strain rate

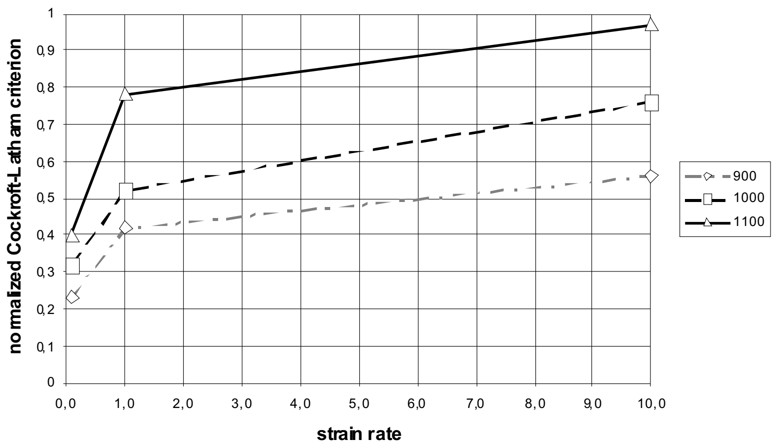

Fig. 3. Relationship of the normalized Cockroft – Latham criterion to the strain rate and temperature

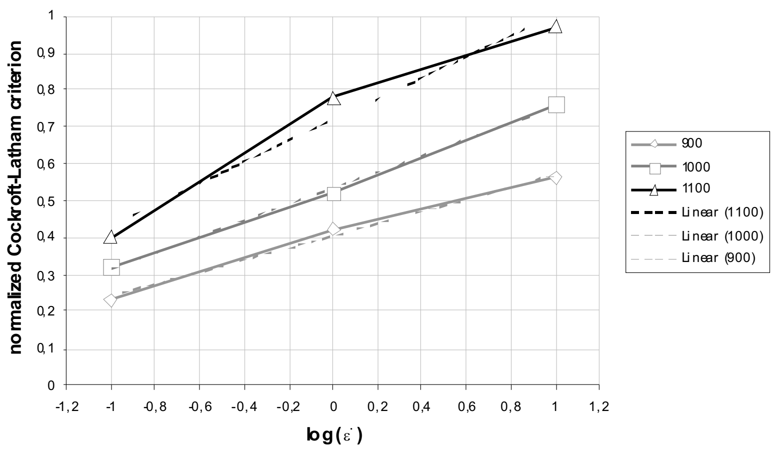

Fig. 4. Relationship of the normalized Cockroft – Latham criterion to the log ($\dot{\varepsilon}$)

The above-mentioned relationship can be employed for the high-accuracy determination of the limiting values of the normalized Cockroft-Latham criterion for steel BSt500S for hot plastic working processes, while assuming similar stress states. The correct determination of the limiting normalized Cockroft-Latham criterion values will enable the evaluation of the deformability range of the steel being examined, which will in turn allow the identification of the locations of potential crack formation during hot plastic working.

4. Determination of the normalized Cockroft – Latham criterion of strands separation

In multi slitting rolling process determination of the critical values is difficult, and could be realized by using the inverse method. Distance between a point, where crack begins, and point of contact metal with the slitting rollers was the parameter for analysis [7].

For the examination of the criterion of separation of strands during rolling with longitudinal band split-ting, a two-strand roll pass design, as used in one of the Polish steelworks for the rolling of 2×ø 16 mm and 2×ø 20 mm round ribbed rods, was utilized. Obtaining of templates originating from the real technological process of ribbed rod manufacture is very difficult. Therefore, templates taken during the preliminary rolling mill setting were used.

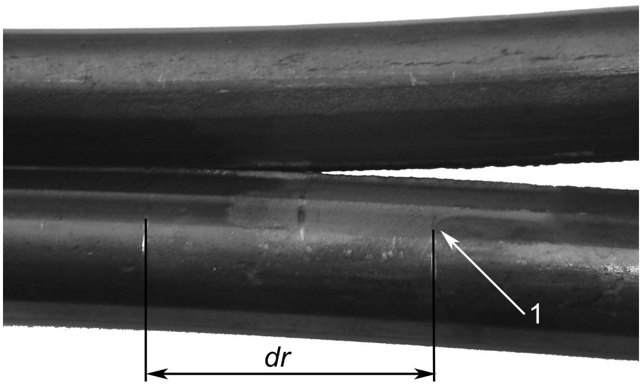

Fig. 5. View of the band obtained in the real rolling process: *dr* – distance between the location of contact of the strands with the separating roller and the origin of the strand-connecting bridge crack, 1 – the point of contact metal with the slitting

Fig. 5 shows the view of a bands obtained in the real ø 16 mm round ribbed rods rolling process, with the indicated distance between the location of contact of the strands with the separating roller and the origin of the strand – connecting bridge (*dr*). For the ø 16 mm this distance was *dr* = 24.1 mm and for the ø 20 mm this distance was *dr* = 22.4 mm.

