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Formation of defects in the steel microstructure during solidification and their effects on the steel material properties

The microstructure of steel is responsible for the macro-behavior of steel or in other words steel's material properties. Surface microcracks and internal flaws can be introduced to steel microstructure during solidification. The soundness of the steel is altered by formation of flaws and microcracks in casting production line. Additive elements to molten steel and chemical element and alloys in the iron slag may produce indigenous and exogenous inclusions in the microstructure. The presence of the inclusions in the microstructure changes the cleanliness of the steel and affects the material properties of the steel products. This paper is a review of literatures on the sources of formation of inclusions and flaws in the as-cast steel and the effect of these defects on the microstructure properties.

Introduction

Different grades of steel have different material properties because they contain different chemical compositions. However, steels with the same grade experiencing a different heat treatment process or deformation processing possess different properties, as well. It is general knowledge that the material components and their arrangement with respect to each other influence the material properties. Properties of elements and compositions in the microstructure and compositional arrangement in the microstructure define the properties of the unit cell in steel. The long-range arrangement of these units in a crystal structure determines local and global properties of the crystal built by these unit cells. The complexity of arrangement and variety of microstructure's unit cells are responsible for the difference between the properties of the unit cells and the properties of bulk material. These arrangements in the microstructure depend on the history of the material relevant to different phenomena such as previous mechanical and thermodynamic processes on the material. Many metallurgists raised the issues of classification and quantifying the microstructure of steel [1,2]. Work on classifying steel was discussed in number of literatures [2-5]. These results helped to identify the microstructure of steel at each stage of the steelmaking process as well as final products of steel. There are number of different national classification systems in different countries. Major classifications in the US are AISI, SAE or AISI/SAE, ASTM and ASME. The well-defined classifications are based on different factors in steel including composition, microstructure, application, specification, commercial name or chemical composition, mechanical properties, and corrosion or heat resistance and formability. ASM Handbook Volume 1, gives the details of all major classifications.

Inclusion, voids, cracks and microcracks can be formed within the steel's microstructure during solidification of steel, [6]. The defects may be generated later, as well, because of the cooling process of the as-cast slab. All these defects in the steel are studied under the title of 'Cleanliness or Soundness of steel. The concept of cleanliness of steel deals with the study of controlling the composition of nonmetallic inclusions. Steel properties of the as-cast steel is affected by desirable inclusions, non-desirable inclusions, voids and cracks present in the iron-carbon microstructure. Studying the effect of defects on mechanical properties of steel and its machinability has become increasingly attractive to many researchers since the middle of the 20th century. Work on steel was started since Iron Age using the trial error method. Progress in optical physics and modern optical electrical as well as electromechanical tools and devices provided precise observation and measurement on a micro and nanoscale. Invention of computers and super computers along with progress in software engineering gave researchers the opportunity to understand the microstructure of steel and the effect of anomalies in machining using computational and numerical methods. Developing new chemical compounds and investing in producing new microstructure etching agents helped researchers to obtain information about the microstructure of the steel. Results from experimental tests, analytical computation and numerical simulation assist promotion of both quality and quantity of steel manufactured around the world. These researchers have mainly focused first on how the microstructure of steel is formed during solidification and second, how the microstructure affects the properties of the steel especially the mechanical and machinability properties.

The discussion in this paper is based on the literature review. It elaborates to find some sources of the inclusions and micro-cracks in the as-cast steel.

Formation of inclusions in the steel microstructure during solidification

The additive elements to steel mainly control the material properties such as tensile strength, formability, toughness, weldability, resistance to stress, cracking, and corrosion behavior. These properties for steel are defined by every special caster application. A portion of the essential and incidental elements react chemically with each other and form non-metallic inclusions like manganese sulfide, aluminum oxide or titanium nitride which may or may not be desirable, depending on application of the steel. However, these inclusions are major sources of additional microcracks in the steel during heat treatment or machining as well. It is evident that formation of nonmetallic inclusions can be occurred in any casting process of the steel, although, their density is less in continuous cast stainless steel in compare to ingot cast stainless slabs [7]. Factors such as inadequate thickness of mold powder slag, large fluctuations in mold level and clogging of the submerged nozzle may cause the formation of the inclusions. The technical process reasons for increasing density of the inclusion in the steel matrix are low bath level in the tundish, poor mold and tundish level control, and insufficient pouring tube depth [8]. Non-metallic inclusions in steel produced by continuous casting can be classified according to their sources and formation process into different categories and subcategories as following [6];

