IMPACT OF ROLLING CONDITIONS ON PROPAGATION OF A POTENTIAL CRACK

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Abstract

The paper reveals information about crack behaviour during hot rolling of heavy-gauge products. FEM-based mathematical modelling has been used to investigate the impact of crack shape (4 V-shaped cracks with different tip angles) and rolling parameters (friction and the deformation zone length/mean product thickness ratio) on the distribution of the principal tensile stress and the magnitude of strain across the section of the product and the Cockcroft-Latham fracture criterion value and on the crack closing capacity. For this purpose, the existing FormFEM simulation software was furnished with a module for computing the Cockcroft-Latham criterion. The results clearly show that the crack shape has the most powerful influence on the observed quantities, followed by the rolling geometry factors. The impact of friction is negligible. A laboratory experiment was performed to find the critical value of the Cockcroft-Latham criterion. The findings have been applied to an industrial process of rolling CCSP-continuously cast semiproduct with the diameter of 525 mm at the Třinecké Železárny, a.s. blooming mill.

1. INTRODUCTION

This paper presents investigation of causes of cracking in the interior of thick rolled products. The process comprised rolling of continuously cast sections of initial 525 mm diameter from 42CrMo4 steel in the blooming mill of the Třinecké Železárny steelworks into blooms of 285 by 285 mm dimensions. Extent and nature of cracks found in the bloom of 285 by 285 mm cross-section are shown in Fig. 1.

If cracks formed during rolling, there might be two underlying mechanisms of their formation. First one entails varying formability across the bloom cross section due to non-homogeneous temperature field after soaking. 3 alternatives are plausible:

- charging of continuously cast sections into furnace with minimum required heating. Hence, the plastic properties of material may have been past the formability peak (which is both theoretically and practically possible). Possible cast section interior flaws may thus be caused by this mechanism.
- homogeneous temperature field over the workpiece cross section (this alternative was the initial one for simulation) achieved via arbitrary combination of delay upon casting, temperature and furnace holding time.
- charging of cold blanks with subsequent insufficient heating of their centres.

Another crack-formation mechanism during rolling might operate due to additional tensile stresses in the centre of the bloom resulting from different horizontal velocities of...
metal across the thickness of the rolling section. These undesirable compressive stresses may also stem from skewing of the rolled product cross section due to instability during rolling. This possibility must not be overlooked – especially in round-shaped sections.

The joint effects of both negative factors cannot be dismissed either.

Regardless of the cracks’ cause, the solution can be the repair of the forming cracks by welding.

In the initial stage of the problem solving, our effort was directed towards increasing the forming reduction of the CCSP-continuously cast semiproduct centre. Computer-based simulation has been performed for this purpose. Its focus was the effect of the CCSP surface cooling on the introduction of the plastic strain into the rolled product centre [1]. Later, attention was paid to the stress and strain distribution across the rolled product section. Again, the effect of the surface undercooling was examined. The CCSP microstructures prior to and upon rolling were examined [2].

This article is based on previous experience, which is why the focus was on the most probable principle of critical crack formation. This includes the propagation of existing cracks, which are present in the original ferrite network along the prior austenite grain boundaries. For this purpose, an extensive experiment was carried out. Its aim was to monitor the behaviour of potential crack sites during rolling. Additional laboratory experiments for determination of the critical fracture criterion.

2. FRACTURE CRITERIA

Fracture criteria are based on assumption, that damage develops during deformation, which leads to cracks. Majority of the criteria are calculated as integral, with respect to time, of functions representing strain and stress history. Crack occurs when this integral achieves certain critical value. Many fracture criteria have been proposed in the scientific literature. Oyane criterion [3], described by equation below is one of them:

\[
\int_0^{\varepsilon_i(t)} \left( 1 + A \frac{\sigma_h}{\sigma_i} \right) d \varepsilon_i(t) \geq C
\]

(1)

where: \( \varepsilon_i \) – effective strain, \( \sigma_h \) – hydrostatic stress, \( \sigma_i \) – effective stress.

According to the Oyane criterion material loses cohesion, when integral in equation (5) reaches a critical value \( C \). In conventional solutions \( C \) is constant for a considered material, however, inverse analysis allows introduction \( C \) as function of such parameters as for example temperature, strain rate or metallurgical character of metal (chemical composition, structure, cleanness):

\[
C = f(M, T, \dot{\varepsilon})
\]

(2)

where: \( M \) - metallurgical character of metal , \( T \) – temperature, \( \dot{\varepsilon} \) – strain rate

Literature [4] mentions inverse analysis as means of finding the relationship (8). This is based on combination of FEM mathematical modelling and laboratory modelling using an appropriate instrument. The laboratory experiment is described and analysed by means of mathematical modelling. The value of the criterion and, if needed, other parameters (temperature, strain rate) are determined for each node. The results are then compared with those of the actual experiment, in which the crack formed. Using appropriate feedback enables transition from micro to macro scale and obtaining information on crack formation in
individual stages of the process. Based on literature search, one can suggest that, in general, the critical value of the fracture criterion increases with temperature and with decreasing strain rate in the single-phase region.

