LIBRARY SEARCH ON OFF CORNER CRACKS IN BILLET & BLOOM CASTING

Number of references: 27

1) Analysis of thermomechanical behaviour in billet casting with different mould corner radii. J. K. Park, B. G. Thomas, and I. V. Samarasekera

As the corner radius of the billet increases from 4 to 15 mm, this gap spreads further around the corner towards the center of the strand and becomes larger. This leads to more temperature non-uniformity around the billet perimeter as solidification proceeds. Longitudinal corner surface cracks are predicted to form only in the larger corner radius billet, owing to tension in the hotter and thinner shell along the corner during solidification in the mould. Off corner internal cracks form more readily in the small corner radius billet. They are caused by bulging below the mould, which bends the thin, weak shell around the corner, creating tensile strain on the solidification front where these longitudinal cracks are ultimately observed.

2) Continuous casting mould for square steel billet optimised by solidification shrinkage simulation. T. M. Wang*, S. W. Cai, J. Xu, Y. Y. Du, J. Zhu, J. J. Xu and T. J. Li

A transient, thermoelastic–viscoplastic finite element model has been applied using ANSYS to study the thermal and mechanical behaviour of the solidifying shell during continuous casting of steels. In the model, a gap dependent heat transfer condition was imposed in the boundary between shell and mould. Thermophysical properties (e.g. thermal linear expansion) depending on temperature and composition were derived from experiment data and empirical correlations. Continuous casting of square billets with different steel grades, B72LX and ER70S6, were simulated to investigate the evolution of shell temperature, stress and shrinkage with an indirect coupled approach. The results indicated that carbon content, pouring temperature and casting speed have obvious influence on shrinkage of billets. According to shrinkage compensating principle, the mould taper and inner cavity geometry were designed and optimised based on average shrinkage histories of the solidifying shell. The new design has performed well in industrial trials.

3) Crack formation in billet casting. How much optimization of mold flux can help? A.Giacobbe, S.Tintori, R.Carli, A.Monaci, M.Luni.

Modern steelmaking requirements need optimal comprehension of physico-chemical properties of all chemical reaction involved, where mold fluxes represent the most critical factor during continuous casting. Aim of present work was appearance of subsurface cracks in higher quality steel on a billet casting plant case and solution of such matter involving mold fluxes. Test was performed casting several heats of different critical steel grades with different mold fluxes, in order to give a reliable and optimal solution to this problem in a particular square section. Always preserving safety during caster operations, mold flux basicity index was slightly increased step by step up to a typical level keeping lubrication properties as first aim. For each casting flux tested all rheological and chemical flux parameters were carefully checked, controlling for each test final results expressed as surface defects index and defining a correlation between flux chemical formulation and final quality obtained. Final target was obtained, giving therefore a new possible approach for designing a mold flux able to satisfy more severe requirements and confirming good results coming from collaboration between fluxes producers and steelmakers.

4) Crack formation in the continuous casting of steel. J. K. Brimacombe, K. Sorimachi

This review examines the different types of internal and surface cracks that can form during the continuous casting of steel. For each crack type, the operating and metallurgical factors that are known to influence crack formation are assessed in the light of the high temperature mechanical properties of steel and a knowledge of the stresses generated in the solidifying shell. The importance of two zones of low ductility in steel is demonstrated by this approach. One zone exists above 1340°C and probably accounts for the formation of all internal cracks and surface longitudinal cracks. The other zone lies between 700 and 900°C and is related to the presence of soluble aluminum, niobium and vanadium. Transverse surface cracks in slabs can be related to the latter zone.

5) Defects in the continuous cast billets and their effect on the quality of rolled products. Anna Moráfková; Jaromír Bača; Jaromír.

Results of quantitative evaluation of continuous cast billets (CCB) were treated statistically. Created database covered more than 25 000 evaluated specimens. Dependence of chemical composition along with geometry of CCB on the defect occurrence was investigated. Selected defects were carefully traced in various stages of the rolling processes. Their effect on the final quality of rolled products was studied.

6) Design of corners of mould in square billet casting. C. Mapelli and S. Semplici

The present paper describes a model implemented by a software tool that can carry out simulation of shell rectangular shapes. The first aim of the software is to simulate formation of the solid shell in the strand and the deformations to which it is subjected.