1. Indigenous inclusions
   a. Deoxidation products
   b. Precipitated inclusions from cooling and solidification of the steel
2. Exogenous inclusions from
   c. Re-oxidation
   d. Slag entrainment
   e. Erosion/corrosion lining refractory
   f. Chemical reaction;

Indigenous inclusions are formed during cooling and solidification of steel and their types depend on the type of deoxidation. Exogenous inclusions are formed because of incidental chemical and mechanical interaction of liquid steel with its surroundings.

The concept of clean steel in continuous casting is bounded between two criteria. These criteria are physical amenability to casting and maintaining ladle treatment composition. The first criterion includes elimination of blowholes in the strand, decreasing the exogenous non-metallic inclusions and creating optimum conditions that lead to separation of suspended deoxidation products. The second criterion refers to treatment for carbon, nitrogen, hydrogen, sulfur and especially oxygen [8]. Higher temperature and Cr density, increases the solubility of oxygen in steel and decreases the cleanliness of the steel product [7]. To do this reduction or elimination, the activity of primary steelmaking slag with high oxygen is used to avoid rephosphorate. Superheating is one way to improve the cleanliness of steel by lowering the amount of inclusions in the slab.

Another way to enhance the cleanliness of steel is to move the inclusions to the surface and collect them. Researchers [9] were able to compute, numerically, the rising velocity of inclusions in molten steel. They verified experimentally the behavior of moving inclusions in the slab continuous casting mold by implementing solution for turbulent flow of molten and inclusion trajectory and show the movement of inclusion has relationship to inclusion diameter.

Effect of inclusions on the properties of the steel microstructure

The subject of steel grade is related to the classification of steel. Thousands of different steels in today's steel industry can be classified in many different classification systems. The main factor in steel classification is by its carbon content because of its effect in final cost of the steel. However, several other elements, such as manganese, phosphorus, sulfur, silicon, nickel, chromium, molybdenum, copper, cobalt, tungsten, and vanadium may be added to steel to obtain certain desired properties but the additional elements to the steel is not limited to these. These elements mainly increase solid solution strength, hardness, hardenability. Nevertheless, some elements have more specific duties in the steel, such as high level of manganese for enhancing wear and abrasive resistance and adding sulfur to improve the machinability. Some elements like oxygen are considered as undesirable elements in the microstructure of steels.

The requirement of high quality steel forces steel industries to pay special attention to cleanliness of steel products. This is because some inclusions affect the machinability of the steel. Other decrease the fracture toughness and some, such as oxides or sulfides, increase the ductility behavior [7]. Hard and brittle oxides, particularly large alumina inclusions, cause fatigue problem in bearing steel. Clean steel is known to have high Charpy shelf energies, high tensile ductilities and very good formabilities [11]. Cleanliness of steel is related to a low content of non-metallic inclusions, mainly oxide and sulfide inclusions, as well as other anomalies [12]. Inclusions due to the nature of the ore and steel making procedure are also present in the steel. Therefore, clean steel is mainly characterized by an inclusion specification. A large body of literature has been published concerning cleanliness of steel [13-16]. McPherason and McLean [13] gave a good description of inclusion types, distribution and tracking methods in the continuous casting process. Zhang and Thomas [14] offered suggestions to improve the techniques for steel cleanliness at the ladle, tundish and continuous caster.

