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INFLUENCE OF THE ARC OF STRAND CORNER ON THE STRESS AND STRAIN DEVELOPMENT IN THE CONTINOUS CASTING INGOT

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Abstract

Formation of surface and internal cracks during solidification and cooling of steel in the continuous casting process is highly affected by the stress and strain field. The development of stress and strain fields depends on many factors. The most important are cooling parameters, strand shape, arc of casting machine, casting speed and chemical composition of steel. All these parameters influence on the local stress and strain and may cause the failures formation. In this case prediction of crack formation is a very important problem in the design of the continuous casting technology. The effect of the arc of strand corner on the strain and stress development in the continuously caste ingot and on the possibility of cracks formation has been investigated. The analysis has been performed on the ground of numerical calculations for selected fracture criterions and two different arc of strand corner. Finite element method has been employed to compute the stress and strain field in the whole continuous casting line. The thermal stresses have been calculated for the strand temperature determined from the three dimensional steady solution to the heat transport equation. Heat of solidification has been included in the finite element model. The thermal strains and stresses which result from non uniform temperature field were computed and coupled with the strains and stresses caused by bending and unbending of the strand.

Key words: continuous casting, crack formation, finite element method

1. INTRODUCTION

Continuous casting of steel has many advantages, which include low cost, high yield, flexibility of operation, and ability to achieve a high quality cast product. Despite the advantages, the quality of the cast strand has suffered from the presence of various defects, such as surface or internal cracks. To the factors that affect on the crack formation, casting technology, geometry of casting machine (Cebo-Rudnicka et al., 2010 a), geometry of cast strand, quenching parameters and chemical compositions of steel (Kim et al., 1996; Gzieło, 2006) can be include. All these factors affect the stress and strain field in the solidifying strand and the modeling of surface and internal crack formation is very difficult. Despite that, the possibility of crack formation prediction is an important problem in productivity improvement, especially at the stage of process designing. It is important to determine the factors which may lead to cracks formation. The experimental analysis of the influence of any technical parameter of the continuous casting line on quality of a cast strand is difficult and very expensive (Brimacombe & Soeimachi, 1977). Much more cost-effective are numerical methods based on specialized software developed specially for this technology of ingot production (Liu et al., 2001; Thomas, 2001).

2. MODEL DESCRIPTION

In the applied solution the mathematical model of heat transfer involves heat transfer in the system which includes: cast strand, casting mould, water spray cooling zones and air cooling. The temperature field in the cast strand subjected to cooling in: casting mould, secondary cooling zones, straightening and withdrawal sections has been computed using steady solution to the Fourier–Kirchhoff equation:

$$\frac{\partial T}{\partial \tau}+v_x\frac{\partial T}{\partial x}+v_y\frac{\partial T}{\partial y}+v_z\frac{\partial T}{\partial z}=$$

$$\frac{\lambda}{\rho c}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{q_v}{\rho c} \qquad (1)$$

where: T – temperature, K; τ – time, s; v_x, v_y, v_z – velocity field, m/s; λ – thermal conductivity, W/(m K); q_v – internal heat source, W/m^3; c – specific heat, J/(kg K); ρ – density, kg/m^3.

have been presented. The developed algorithm used to handle internal heat source and overall heat balance gives significantly higher strand temperature. Accurate determination of solidifying strand temperature is of great importance in modeling of stress development and cracks formation The more detailed description of the mathematical model of heat transfer has been presented by Hadała & Malinowski (2009).

In numerical model that has been used to analyze crack formation, the elastic–plastic finite element model is used to determine the stress and strain field in the cast strand. In these model the local stresses and strains resulted from bending and unbending of the cast strand has been taken into account. In figure 2 bending effect on mean stress at selected points of strand has been presented. Also the thermal stresses caused by non uniform temperature field has been calculated. Mean stress distribution caused by non uniform temperature field has been presented in figure 3. Comparison of the results presented in figure 2 and 3 clearly shows that bending effect must be included in the stress model in order to determine fracture behavior.