The theoretical analysis was performed for the real rolling conditions: the initial strip temperature – 900°C, the rolling speed – 1 m/s, the working roll diameter D = 350 mm, the slitting roll diameter d = 164 mm. The distance of the working rolls axis from the slitting rollers axis is 350 mm. The slitting rolls did not have a constant speed and were not propelled. In order to reduce the computation time, a ¼ of the band was used. Moreover the following were taken for simulations: tool temperature – 60°C, ambient temperature – 20°C, friction factor – 0.8, coefficient of heat transfer between the material and the tool α – 3000 W/Km^2, coefficient of heat transfer between the material and the air α_{air} – 100 W/Km^2.

The theoretical analysis was performed for four different values of normalized Cockroft – Latham criterion: 0.50, 0.55, 0.60, 0.65. Similar measurements of the *dr* distance were carried out for bands obtained from the theoretical analysis of 2×ø 16 mm and 2×ø 20 mm round ribbed rods rolling process (Table 4).

TABLE 4
Results of *dr* measurement obtained from theoretical analysis

Value of normalized Cockroft – Latham criterion	0.50	0.55	0.60	0.65
dr [mm] (2×ø 16)	28.50	25.45	23.80	22.20
dr [mm] (2×ø 20)	27.10	25.05	22.10	20.20

Based on the obtained results (Table 4), the graph of the relationship of the distance between the location of contact of the strands with the separating roller and the origin of the strand-connecting bridge crack – *dr* versus the aplied value of normalized Cockroft-Latham criterion was plotted (Fig. 6 and Fig. 7).

To determine the actual value of the strand separation criterion, a straight line corresponding to the value of dr obtained during the real rolling process was drawn. The point of intersection of the straight line with the graph of the relationship f(*dr*) = C allowed the determination of the value of the criterion, for which a separation of the strands takes place.

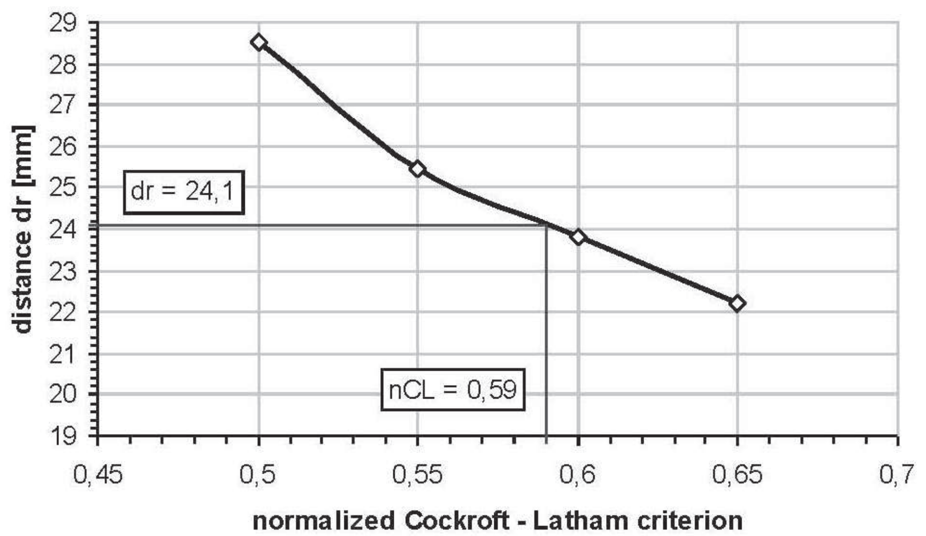

Fig. 6. The relationship of *dr* vs. normalized Cockroft – Latham criterion for 2×ø 16 mm ribbed rods rolling