In very clean steel, fatigue damage is related to the square root of the area of the inclusion. Consequently, the size of the inclusion is more important than its shape and composition [17-18]. Different theoretical methods such as Statistics of Extreme Values (SEV) [19] and Generalized Pareto Distribution (GPD) [20] have been developed to determine the maximum size of the inclusion in large volume steel. The effect of the composition of the inclusion on the distribution of the stress concentration zone in the matrix was studied by two dimensionless factors [21]. These factors were introduced as the stress concentration factors and the inclusion rigidity factor. Variation of the rigidity of the inclusion in a given matrix shows local extremum points within the interface and matrix contact surface at the interface. However, the average stress concentration inside the inclusion is higher for more rigid inclusions. The defined properties for the interface govern the average stress concentration around soft inclusions but the stress concentration around the inclusions with higher rigidity factor is related to the properties of the matrix. From the results of the simulation of the interaction of the inclusion in the steel matrix, it can be deduced that the smaller inclusions localize the residual stresses and create a higher stress concentration. Investigation of the size effect of the inclusion on the level of the stress concentration reveals a critical size of the inclusion where the stress concentration does not increase with the growth of the inclusion for a given applied load and boundary conditions.

Reoxidation of steel is the main source of the oxide inclusions. Pontius [22] studied the aluminum oxide formation during solidification. Many published papers have shown that inclusions have their own impact on material properties of steel. Studies on MnS inclusions have shown that they are responsible for chip fracture during machining by initiating cracks as a result of increasing stress in the machining shear zone [23-25]. Manganese sulfide also improves machinability by decreasing tool wear by lowering tool chip friction and, consequently, cutting temperature and cutting force [26]. However, other researchers said that the presence of oxygen causes sulfur to improve machinability [27, 28]. Other researchers have shown that the manganese selenide phase remains larger and more globular in the final hot rolled product [29]. Tellurides and selenides lower the quality of the sliding surfaces by resistance on seizing [30] while lead decreases shear resistance [30- 32]. Taylor emphasizes that the uniform quality working material as the most important factor among other factors playing a role in the machinability of the steel. He explained the advantages of high sulfur steels on machinability [33]. However, some research work showed these additive elements may also degrade steel quality. Sulfur content can increase the extent of cracking at high temperature. The susceptibility of steel to overheating depends on alloying and micro-additions [34].

Segregation of sulfur and phosphorous from the liquid film at grain boundaries into the interdendritic region creates a low ductility and strength region and, consequently, forms cracks in the microstructure of steel between the solidus and 1326 degrees Celsius [35, 37]. The ratio of precipitation of MnS in the matrix and precipitation of AlN along grain boundaries generates cracks in steel during solidification by forming different low ductility regions at different temperature ranges. Vanadium and niobium precipitation by cyclic heating and cooling in secondary cooling zone also causes embrittlement of the steel.

Crack formation in microstructure during solidification

Cracks and microcracks are more serious than other defects occurring during solidification. Voids and cracks have irregular shapes compared to hard inclusions. Different type of defects such as surface and internal cracks, bulging, pinholes, inclusions, central unsoundness defects caused by mold oscillation and lubrication process have been seen in blooms and slabs [22]. Brimacombe and Sorimachi have classified the origin of cracks systematically [38]. Cracks may be formed by internal and external forces higher than ductility to fracture stress concentration of the steel [39]. Internal stresses during surface reheating create cracks because of zero ductility of steel at solidification temperature [40]. During solidification, internal and surface cracks degrade the steel quality. Surface cracks may be caused by uneven heating, which introduces transverse and longitudinal facial cracks [41]. Figure 1 presents an example of transverse cracks on a steel slab produced by continuous casting.