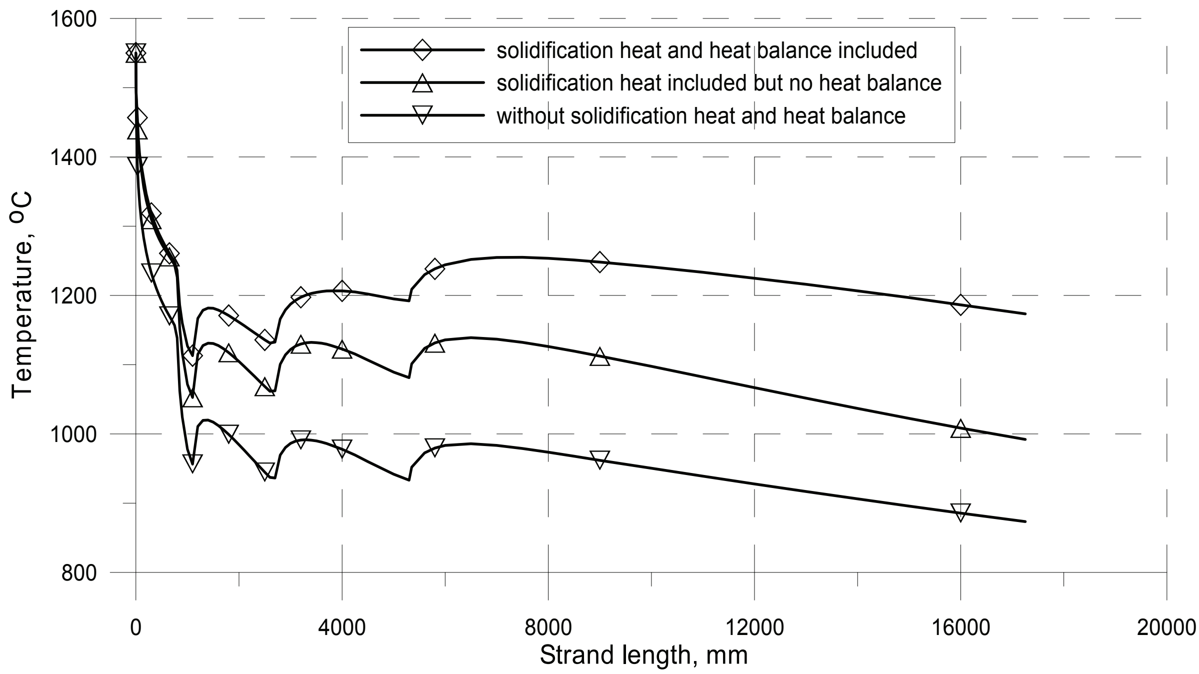

Fig. 1. *Temperature distributions at strand surface computed for different algorithms employed to handle internal heat source and energy balance.*

The heat of solidification has been included in the model in the form of the internal heat source. The energy balance of a strand moving through the control volume has been used to improve the solution accuracy. In figure 1 temperature distributions at strand surface computed with the new algorithm

The influence of the gravity forces on the mean stress was neglected. Also the local changes of stress and strain fields at the rolls contact zones were not computed. The more detailed description of the stress and strain model has been presented by Gołdasz et al. (2010).

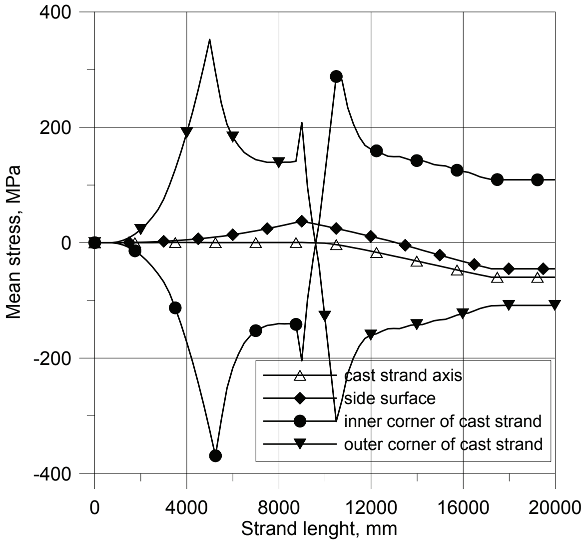

Fig. 2. Average stress distributions at selected points of the continuously cast strand resulting from bending of the strand only.