7) Fabricación en colada continua de una palanquilla de acero de fácil mecanización y bajo carbono que dé lugar por laminación directa a un producto

que en defectos y maquinabilidad sea equivalente a lo que se obtiene por métodos convencionales. E. Laínez, J.C. Busturia

La investigación ha estado centrada en el campo de la fabricación de palanquilla de colada continua, de aceros de fácil mecanización bajos en carbono. El objeto de la misma fue determinar los parámetros a utilizar en la fabricación de la palanquilla, para que laminada sin acondicionamiento obtener un producto similar en defectos y maquinabilidad al obtenido de forma convencional. Durante el primer periodo de la investigación se controlaron los parámetros de fabricación en H.E.A, Tratamiento en Cuchara y Colada Continua de 44 coladas en formatos de 0 145 y 0 170 de aceros de fácil mecanización bajos en carbono, con el fin de relacionarlos con la calidad de la palanquilla (grietas, poros, etc.) y más lejos aún con los rendimientos y calidad en producto acabado. De este estudio resultó que la aparición de grietas subcutáneas cercanas a las esquinas ("off-corner cracks") parecía depender del contenido de carbono de la palanquilla, aumentando el índice de grietas al aumentar el carbono. Esta circunstancia fue ratificada al comprobarse posteriormente en nuevas coladas que este tipo de defectos desaparecía prácticamente con contenidos máximos de carbono de 0.08%. - El índice de poros superficiales en la palanquilla tenía una cierta dependencia con el contenido de carbono alcanzado al final de la descarburación en el horno, aumentando al disminuir el carbono.

8) Formation of Off-Corner Internal Cracks in Continuously-Cast Billets. Brimacombe, J. K.; Hawbolt, E. B.; Weinberg, F.

The size, frequency and distribution of internal, off-corner cracks in strand-cast billets have been determined from sulphur prints of as-cast transverse sections. These measurements, combined with SEM observations of the crack surface and computer predictions of the thermal field in the billets during casting, indicate that the cracks form in the mould and upper-spray regions. Cracking occurs close to the solidification front near the solidus where the steel has low ductility. The cracks are believed to result from bulging of the solid shell in the lower part of the mould. As bulging occurs, a hinging action develops near the colder and stronger corners causing off-corner tensile stresses near the solidification front and cracking. The off-corner cracks were found to be distributed randomly on the eight available off-corner sites which indicates that bulging of individual billet faces occurs in a random fashion. This is likely a result of the strand moving about in the lower region of the mould. Because bulging is affected by mould taper, mould alignment, mould wear and foot-roller guidance of the strand these variables should affect the formation of off-corner cracks. Since the off-corner cracks extend into the upper spray zones, the extent of cracking may be reduced by increasing the water flux slightly, which reduces bulging and imposes a compressive strain at the solidification front.

9) Finite element numerical simulation on thermo-mechanical behavior of steel billet in continuous casting mold. Engang Wang, Ji Cheng He

The thermo-mechanical behavior of a thin, growing shell during the early stages of solidification in a continuous casting mold is very important to the ultimate quality of the final billet. A model was developed to be applied to predict the extent of the gap between the mold and the shell and focus on the influence of mold taper on the thermo-mechanical behavior of the steel billet to help to understand the formation of off-corner cracks and breakouts in the solidifying shell.

10) Finite element numerical simulation for influence of mold taper on thermomechanical behavior of steel billet in continuous casting process. Engang Wang, Jicheng He

The thermomechanical behavior of the thin, growing shell during the early stages of solidification in the continuous casting mold is very important to the ultimate quality of the final billet. A two-dimensional, transient finite element model has been developed to treat the heat flow and deformation of solidifying shell in the continuous casting mols as coupled phenomena. The major application of the model is to predict the extent of the gap between the mold and the shell, and focus on the influence of mold taper on the thermomechanical behavior of the steel billets to help understand the formation of off-corner cracks and breakouts in the solidifying shell.

11) From CONVEX Technology to INVEX. N. Grundy, F. Kawa, B. Kündig and M. Hogenschurz

CONVEX Technology has become synonymous for Continuous Casting Technology for long products for highest demands in terms of productivity and product quality. INVEX Technology is the evolution of the CONVEX Technology allowing steel plants to reach the next level of productivity and product quality for any dimension (billet, bloom) or shape (square, rectangular, round). The unique corner configuration of the INVEX Mould tube, the minimized wall thickness and the design of the water jackets result in uniform shell growth in particular in the critical off-corner area of the hot strand. The elimination of the cold, "black" corners of the - with the INVEX Mould cast billets is further allowing the direct hot charging into the rolling mill without the traditional reheating furnace reducing the overall processing cost

12) Heat transfer, oil lubrication and mold tapers in billets casting machines. S. Chandra.