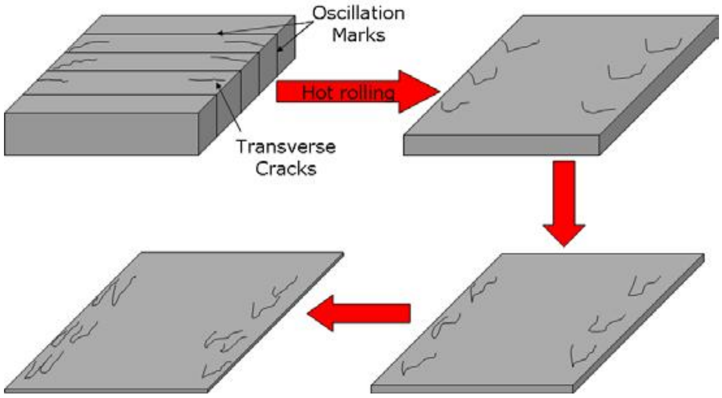

Figure 2: Propagation of transverse crack during hot rolling [42]

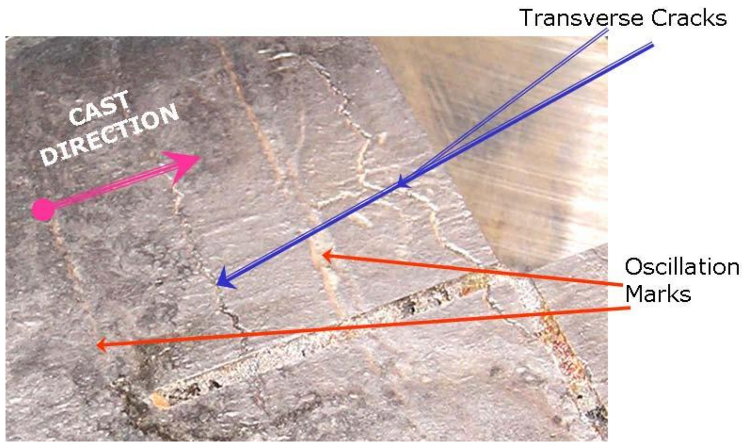

Figure 1: An example of transverse cracks formed during solidification of continues casting steel process [41].

Journal of longitudinal cracks are sensitive to certain chemical composition, insufficient narrow face taper, non-uniform mold powder slag level and poor mold level control. Longitudinal cracks can be formed from stress at the meniscus during solidification by high mold wear and poor mold surface as well as insufficient strand support below the mold, including caster or mold misalignment and thermal stresses due to non-uniform cooling [8]. Transverse cracks in steel may be generated by too large mold taper, poor oscillation conditions, a low surface temperature at straightening and abrupt cast speed changes. Three main in line sources have been reported for transverse cracking in Mittal plants [42]: (1) falling the strand surface into ductile behavior range and straightening strains (2) intrinsic hot tearing in the mold because of thermal contraction (3) external hot tearing at or near the mold because of applied external stresses. Figure 2 shows how these transverse cracks can extend to more severe cracks during hot rolling.

High content of foreign elements, such as aluminum, niobium, vanadium or copper, form crazing cracks due to local shortness of the steel [37]. Uneven cooling of the surface also causes local type star cracks [8].

Figure 3 illustrates different types of defects on a continuous cast steel slab. Internal cracks formed during solidification can be classified into five groups of halfway and midway cracks, start or centerline cracks, diagonal cracks, bending cracks, and pinch roll cracks. This sudden change can be caused by an unbalanced rate between radiation and convection cooling along secondary cooling zones or different boundary conditions, such as below the mold, where the hot surface is cooled suddenly by water spray. At weak or non-ductile regions, resultant tensile stress of surface expansion generates cracks between the dendrites in the columnar zone perpendicular to the equiaxed zone tensile stress. Likewise, centerline cracking is due to tensile stresses raised by abrupt change in temperature of the centerline with completion of solidification because of bad machine conditions at the final solidification area, or too low secondary water-cooling [8]. Too high

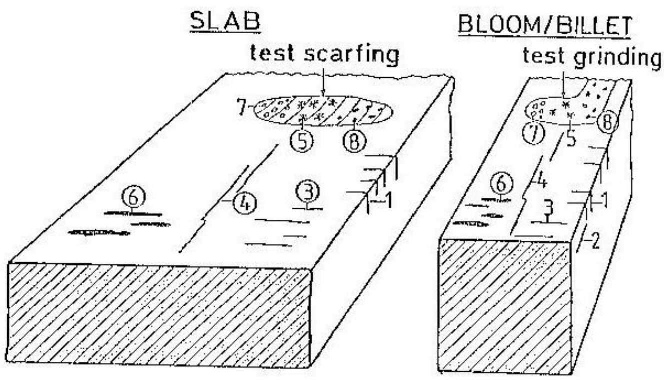

Figure 3: Surface cracks on a continuous cast steel slab: (1) Transverse corner cracks (2) Longitudinal corner cracks (3) Transverse cracks (4) Longitudinal cracks (5) Star cracks (6) Deep oscillation marks (7) Pinholes (8) Macro inclusions [8]