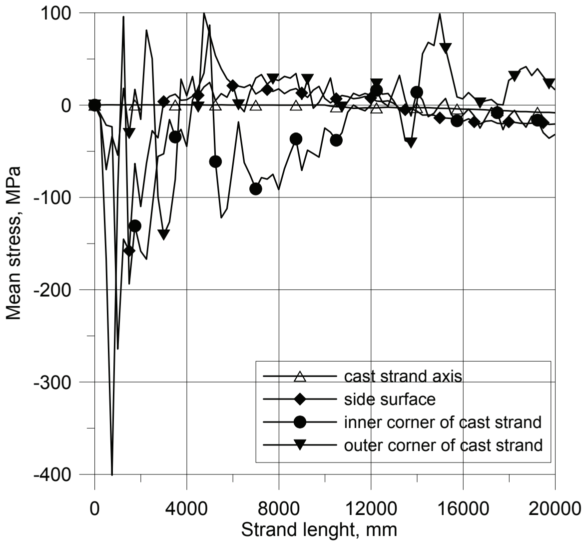

Fig. 3. Average stress distributions at selected points of the continuously cast strand resulting from temperature field only.

3. ANALYSIS OF THE RESULTS

Analysis of crack criterions has been performed for the square cast strand. The following chemical composition of steel has been assumed for calculations: 0.45% C, 0.65% Mn, 0.27% Si, 0.95% Cr and 1.55% Ni. Thermo physical properties of steel were selected based on chemical composition of steel (Wang et al., 2007). The dependence of thermal conductivity, density and specific heat on temperature for considered steel has been presented in figures 4, 5 and 6. Solidus temperature was assumed as 1340 C, liquidus as 1500ºC. In the solid state the austenitic transformation boundaries were assumed as: 760ºC and 700ºC. Analysis has been performed for two different values of the arc of strand corner: case I (arc of strand corner *r* = 6 mm); case II (arc of strand corner r = 16 mm). To analyze crack formation three criterions have been chosen:

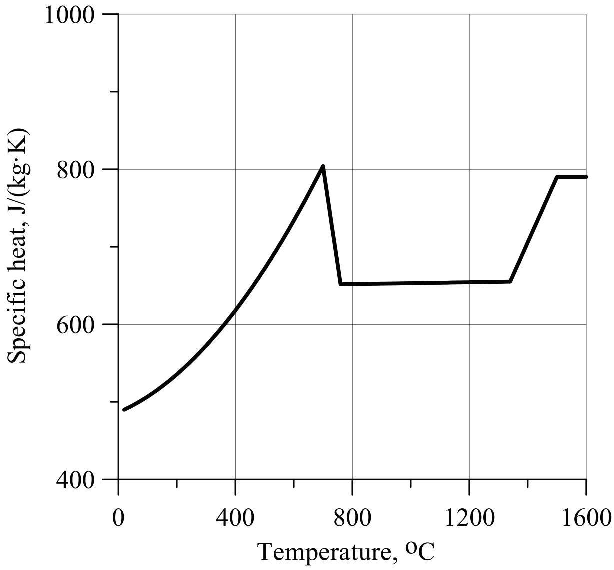

Fig. 4. Specific heat as a function of temperature for the steel employed in computations.