The Cockroft-Latham criterion used in this paper is expressed with the following equation:

\[ \int_0^{\varepsilon_f(t)} \sigma_i d\varepsilon_f(t) \geq C, \]

where: \( \sigma_i \) – maximum principal stress, \( C \) – critical value of integral.

3. MATHEMATICAL ANALYSIS OF CRACK BEHAVIOUR DURING ROLLING OF BLOOMS

3.1. Effect of the Crack Shape, Friction and the ld/hs ratio

This experiment is based on rolling of 525 mm-diameter continuously cast semiproducts (CCSP) at the Třinecké železárny blooming mill and uses 2D simulation with the FormFEM programme. Four types of cracks were examined and two values of the friction coefficient and three values of \( \rho \), \( l_\rho/h \), ratio used. The V-shape was selected as the basic crack shape. It is one of the most unfavourable alternatives with regard to the crack response to stress. The shape and identification of cracks is shown in Fig. 2. Their locations were in the centre along the axis of the rolled product.

![Fig. 2. The shape and identification of cracks.](image)

The values of the friction coefficient were 0.7 and 0.95. They were set this high in order to provide for smooth computation of the mathematical model. The values of \( l/hs \), ratio were as follows: 0.2, 0.35 and 0.5. They were the ordinary values found both in the Třinecké železárny and in the Kladno plant. The initial thickness of the semiproduct was 525 mm. Absolute values of reduction were 25 mm, 70 mm and 126.8 mm. The roll diameter was \( D = 994 \) mm.

The examined parameters included: crack shape after deformation and fracture criterion value according to the equation (3). The FormFEM program does not typically enable calculation of this parameter. For this reason, an auxiliary module has been constructed.

First three figures (3 through 5) show the effect of rolling parameters upon the introduction of the plastic strain into the bloom core. The figures show a longitudinal section through the top half of the product. The expected increase in depth of the introduced strain with increasing \( l/hs \) ratio is evident. Apparently, the effect of friction is less perceptible. However, it increases with the \( l/hs \) ratio. The effect of the increase in the friction coefficient is similar to that of the undercooled surface. Both raise the friction, resulting in greater depth of introduced strain towards the centre of the product. Naturally, the technological side effect of higher friction coefficient is the above discussed increase in sideways expansion of the product.
The images below (fig. 6 through 9) show the behaviour of the cracks under the examined conditions. The parameter shown in all cases is the Cockroft-Latham criterion value (LCK).

Considering the crack shape, it is evident that cracks with greater tip angle tend to close more readily. Despite, the complete closing of a crack was only observed in the V6 and V3 cracks at ld/hs. = 0.5.

The effect of the examined parameters on the LCK value is rather complex. The impact of the ld/hs ration is very clear in this case. With the growth of the ld/hs value, the LCK value rises by about 20 MPa. The friction raises the LCK value at low strain. Where higher strain is involved, the effect of friction is the reverse. The impact of the crack shape is the most
complex one. The graphs in Fig. 10 a, b, c show this effect within the following coordinates: distance of the product from the plane of exit (mm) and LCK (MPa) for all types of cracks. Highest LCK values were observed invariably in the V6 crack. The V02 crack took the second place. The difference between them increases with the strain value. The V1 trend is interesting, as the LCK value showed decrease (at friction value of 0.7) with increasing strain. The unusual behaviour of the V3 and V1 cracks can be explained by the shift of the maximum LCK value away from the crack tip (the values characterizing the crack tips were plotted in these charts).

![Graphs showing LCK vs. crack shape and distance from the exit plane](image)

**Fig. 10.** LCK vs. crack shape and distance from the exit plane, $\mu = 0.7$. a) $l_d/h_s = 0.2$; b) $l_d/h_s = 0.35$; c) $l_d/h_s = 0.5$

### 3.2. Determination of the Critical Value of LCK

Laboratory rolling of a wedge-shaped notched sample of 42CrMo4 steel was performed for this purpose. The total of 8 samples were rolled between 1.275 and 975°C. The roll speeds were 30 and 170 min$^{-1}$. Dimensions of the samples are listed in Fig. 11. The distance between first notch and the sample front face was 5 mm, while the notches were 18 mm apart. Samples were rolled to $h_1 = 3$ mm.

No visible crack has formed in any of the cases, whether in the notch or elsewhere. A close-up view of the wedge rolled at highest speed and lowest temperature (i.e. posing the highest probability of crack formation) is shown in Fig. 12.