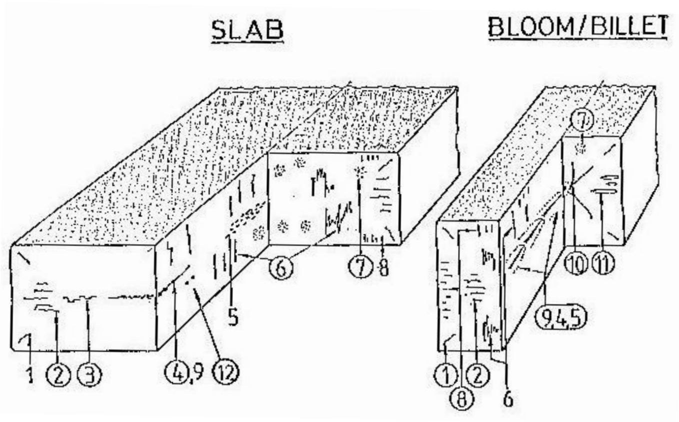

Figure 4: Internal defects in continuous cast steel slab: (1) Internal corner cracks (2) Side halfway cracks (3) Centerline cracks (4) Centerline segregation (5) Porosity (6) Halfway cracks (7) Non metallic inclusion clusters (8) Sub surface ghost lines (9) Shrinkage cavity (10) Star cracks diagonal cracks (11)Pinholes (12) Semi macro-segregation [8]

or too low cooling of slab's side surfaces as well as bad equipment conditions can introduce triple point cracks in the slab [8]. Figure 4 is a schematic view of different internal defects on the continuous cast steel slab. Tensile stress raised by a high, different, temperature at surfaces making an obtuse corner creates diagonal cracks at right angle to the strain [44]. Straightening or bending operations when center steel is above 1327 °C, forms straightening or bending cracks in the non-ductile region. For the same reason as straightening or bending cracks, high roll pressure at any point of the strand during solidification can generate pinch roll cracks [41].

Researchers have shown that solidification parameters play a role in characterizations of defects. Casting speed or tundish temperature controls axial porosity of the steel. The size of the hole in the middle section of the ingot increases with larger amounts of water during secondary cooling. Also in low casting speed, gravity accumulates the inclusions unevenly due to floating of inclusions. Uneven non-metallic inclusion distribution in dendrites and cluster arrangement makes the microstructure dangerous to fracture by decreasing the energy absorbed in the microstructure [34]. Billet dimensions control the effect of corner radius on longitudinal cracks such that more cracks are formed in larger billets. Experiments on tundish temperature show that after a critical temperature, the length of cracks increases as the temperature of the tundish increases [33, 45]. Different solid-solid phase transformations during cooling of hot solidified steel can also introduce cracks in the microstructure of steel.

Experimental results [46] showed that the tendency for crack formation is higher with a range of cooling rates and it decreases for the cooling rate higher or lower than this critical cooling rate range as a function of quenching rate. The factors governing the behavior of material at high temperature are time, temperature, stress, and environment or atmosphere. At low temperature mechanical behavior like fatigue damage, is controlled by the level of the mean stress, amplitude of stress fluctuation and number of cycles [47]. Quasi-cleavage may occur within regions of grains with different orientation in quenched and tempered steels, and they may result in lower resolved normal stress and, consequently, ductile fracture mode.