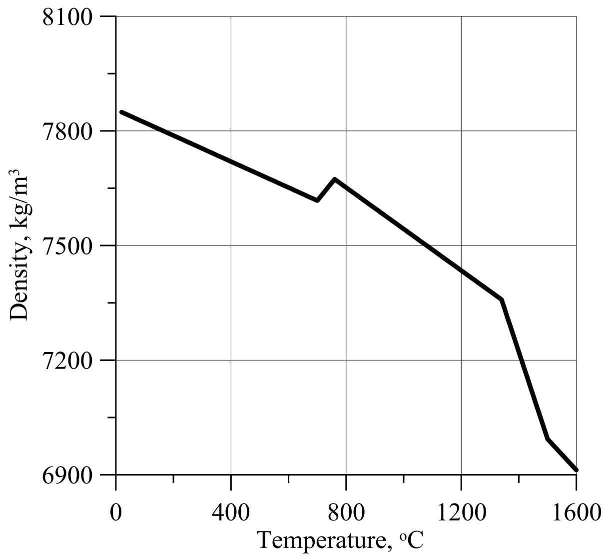

Fig. 5. Density as a function of temperature for the steel employed in computations.

Plastic work criterion,

$$C_{EP} = \int_0^t \dot{\bar{\varepsilon}}\bar{\sigma}dt \quad \text{for } \sigma_m > 0 \qquad (2)$$

Latham criterion,

$$C_{LA} = \int_0^t \dot{\bar{\varepsilon}}\bar{\sigma}_{max}dt \quad \text{for } \sigma_m > 0 \qquad (3)$$

Strain criterion,

$$C_{LA} = \int_0^t \dot{\bar{\varepsilon}} dt \quad \text{for } \sigma_m > 0 \qquad (4)$$

where: $\dot{\bar{\varepsilon}}$ – effective strain rate, $\bar{\sigma}$ – effective stress, σ_m – mean stress, $\sigma_{\max}$ - maximum stress.

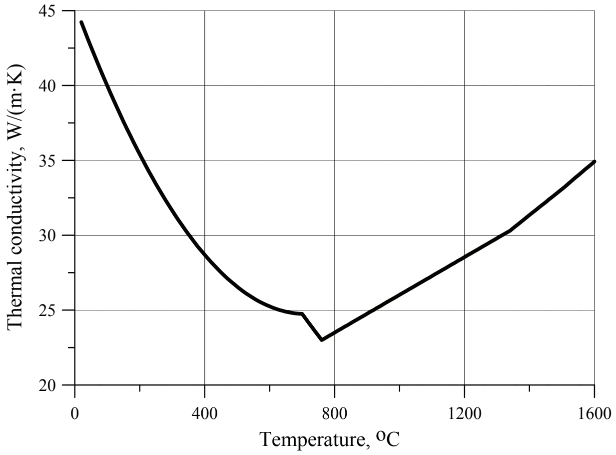

Fig. 6. Variation of thermal conductivity with temperature for the steel employed in computations.

Criterions (2) and (3) indicate a possibility of cracks formation if plastic work exceeds a limit value. This two criterions have been analyzed in continuous casting process by Cebo-Rudnicka et al. (2010a; 2010b). The third criterion given by the integral (4) is a very simple one and assumes, that cracks would occur, if the sum of effective strain has passed a limit value. The integrals (2), (3) and (4) are calculated at material points for which mean stress is positive. For all criterions mentioned above, the limit values of: C_{EP}, C_{LA} and C_{EF} parameters which indicate a possibility of crack formation for a specific grade of steel can be determined from the tensile test. From the industrial practise it is know that fracture occurs mainly at corners of the cast strand. The influence of the arc of casting machine on the value of crack criterion parameters has been studied by Cebo-Rudnicka et al. (2010a; 2010b). Calculated values of the crack criterion parameters indicated that the most sensitive to crack formation are inner and outer corners of the cast strand. Further, it has been observed in industry that fracture takes place when the arc of strand corner increases. This phenomenon has not been explained by numerical simulations so far. The influence of the arc of strand corner on stress and strain field is significant. In figure 7 variation of the mean stress for two values of the arc of strand corner has been presented. It can be noticed, that larger arc of the cast strand corner increases the mean stress. The difference in the maximum value of the mean stress at the inner and outer corner of cast strand reaches 200 MPa.