It has been possible to link various sensor signals to the generation of defects in the billet, in particular to the formation of off-corner internal cracks, transverse depressions and billet rhomboidity. This together with linkages between mould heat transfer and operating variables now makes it possible to conceive of a control system consisting of an instrumented mould and an expert system that not only can assess billet quality on-line but can also initiate corrective action by changing operating conditions that alter the heat transfer in the mould

13) High speed casting mold for billet caster (NS Hyper Mold). S. Kittaka et al.

Prevention of off-corner cracks and breakouts during high-speed continuous billet casting calls for optimization of mold taper and prevention of bulging beneath the mold. The NS Hyper mold can continuously cast 130 mm square billets at a speed of 5.0 m/min without occurrence of off-corner cracks and breakouts.

14) Ideal taper prediction for billet casting. Chunsheng Li and Brian G. Thomas

Mold taper is an important control parameter in the continuous casting of steel billets. Properly tapered mold walls compensate for shrinkage of the solidifying strand to maintain good contact and heat transfer between the mold wall and shell surface without exerting extra force on the hot and weak shell. The amount of taper needed varies with steel composition and casting conditions, such as mold length, casting speed, and type of lubrication. Inadequate mold taper leaves an air gap between the mold wall and shell surface which leads to a hotter and thinner shell within the mold. Ferrostatic pressure from the liquid core will bulge the weak shell within and out of the mold and even break out the shell in extreme situations. Excessive taper exerts extra load on the solidifying shell and increases dragging friction. Transverse cracks, shell buckling or even shell jamming and breakouts may occur. Past efforts conducted to assist mold taper prediction includes mathematical models to calculate thermal shrinkage of the steel billet [1-3] and thermal distortion of the mold [3-6]. These previous investigations assume optimal taper should match the shell shrinkage, presuming this should produce good heat transfer across the interfacial layer between mold wall and billet surface at the face center along the mold axial direction. Corner effects have received little attention. The first objective of this work is to investigate the criteria for taper optimization by considering conditions at the billet corner needed to avoid cracks and defects both within and below the mold assuming the good mold taper is already provided along the face center. Current billet molds often adopt simple flat walls, which produce inadequate taper in the central portion down the mold. This will lead to gap formation near the corner and off-corner hot spots leading to longitudinal corner cracks or bulging and sub-surface off-corner cracks when the billet leaves the mold. Even if the taper design is optimized down the mold to match shrinkage of the face center, a gap can still form near the corners. This optimization task itself is difficult because the shell will always bulge under ferrostatic pressure towards the mold walls as taper is not perfect. On the other hand, if the taper is designed to prevent any air gap around the billet parameter, the cold and strong corner will prevent the shell from bulging when it leaves the mold.

15) Influence on Mn/S ratio and casting speed on off-corner cracking of billet. S.K. Ray et al.

An investigation of steel chemistry and casting parameters to find the cause of sub surface off-corner cracks in billet identified the Mn/S ratio and the casting speed to be the most influential factors. Optimum parameters are dependent on the steel grade and caster characteristics.

16) Lingotera perfeccionada y lingote obtenido con la misma (solicitud de patente). E. Laínez Villabona

Analizando este problema, esta parte ha constatado que las grietas off-corner no aparecen cuando el lingote es cilíndrico y, tras numerosas observaciones y estudios, ha llegado a la conclusión de que el origen de tales grietas está en la brusquedad de la transición geométrica y térmica que en las lingoteras actuales se da entre caras contiguas, incluso si estas son aconcavadas, mediante unas esquinas de radio muy pequeño que producen aristas acusadas en las que el enfriamiento es notablemente más rápido que en las caras adyacentes, produciéndose por ello las referidas grietas "off-corner" de origen dendrítico. Como resultado de los estudios realizados se han determinado dos parámetros y los valores de los mismos que sirven de frontera para el riesgo de aparición o no de las grietas "off- corner".

17) Maximum casting speed for continuous cast steel billets based on sub-mold bulging computation. Chunsheng Li and Brian G. Thomas