Three major fracture modes in the microstructure are ductile fracture by nucleation and growth of voids, and brittle fracture via trans-granular fracture or inter-granular separation. The trans-granular cleavage is the most common one. Kametani [48] analyzed the length of longitudinal cracks on the surface of continuously cast steel slabs and gave crack frequency as a function of crack length using fractal distribution methods. Quantitative characteristics of the crack growth are peak load of the force displacementcurve, nominal specific energy of the formation of new unit surface, average force, fractal dimension of fracture surface, and height of the surface roughness peaks [49]. Cracks initiate or propagate in a different manner depending on the microstructure, composition, and properties. Tensile test experiments on tool steel showed that cracks initiate (or exist) in the carbide band growth straight forward in the matrix and after kink type dislocation in the carbide rich region split in the same direction of the region then jump to the next carbide band and grow in the same manner and so on [50, 51].

Conclusion

Customer defined properties for steel products called upon the metallurgists for new challenges in adding different additive elements and components to steel in order to modify material properties. Many publications discussed the relationship between mechanical and machining properties of steel and additive elements in steel microstructure. Additive elements to molten steel during continuous casting may introduce inclusions to the microstructure of the strand, which affect the microstructure configuration of the as-cast steel. In addition to inclusions, many other defects can also be introduced into the microstructure of steel. Formation voids and cracks are inevitable during solidification and may increase in the cooling process of hot solid steel slabs to room temperature or any future heat treatment and machining of the steel.

However, some research work defined the conditions to produce clean steel for many different steel compositions. This ideal condition cannot be obtained because of extra processing cost and its contradiction with customer demands for quality. Another reason for deviation from the ideal clean steel is to keep the casting process continuous at the cost of lower grade products.

This paper discussed the formation of more common inclusions in the as-cast steel and their effects on the steel microstructure and bulk steel product. The paper explained the sources of the microcracks which can be found often in the microstructure of steel in the casting production via review on published research works about this topic.

Study of the sources of defect formation utilizes the control of the quality and material properties of the cast steel. The growing demand for new steel products and competition to produce steel with higher quality will attract many new ideas and researchers to this research topic.

References

[1] B.L.Bramfitt and J.G.Speer, "A perspective on the morphology of bainite", Met Trans, 21A, April 1990, 817-829.

[2] H. I Aeonson; "Decomposition of austenite by diffusioinal processes", 389, 1960, Philadelphia, PA, AIME.

[3] International Institute of Welding, "Compendium of weld metal microstructures and properties", 1985, Abington, Woodhead Publishing.

[4] Classification of microstructures in low carbon low alloy steel weld metal and terminology; Committee of Welding Metallurgy of Japan Welding Society, IIW Doc IX-1282-83.

[5] T Thewlis.; "Classification and quantification of microstructures in steels"; Materials Science and technology; (Feb. 2004), Vol. 20, 143-159.[6] L. Zhang, B. G. Thomas; "Inclusions in continues casting of steel"; XXIV National steelmaking Symposium, Morelia, Mich, Mexico (2003), 26-28, pp 138-183, Nov.

[7] K. Nemethy, E Stock., B. F. Mackay; "Progress in Continuous Casting Stainless Steel Slabs at Atlas Steels Limited"; Continuous Casting, (1962), No. 62-18699,pp:119-154.

[8] Continuous Casting of Steel (1985)-A Second Study; International Iron and Steel Institute; Committee on Technology; Brussels; (1986).

[9] H. Lei, M-Y. Zhu, J. C. He; "Simulation of nonmetallic inclusion behavior in the continuous casting mould"; Guocheng Gongcheng Xuebao (The Chinese Journal of Process Engineering) (China). (Apr. 2001), Vol. 1, no. 2, pp. 138-141.

[10] Allazadeh Mohammad R.;" Stresses introduced during cooling the as-cast steel slab", STEEL GRIPS 8 (2010) , Process technology, p. 285/289.

[11] A. J. DeArdo, C. I. Garcia, Palmiere E. J., " Basic Metals Processing Research Institute", Department of Materials Science and Engineering, University of Pittsburgh; ASM Handbook, (1991),Vol 4, Heat Treatment,.