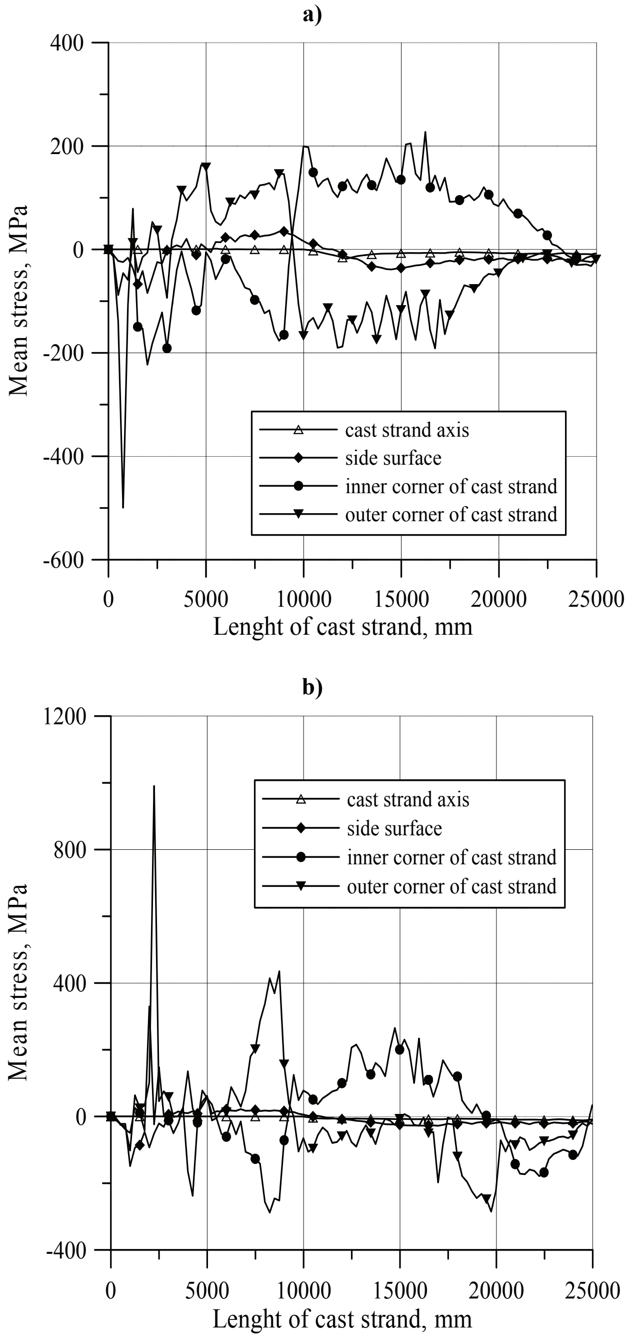

Fig. 7. Mean stress distributions at selected points of the continuously cast strand a) arc of strand corner r = 6 mm, b) arc of strand corner r = 16 mm.

Similar relation is observed for the effective strain distribution presented in figure 8. Effective strain at the end of casting line reaches 0.1 for the arc corner of 6 mm and is almost 5 times higher for the arc corner of 16 mm. In the same time the effective stress distribution shows opposite behavior presented in figure 9. Effective stress has higher values for the arc corner of 6 mm. The highest values of the effective stress were observed between the second and the fifth meter of the length of a cast strand where strand bending take place. In a bending section the effective stress is about 80 MPa for the arc corner of 6 mm, and about 45 MPa for the arc corner of 16 mm. Mean stress in that section is positive in the case of outer corner of a strand. It means that thermal – mechanical conditions are suitable for cracks formation and development. It has been clearly indicated by a rapid increase in crack criterions integrals presented in figures 10, 11 and 12. All crack criterions predict very similar qualitative distributions of crack criterion integrals along the length of a cast strand. The crack criterion integrals are definitely higher in the case of a lager value of the arc of strand corner (figures 10-12).