![Sample dimensions](image)
Although no crack formed in any of the cases, mathematical modelling of the experiment was used to determine highest LCK value, at which still no crack occurred.

The FORGE 2005 package by Transvalor was employed for the FEM-based mathematical simulation. The rolling was simulated with temperatures of 1,275 and 975°C to enable comparison with results related to actually rolled samples. A model of a grade of steel matching 42CrMo4 was selected from the database of materials. The most difficult boundary condition value to select was the friction coefficient. It seems that m = 0.4 is the optimal value. Definition of the initial conditions incorporated the actual rolling conditions (roll diameters, sample geometry, roll speed and temperatures of the rolls and the wedge).

In terms of the state of stress during the rolling itself, the stress distribution around the notch was examined. Fig. 13 clearly shows that tensile stresses occur in and around the notch. This is expressed with the value of the first principal stress (along the axis 1). At even low value of strain, formation of the tensile stress around the notch prevails over that near the edge of the sample when leaving the rolling gap.

LCK values found in individual notches of the wedge specimen formed at 975°C are shown in Fig. 14. The figure shows that the notch results in stress concentration. Particular values pertain to mesh elements (not to nodes, which would be a more common case). The maximum value can therefore depend on the element size. Despite, it is clear that the values of LCK achieved considerably exceed the values found to describe the rolling of blooms in Třinecké železáry. Possible explanation can be found in the equation (8). The LCK critical value is a function of the metallurgical quality of the metal, among other factors. Evidently, the state of the steel structure is the key. This holds particularly for the prior austenite grain boundaries, where cracks form and then propagate. The value of LCK in these locations can be up to two orders of magnitude lower than the values found by the wedge sample test. Still they become the spots, where critical cracks grow. Overheating of steel (involving grain coarsening and diffusion migration of impurities to grain boundaries) degrades formability in steel, which is otherwise quite well formable.
3.2 Simulation of the Crack Behaviour during Actual Bloom Rolling

This is a simulation of rolling of a 525 mm-diameter CCSP. Its centre part along the axis has the V02 crack, which is perpendicular to the rolling direction. The aim of this simulation is finding whether and when the crack closes by welding. Results of the simulation (crack shape after deformation and LCK value) are shown in Figs. 15 through 20.

This type of cracks closes completely soon: after 10th pass. Passes no. 13 to 15 then serve as backup passes, which can close even slightly larger cracks thanks to the favourable ratio ld/hs. > 0.4. The LCK value does not exceed 18 MPa at any time during rolling. In first three
passes, the initial narrow crack gradually opens to a 3.5 mm width. In terms of the crack propagation, this stage of rolling is essential. If the crack propagates along the compromised austenite grain boundary at this stage (or even more microcracks join), the crack length exceeds the critical value. It is impossible to close such crack by means of a standard sequence of passes. Furthermore, it will probably propagate further.

4 CONCLUSION

Computer-based simulation of the existing sequence of rolling passes was carried out focusing on the behaviour of a potential crack (perpendicular to the CCSP axis) within ferrite on a prior austenite grain boundary. The crack propagation due to stress concentration at its tip was examined, as well as the crack broadening caused by tensile stress in the central part of the CCSP and the possibility of the crack closing by deformation upon tilting. The results show that it is possible to close small cracks by means of the existing procedure. However, if the grain boundaries are degraded and the crack propagates past the critical limit, e.g. due to inadequate heating procedure, the propagation of the crack will prevail over its closing. The reason is the tensile stress present in the centre of the rolled product. In such case, the presence of plastic deformation in the crack tip, which is necessary for the crack closing, combines with the mentioned tensile stress and results in an increase in the LCK value. This, paradoxically, strengthens the propagation potential of the crack.

In this project, rolling conditions were sought ($\Delta h, l_d/h_s, \mu$), under which the cracks could be expected to close owing to introduction of plastic strain deep below the surface and elimination of unfavourable state of stress. The results clearly show, that the technological conditions identified are outside the existing capacity of the Trinecké železárny, a.s. blooming mill. Therefore, it is not possible in the Trinecké železárny, a.s. company to provide such rolling parameters, which would completely eliminate critical cracks in the rolled billet. There are certain changes, which can improve the stress conditions (increasing the $l_d/h_s$ ratio, increasing the absolute reduction $\Delta h$ in individual passes and the friction coefficient $\mu$ by, for instance, roughening the roll surfaces or reducing the roll speed, increasing the working rolls’ diameters, changing the adjustment or undercooling the rolled piece surface). However, all such measures require significant changes in the existing technology (chiefly owing to the sideways expansion of the product). For this reason, it may not be possible to introduce them.

LITERATURA


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