[12] Chunhui Luo; "Modeling of the behavior of inclusions in plastic deformation of steels", Doctoral thesis; division of Materials forming, Department of production engineering, royal Institute of technology, Stockholm, (2001).

[13] N. A. McPherson, A. McLean, "Continuous Casting Volume Seven- Tundish to Mold Transfer Operation"; (1992), ed s 7,ISS, Warrendale, PA, 1-61.

[14] Zhang, L., and B.G. Thomas, "State of the Art in Evaluation and Control of Steel Cleanliness," ISIJ International, Vol. 43, No. 3, 2003, pp. 271-291.

[15] Mu D., L. Holappa; "Gov. R.es. Announc. Index (USA); (1993), Report No. PB93-179471/XAB,.

[16] A. W. Cramb; in Impurities in Engineered Materials; Impact Reliability and Control, C. L. Briant, eds., Marcel Dekker Inc., New York, (1999), 49-89.

[17] Y. Murakami, S. Kodama and S. Konuma, 1989, Quantitative evaluation of effects of non-metallic … Int. J. Fatigue, 11(5), 291–298.

[18] Murakami, Y., Kawakami, K., Duckworth, W.E., "Quantitative-evaluation of effects of shape and size of artificially introduced alumina particles on the fatiguestrength of 1.5Ni-Cr-Mo (En24) steel. International Journal of Fatigue, (1991), 13(6):489-499..

[19] S. Beretta, Y. Murakami, Statistical Analysis of Defects for Fatigue Strength prediction and Quality Control of Materials; Fatigue & Fracture of Engineering Materials & Structures, (September 1998), Volume 21, Number 9, pp. 1049-1065.

[20] G. Shi, H.V Atkinson, Sellars, C.M.; Anderson, C.W. Comparison of extreme value statistics methods for predicting maximum inclusion size in clean steels; Ironmaking & Steelmaking, (1999), Volume 26, Number 4, August pp. 239-246(8).

[21] M. R. Allazadeh, C. I. Garcia , A.J. DeArdo and M. R. Lovell; "Analysis of Stress Concentration around Inclusions due to Thermally Induced Strain tothe Steel Matrix"; Journal of ASTM International, paper (MAY-2009), No. 016905JAI, volume 6, issue 5,.

[22] BISRA, "Definitions and Causes of continuous Casting Defects"; I. S. I.; Pub. 106,1967.

[23] R. Kiessling, " Nonmetallic Inclusions in Steel (Part III)", ISI Publication 115, (1968).

[24] V. A. Tipnis, N. H. Cook, "Influence of MnS-Bearing Nonmetallic Inclusions on Flow and Fracture in a Machining Shear Zone", AIME mechanical working, 1965, p. 285-308.

[25] J. Harza, D. Caffarrelli, S. Ramalingma, "Free Machining Steels- the behavior of type I MnS inclusions in Machining", (1973)No. 73-WA/Prod-10, Transactional ASME.

[26] H. Optiz, W. Konig, n. Diederich, "Verbesserung der Zerspanbarkeit von Unlegierten Baustahlen Nicht-metallische Einschlusse bei Verwendung Bestimmter Desoxydationslegierrungen", Westdeutscher Verlag, Köln and Opladen, (1967).

[27] E. J. Paliwoda, "The role of oxygen in free cutting steels", Proceeding AIME Mechanical working of steel 2, (1964), Volume 26.

[28] W. Crafts, D. C. Hilty, "Sulfide and oxide formulation in steel", Proceedings of Electric Furnace steel conference, (1953), 121ff.

[29] Kiessling, B Hassler, C. Westman, "Selenide-Sulfide inclusions and synthetic compounds of (Mn, Me) (Se, S) type", J. Iron and steel Institute, (1967), volume 205, pp. 380-39.

[30] R. H. Aborn, " The Role of Metalurgy, Particularly Bismuth, Selenium, and Tellurium, in the Machinability of Steel", Pamphlet published by American Smelting and Refining Company, 120 Broadway, New York, NY (1968).