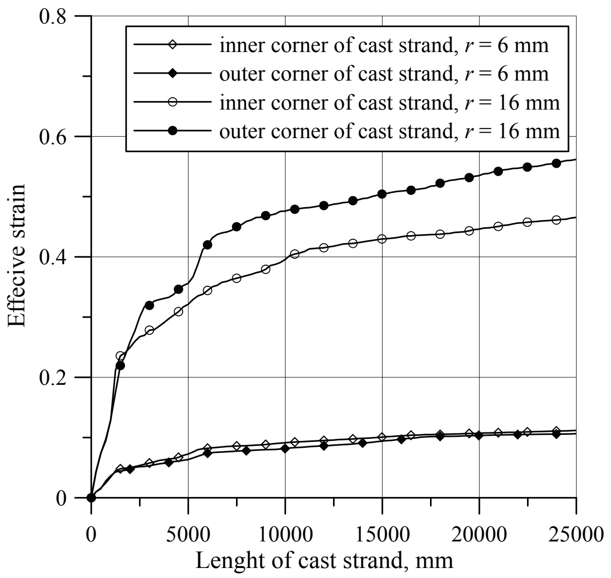

Fig. 8. Distribution of the effective strain at inner and outer corner of a cast strand for the arc of strand corner r = 6 mm & 16 mm.

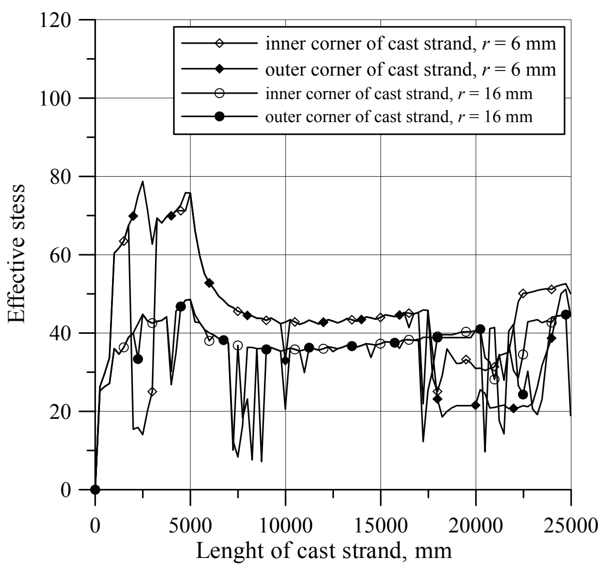

Fig. 9. Effective stress distributions at inner and outer corner of a cast strand for the arc of strand corner r = 6 mm & 16 mm.

The places that are most exposure to crack formation has been indicated by a rapid increase in fracture criterion integral values. According to the computation results most probably cracks can be initiated between the first and second meter at the outer corner of a cast strand length for the arc corner of 16 mm of (figures 10-12). In these region cast strand is subjected to bending. In case of 6 mm arc of strand corner growth in fracture criterion integrals takes place between first and sixth meter of a cast strand length, but the maximum values of crack criterions parameters are much smaller. The inner corner of cast strand is exposed to crack formation after leaving the casting mould at about 1 m of strand length. Cracks development can continue along bending and unbending sections of a casting machine. However, integrals of fracture criterions have essentially lower values in the case of 6 mm radius of strand corner.