As the steel industry continues to improve quality and reduce cost, there is growing interest to maximize the productivity from a single continuous casting machine. Many different processes are currently competing, from conventional thick slab and blooms to thin slabs and strip casting, whose economic feasibility depends on their eventual productivities. Considering the high cost of plant experiments, it is appropriate to apply computational modeling to explore the theoretical limits of continuous casting speed and productivity. Productivity increases with increasing casting speed and increasing cross-section area. The casting speed is limited by several different phenomena, listed below. 1. Excessive level fluctuations and waves at the meniscus become worse with greater casting speed [1, 2]. This can cause surface quality problems and even sticker breakouts. This problem can be addressed by changing nozzle design (directing the flow more downwards, or possibly by adding a bottom vertical port), applying electromagnetic forces, changing mold flux, and using other methods to control the flow pattern in the mold. 2. Excessive axial strains may be caused by the oscillation and withdrawal forces needed to overcome friction at the interface between the solidifying shell and the mold. The associated transverse cracks and breakouts may limit casting speed, especially if there is misalignment, excessive taper, or a discontinuous liquid flux layer. Stresses are small if the liquid layer of the mold flux can be kept continuous over the entire mold surface [3] and alignment is good. 3. Excessive membrane strains may be generated in the thin shell by the ferrostatic pressure of the liquid pool below the mold. This can lead to cracks and breakouts if the shell is not thick enough at mold exit. The critical shell thickness was predicted by C. Li[4] to be on the order of 3mm for most grades. This is easily achieved by any feasible casting speed, which shows that other criteria are more important. 4. Any local non uniformity in the shell growth can lead to locally hot and thin regions in the shell, which can initiate longitudinal cracks and breakouts even if the shell is above the critical thickness on average. This problem, which has been investigated by Brimacombe and others[5], can be addressed by optimizing mold flux behavior during initial solidification, oscillation practice, and taper design.

18) Melhoria de qualidade nos tarugos produzidos pela Belgo para aplicações na industria automotiva. Lucas Vieira Penna, Roberto Parreiras Tavares, Wéllerson Júlio Ribeiro, João Garcia Ramalho, César Takaci Sato

Um importante problema de qualidade relacionado ao processo de lingotamento contínuo é a ocorrência de trincas internas. Este trabalho apresenta os resultados de testes realizados na Belgo, usina de João Monlevade, para se avaliar a influência dos principais parâmetros de lingotamento na ocorrência das trincas internas do tipo *off-corner* através do uso de uma ferramenta estatística, denominada DOE – *Design of Experiments*. Foi possível verificar a importância do fluxo de água no molde, da viscosidade do pó fluxante e da intensidade da agitação eletromagnética no molde na formação das trincas internas *off-corner*. A eliminação das trincas internas nos tarugos produzidos na Belgo, usina de João Monlevade, tornou possível o desenvolvimento de aços para a indústria automotiva.

19) Minimization of off-corner longitudinal cracks in continuous cast blooms. M.J. Lu et al.

The formation mechanism of off-corner longitudinal cracking had been reported early. However, it still was the main defect of the continuously cast blooms in China Steel, which obstructed the increasing ratio of hot charge. Then, the possible causes of the off-corner crakcs were identified from the statistics and operational data of the three bloom casters, and five approaches were taken to minimize the defects.

20) Mould taper, heat transfer and spray cooling in high speed continuous casting. Junlong Fu

A plant trial was conducted at Co-Steel Lasco for the purpose of assessing the performance of a 1016 mm long mould having a parabolic taper on the high speed casting of six grades of steel billets. The mould was instrumented with 52 thermocuples. Off-corner internal cracks and face concavity were noted on all billet samples. It was demonstrated that the taper was too tight for the low carbon grades which caused squeezing of the shell by the mould and was responsible for the off-corner internal cracks and face concavity of the billets.

21) Mould taper optimization for continuous casting steels by numerical simulation. Wang Tongmin et al.

A transient, two-dimensional, coupled finite element model was employed to simulate the solidification and shrinkage of continuous casting steels by means of ANSYSTM. In the model, a gap-dependent heat transfer condition was introduced to modify the heat flux function, and the variations of material thermal properties, mechanical properties as well as the yield function with temperature were considered. The solidification and shrinkage processes of four round billets and two square billets were simulated by indirect coupled method. Simulation results show that carbon content, pouring temperature, casting speed and shape of billets have distinct influence on the solidification shrinkage of billets. Ideal continuous parabolic tapers were designed and optimized according to the calculated shrinkage curves of billets.

22) Mould technology for the future. A. N. Grundy, M. Hogenschurz, F. Kawa, B. Kündig

Mould technology for long products has remained the same for many years. The newly developed Mould Technology with large corner radii and reduced mould tube thickness for optimised heat transfer and minimum mould tube temperature has successfully been implemented on trail basis in several plants. Independent from the section cast (billet, bloom, round, rectangular, square) the INVEX Mould Technology is the tool to increase productivity, improve quality or reduces conversion costs. In addition to the technological details the metallurgical basis and the operational results achieved are outlined in this publication.