[31] R. W. Thompson, D. t. Quinto, B.S. Levy, "Scanning electron Microscopy and Auger Electron Spectroscopy Observations on the role of lead in the machining of steel", Proceedings NAMRC-II, (1974), pp. 545-559.

[32] S. ramalingam, K. Basu, J Hazra, " The role of Lead and Its Effect on MnS Inclusions in Leaded free Cutting Steels", Proceedings NAMRC-III, (1975), pp. 374-384.

[33] Taylor F. W.; "On the art of cutting metals",

Transactions ASME, Volume 28, (1907).
[34] M. A. Shtremel; "Problems of the Metallurgical Quality of Steel (Non-metallic Inclusion)"; Moscow Institute of Steel and Alloys (Translated from Metallovedenie i Termicheskaya Obrabtka Metallov); (1980), No. 8 pp 2-6.
[35] H. F. Hall: "Second Report of Steel Castings. Research Committee", The Iron Inst., London, (1936), p. 65.
[36] D. P. Evteev; N. K. Stepanov; V. P. Druzhinin; N. G. Gladyshev; V. N. Ustyuzhanin; "Continuous Casting of Steel"; ed. O.V. Matynov, Metallurgya Press, (1970), pp. 240-251.
[37] A Fuchs; ESTEL- Berichte aus Forschung und Entwicklung unserer Werke, 1975, no. 3; pp. 127-135.[38] Brimacomb J., sorimachi K., "Crack formation in the continuous cast products"; Continuous Casting, Volume 9, The Iron &Steel Society, (1997).
[39] J. K. Brimacombe; "Short Course on Continues Casting"; 33rd Electric Furnace Conference; Houston Texas;(1975).
[40] Grill, Brimacombe; Weinberg; presented at the 104th AIME Meeting;(Feb 1975).
[41] J. K. Brimacombe; "Defect Problem in Continuous casting";33rd electric furnace conference; Houston, texas, (1975).
[42] Tsai H. T., Yin H., Lowry M., Morales W.; "Analysis of Transverse Corner Cracks in Slabs and Countermeasures"; Iron & steel Technology; (July 2006); 23-31.
[43] K. P. Korotkov et al; "The continous Casting of Steel in commercial Use", (1960), Oxford, Pergamon.
[44] H. Mori; Tetsu to Hagane; “Causes and Prevention of Defects in Continuous Casting: Pt. 1” (1972),vol. 58(10), pp. 1511-1525.
[45] A. A. Skvortsov, et al; "Continuous Casting of Steel"; p. 126, Metallurgizdat Press, Moscow, 1970, HB #7594.
[46] Mohammad Reza Allazadeh, “COOLING RATE OPTIMIZATION FOR QUENCHING AS-CAST STEEL IN INDUSTRY: INTRODUCING A TECHNICAL ROAD MAP TO OPTIMIZE THE COOLING RATE OF THE AS-CAST STEEL PRODUCED BY CONSCIOUSLY CAST STEEL METHOD”, VDM Publishing House, ISBN-13: 978-3639316612, (2010).
[47] J. C. Prince, Marono R., Leon F, ;"Thermo-mechanical analysis of a piercing mandrel for the production of seamless steel tubes"; Proc Instn. Mech. Enhrs Vol. 217 Part E: Process Mechanical Engineering.
[48] H Kametani.; "Fractal Analysis of the Surface Cracks on Continuously Cast Steel Slabs"; Metallurgical and Materials Transactions, (December 1998), V 29B, 1261.
[49] L. Mishnaevsky, N. Lippmann, Schmauder S.; "Mesomechanical simulation of crack propagation in real and quasi- real idealized microstructures of tool steels"; ECF 13--13th European Conference on Fracture; San Sebastian; Spain; 6-9 (Sept. 2000), 251 pp. 2000.
[50] H. Berns, C. Broeckmann, D Weichert.; Eng. Fract. Mech., 58, 4, pp:311-325
[51] A. Gross-Weege, D Weichert., Broeckmann C.; (1996), Comp. Mat. Sci., 7, pp:123-130.

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