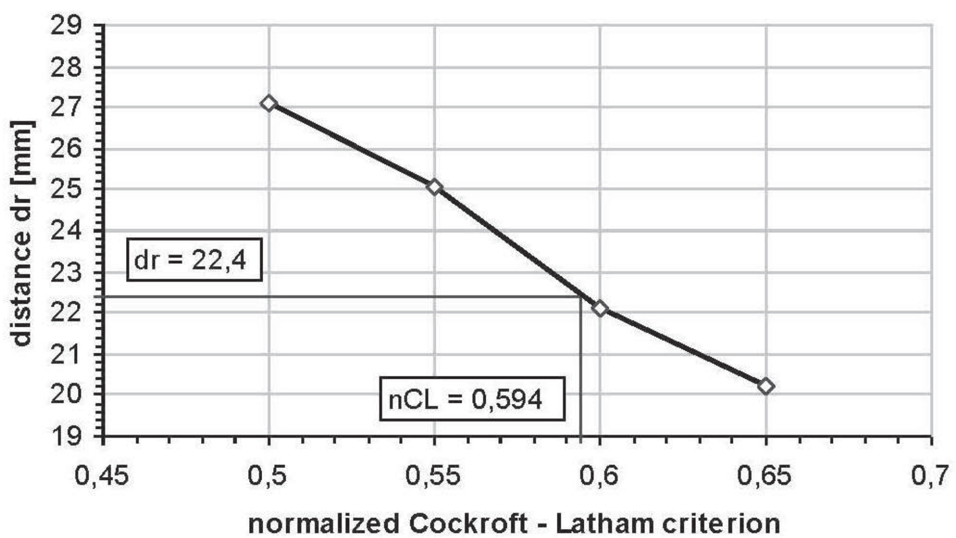

Fig. 7. The relationship of *dr* vs. normalized Cockroft – Latham criterion for 2×ø 20 mm ribbed rods rolling

For the case I value of normalized Cockroft – Latham criterion was 0.590 and for case II the value was 0.594. The obtained critical values of normalized Cockroft – Latham criterion ale very similar for both cases, and are lower than the values commonly used during the analysis of material continuity loss in hot plastic working. For the real rolling process, the increase in rolled band temperature and in deformation speed should be accounted.

5. Determination of the relationship between limiting values of normalized Cockroft-Latham criterion in tensile test and multi slit rolling process

In order to determine the relationship between the limiting normalized Cockroft-Latham criterion values for the process of multi slit rolling, as determined from the notched specimen tension test, it is necessary to establish the strain rate and temperature of the strip in the area of the strand – connecting bridge at the moment preceding the ultimate breaking.
It can be assumed that:

$$C_W = \kappa * C_L \tag{4}$$

where: C_W – limiting normalized Cockroft-Latham criterion value at which strand separation occurs; C_L – limiting normalized Cockroft-Latham criterion value, as determined from the notched specimen tension test, κ – factor of proportionality.

The factor of proportionality κ, is the value of the ratio of the limiting normalized Cockroft-Latham criterion value at which strip separation into individual strands occurs, as determined for the multi slit rolling process – C_W, to the limiting normalized Cockroft-Latham criterion value as determined during laboratory tests – C_L, with the identical deformation conditions being maintained.

Based on formula (3), the limiting value of the normalized Cockroft-Latham criterion was determined for a temperature of 920°C and a strain rate of 8.2 s^{-1}, at which breaking of the test specimen occurred during the uniaxial specimen tension test – C_L. The limiting normalized Cockroft-Latham criterion value amounted to 0.531. The limiting value of the cohesion loss criterion, as determined in the uniaxial notched specimen tension test, is smaller than that established for the real rolling process.

$$\kappa = \frac{C_W}{C_L} = \frac{0.592}{0.531} = 1,12 \qquad (5)$$

The κ factor determined from formula (5) enables the limiting values of the criterion under analysis, as determined in the uniaxial tension test, to be adjusted to the conditions of the actual technological process.

6. Summary

Adoption of the comparative method allows to determine the limiting values of normalized Cockroft – Latham criterion, for which the destruction of the material during hot plastic working process. Using the inverse method can be determined the limits values of normalized Cockroft – Latham criterion for separation of strands during rolling with longitudinal band splitting occurs.

Increasing the temperature of 900°C to 1100°C and strain rate range 0.1 to 10.0 s^{-1} increases the limit of a normalized Cockroft – Latham criterion for which rupture were observed, resulting in improved limiting of plastic working conditions for the tested steel of the species BSt500S.

For the analysis performed in this study, it was found that for ø 16 mm, and ø 20 mm ribbed rods rolling the limiting value of the strand separation was very similar and it could be used 0,59. With the increase in the present value of the normalized Cockroft – Latham criterion, the distance between the strand split point and the separating rollers decreases.

Determined in this work equations allows to use a limiting values of normalized Cockroft – Latham criterion, set out in the uniaxial tensile test of notched specimens, as the criterion of limiting values of the strand separation during multi slit rolling process.

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