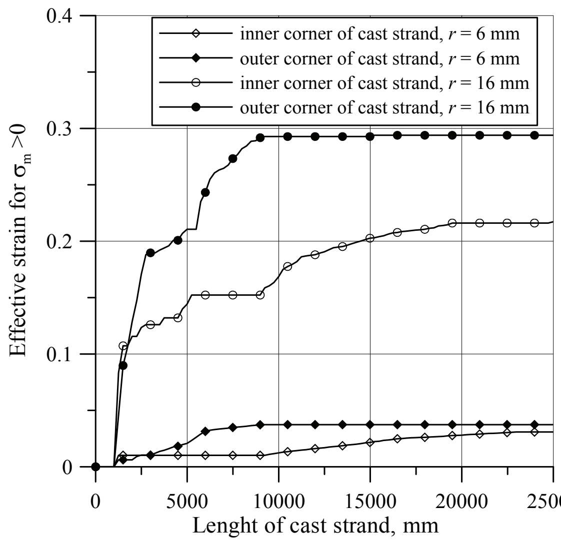

Fig. 10. Results of effective strain criterion for the arc of strand corner r = 6 mm & 16 mm.

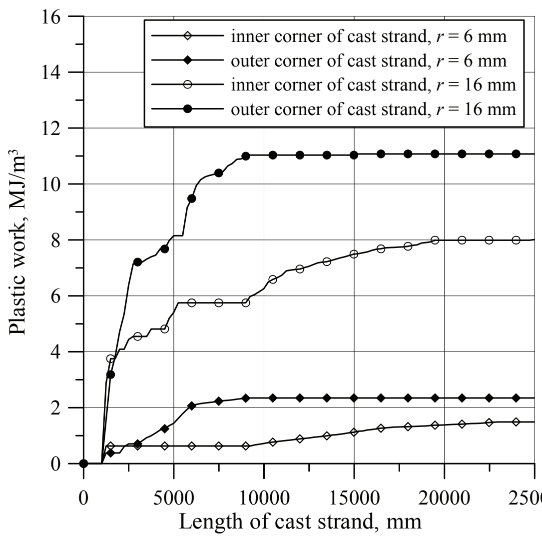

Fig. 11. Results of plastic work criterion for the arc of strand corner r = 6 mm & 16 mm.

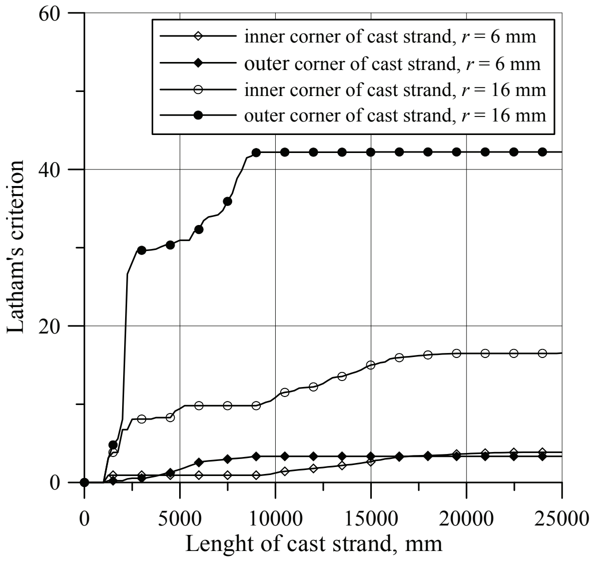

Fig. 12. *Results of Latham criterion for the arc of strand corner r = 6 mm & 16 mm.*

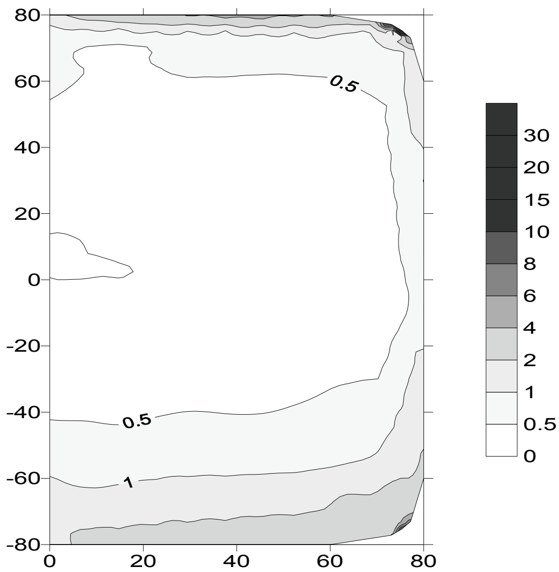

Fig. 13. *Distribution of Latham criterion in the strand cross section for the arc of strand corner r = 16 mm.*