23) Optimisation of geometry of 185 x 185 mm square billet mould of Sidenor continuous casting machine. M. R. Ridolfi, A. Gotti, J. J. Laraudogoitia and V. Santisteban

Industrial trials conducted at Sidenor Basauri Works, and numerical modelling at Centro Sviluppo Materiali (CSM), have been combined in order to find a square 185 x 185 mm billet peripheral geometry that improves the quality of cast products by eliminating the occurrence of off corner cracks and depressions, and reducing the percentage of rejection. The idea is to change the square shape of the mould section to a new profile having a larger corner radius and outward bulging faces. Experimental trials using moulds with convex faces and larger corner radii resulted in an interesting decrease in the percentage of rejected bars. The presence of longitudinal defects has not been completely eliminated, but the adoption of moulds with larger corner radii has been demonstrated to be successful. Numerical modelling has been used to verify that the larger corner radius is the most important variable that guarantees the improved result, while it is less sensitive to different deflections of the faces. This encourages the use of moulds with flat faces, which produce billets that are much easier to handle with conventional tools for their transfer. It can be concluded that by using moulds with a corner radius of 40 mm, instead of conventional moulds with 10 mm corner radius, and flat faces, the risk of longitudinal off corner defects is significantly reduced.

24) Physical modeling of billet rhomboidity phenomena during solidification in the CCM mould. O. Smirnov, V. Ukhin, Y. Smirnov.

The growth rate of the solid steel shell in the concast mould is found to be of inhomogeneous nature. At the initial solidification stage, solidification factor k value is observed to increase continuously; afterwards, its value turns out constant. Solid shell growth rate at corner regions 1.5-2 times exceeds the growth rate measured at off-corner regions. Inhomogeneous growth rate of solid shell around the billet perimeter determines the internal stresses rise in the solid structure, which are ultimately responsible for the billets contour distortions and for producing typical geometry and surface defects, i.e. rhombic deformation and subsurface longitudinal off-corner cracks.

25) Redução do índice de perfurações na máquina de lingotamento contínuo da ArcelorMittal Piracicaba. André Maciel Pereira et al.

Observamos com os resultados finais que para o controle das trincas *off-corner* as seguintes ações se mostraram efetivas: aumento da vazão da água de refrigeração do molde; aumento da vazão da água na primeira zona de *sprays*; e limitação da vida útil das lingoteiras. Com relação aos "agarramentos" sucessivos observados, as ações seguintes foram efetivas: avaliação da diferença de performance dos fornecedores e dos respectivos tappers de suas lingoteiras; e otimização da lubrificação da lingoteira. A ausência de perfurações na última zona de resfriamento após a realização do trabalho pode ser atribuída às seguintes ações: limitação da vida útil das lingoteiras, que resultou em uma limitação da perda da eficiência de refrigeração no molde.

26) Thermomechanical behavior of the solidifying shell within continuous-casting billet molds-a numerical approach. Kristiansson, J.O.

A two-dimensional numerical model is given for the analysis of the coupled thermal and mechanical behavior of the solidifying shell within the mold during continuous casting of steel. The influence of different mold wall profiles on gap formation and heat flow during casting of billets is investigated. The calculated temperatures, stresses, and strains in the shell are used to estimate the risk for formation of longitudinal cracks. The effect of an initiated and growing macroscopic subsurface crack on the shell behavior is studied. The genesis of surface cracks is discussed. The calculated results are shown to be in reasonable agreement with experimental observations reported in the literature.

27) Trinca de solidificação off-corner no lingotamento contínuo de tarugos. L.A. Vieira

Na usina da Belgo, localizada em João Monlevade, a trinca interna, denominada *offcorner* é a mais comum encontrada. Este tipo de trinca ocorre com maior freqüência nos aços médio teor de carbono (percentual de carbono entre 0,25 e 0,45). O foco deste trabalho é a identificação e análise dos principais fatores que afetam a formação das trincas *off-corner* em tarugos de aços médio teor de carbono. Os fatores que foram considerados neste trabalho foram:
- Tipo de pó fluxante;
- Intensidade do resfriamento secundário;
- Tipo e conicidade da lingoteira
- Intensidade da agitação eletromagnética no molde;
- Vazão de água no molde;
- Raio de canto da lingoteira.

Através de uma técnica estatística chamada DOE (*Design of experiments*), experimentos foram realizados para determinar os efeitos de cada um dos fatores listados acima na formação da trinca *off-corner*. Baseado nos resultados destes experimentos foi possível concluir que aumentando-se a vazão da água no molde e a intensidade da agitação eletromagnética além do uso de um pó fluxante com baixa viscosidade, tem-se a a minimização da formação da trinca *off-corner*.