In figure 13 distribution of Latham criterion in the strand cross section at the end of straitening section of casting machine has been presented. It can be seen that the highest values of fracture criterion are observed near the strand surface. Rapid growth of fracture criterion is observed in the strand corner zones.

4. CONCLUSIONS

Accuracy of the finite element solution to the temperature field of the cast strand has been improved. The major problem lies in the overall heat balance discrepancy. It is necessary to include the overall heat balance calculation in the finite element algorithm in order to improve solutions accuracy. The solidification heat has significant influence on the temperature filed computed from steady 3D model. The differences between models results are very important. The results of calculation let to identify the regions were cracks might be formed while continuous casting of steel. From the selected crack criterions the most useful were strain work criterion and Latham criterion. Numerical calculation made on the basis of these two criterions indicated the same regions of cracks formation as the ones known from industrial practice. Increase of the arc radius of a strand corner from 6 mm to 16 mm has caused significant increase in the effective strain and mean stress values. It has resulted in higher values of fracture criterions. These clearly indicates that the probability of fracture development in the case of 16 mm arc of strand corner radius is much higher than in the case of 6 mm corner radius.

ACNOWLEDGEMENTS

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WPŁYW PROMIENIA NAROŻA PASMA NA ROZWÓJ NAPRĘŻEŃ I ODKSZTAŁCEŃ WE WLEWKACH ODLEWANYCH W LINII COS

Streszczenie

Powstawanie pęknięć na powierzchni wlewków odlewanych w sposób ciągły w istotny sposób ogranicza wydajność urządzeń lub przyczynia się do obniżania jakości odlewanych wyrobów. Wpływ na powstawanie pęknięć ma wiele czynników. Do najważniejszych należy zaliczyć: kształt przekroju poprzecznego pasma, promień łuku maszyny do ciągłego odlewania, prędkość odlewania i skład chemiczny stali. Wymienione czynniki wpływają na rozwój naprężeń i odkształceń w odlewanej stali. Dążenie do zwiększania prędkości odlewania wymusza stosowanie intensywnych metod chłodzenia powierzchni wlewków ciągłych. Powstające duże gradienty temperatury skutkują znacznymi naprężeniami cieplnymi. Szczególnie trudne jest odlewanie wlewków z zaokrąglonymi narożami. Taki typ wlewków o promieniu zaokrąglenia naroży około 15-20 mm jest poszukiwany przez producentów wyrobów walcowanych długich. Ze względu na pękanie zaokrąglonych naroży wlewków, stosuje się bardzo małe promienia zaokrąglenia od 3 do 5 mm. Dotychczas nie wyjaśniono dlaczego zwiększenie promienia naroża sprzyja powstawaniu pęknięć. Do obliczeń naprężeń i odkształceń wlewków ciągłych zastosowano poprawione modele cieplne i mechaniczne. W obliczeniach pola temperatury uwzględniono ciepło krzepnięcia stali i poprawiono dokładność symulacji poprzez uwzględnienie w algorytmach numerycznych bilansu ciepła pasma. W obliczeniach pola naprężeń uwzględniono zarówno naprężenia cieplne jak i naprężenia powodowane wyginaniem pasma na łuku maszyny COS. Wyniki symulacji potwierdziły wzrost wartości wybranych kryteriów pękania w przypadku wlewków ciągłych o promienia naroża 16 mm w stosunku do wlewków o promieniu naroża 6 mm.

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