NON-METALLIC INCLUSIONS CONTENT IN MEDIUM CARBON STRUCTURAL STEELS AND DEFORMATION BEHAVIOR DURING HOT ROLLING

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ABSTRACT

Non-metallic inclusions found in steel can affect its performance characteristics. Their impact depends not only on their quality, but also, among others, on their size and distribution in the steel volume. The amount of non-metallic inclusions found in medium carbon steel under industrial conditions. Molten steels are cast into what are usually known as pencil ingots/billets and do not have any refining facilities. In absence of proper refining and quality control, these ingots/billets usually contain slags, non-metallic inclusions, inhomogeneities and deformed bars produced from these pencil ingots/billets contain significant amount of slags and inclusions. Finished products of these pencil ingots are in general of inferior quality and give substandard reinforcing bars. Proper refining (ladle refining) of induction melted assorted scrap can give fairly clean and refined liquid steels. Reinforcing bars produced from such refined melts are generally free from inclusions and slags. The amount of non-metallic inclusions was determined by optical and extraction methods. Inclusions are characterized by measuring ranges. Metallographic studies of the deformed bars show the deformation behavior of the inclusions.

Keywords: Non-metallic inclusions; structural steel; deformation behavior

INTRODUCTION

Advances in steelmaking during the last six decades have resulted in steel grades with very low level of impurities. In recent years, new “clean and ultra-clean” steels have been developed and commercialized by steel producers around the world, thereby responding to the current and future market demands of steel having significantly improved mechanical properties (Niclas et al., 2015). In Bangladesh most of the steel bars used for reinforcement of concrete are produced by melting iron and steel scrap in induction furnaces. Because of the nature of induction heating, the melt in the furnace is continuously stirred and complete separation of inclusions cannot take place (Millman, 1999). An induction furnace is a melting unit. Very little, if any, refining takes place in an induction furnace. Thus the quality of steel produced in an induction furnace is directly related to the quality of scrap and other raw material. In Bangladesh only limited number of steelmaking units use ladle refining furnaces for enhancing the quality of steel produced (Millman, 1999; Amit and Ojha, 1997).

In many instances molten steel is poured into moulds to produce pencil ingots. The moulds are themselves massive castings with a square, rectangular, round or polygonal cross-section. The growth and development of steel plants has coincided with the introduction and acceptance of continuous casting. In some plants ladle metallurgy has also been introduced. Few of them have gone for inert (argon or nitrogen) gas purging in order to reduce inclusion content, gas content and make composition and temperature in the ladle homogeneous. Ladle metallurgy incorporates inert gas stirring for homogenization of temperature and composition of the steel in the ladle as well as for floatation of inclusions. For continuous casting, inert gas stirring of steel in the ladle has become a standard practice to improve the quality of steel.

The quantity and quality of non-metallic inclusions is determined mostly by the steel melting technology. Out-of furnace treatment regimes are also introduced to minimize the quantity of non-metallic inclusions. The quantity of non-metallic inclusions in steel is relatively low, nevertheless, they have a significant impact on the structure, technological and strength parameters of the resulting alloy (Lis, 1999; Wypartowicz and Podorska, 2006; Lis, 2002; Fernandes et al., 2003). The distribution of inclusions is an equally important factor. Single inclusions and clusters of inclusions exert different effects. Large, individual inclusions can produce discontinuities that grow rapidly under variable load. During processing, the shape and distribution of micro particles change, and impurities undergo anisotropic deformation. Non-metallic inclusions play a special role in the process of steel hardening. Due to differences in the physical properties of steel and inclusion-forming phases, structural stresses are formed along inclusion boundaries (Kocańda, 1985; Wang et al., 2012; Bao et al., 2012; Yang et al., 2006; Murakami et al., 1989). Most non-metallic inclusions present in steel have detrimental effects on properties, which will lead to poor formability of the product as well as problems associated with fatigue life. In addition to improved formability, cleaner steel also benefits the coating and corrosion resistant properties. Cleanliness requirements for steel products are often measured in total oxygen, and maximum particle size (Zhang and Thomas, 2003).

A literature analysis shows that, for these steels, the phenomena occurring during their use with respect to their microstructure and non-metallic inclusions have been analyzed most deeply. Fatigue tests are a particularly sensitive method for testing a material's durability. A comparison of fatigue properties and the size of impurities suggests that Sub-microscopic inclusions in high-plasticity steel inhibit dislocation motion. Inclusions absorb energy which contributes to the formation of discontinuities and slows down decohesion. Their results set strict criteria as to the allowable steel impurity. In hard steels, reduced mechanical properties at changing loads are unambiguously attributed to non-metallic inclusions (Lipiński and Wach, 2010; Barrie et al., 2008; Park and Park, 2014; Gulyakov et al., 2012; Srivastava et al., 2014; Lipiński and Wach, 2010; Spriestersbach et al., 2014; Evans et al., 2014; Lipinski and Wach, 2009; Roiko et al., 2012; Shih and Araki, 1973; Genel, 2005).

The aim of this study was to determine the extent of variation of inclusion content with the liquid metal processing routes and analyze dimensional structure of non-metallic inclusions in the reinforced bars.

EXPERIMENTAL PROCEDURE

This study was based on analysis of samples collected from the process stream of a steel plant in Bangladesh (Fig.1).Care was always exercised to collect a representative sample. The plant concerned produces different grades of deformed bars from ingots produced in metal moulds (pencil ingots) and also from billets produced by a continuous casting machine. The plant has a ladle refining furnace and samples of continuously cast billets, both ladles refined and not refined, were collected.

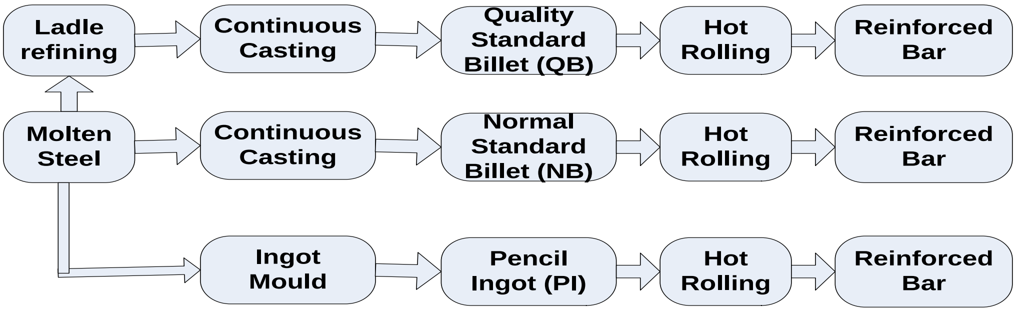


Fig 1: Flow diagram of different route of processing reinforcing bar

A number of pencil ingots of different heats, normal standard billets and quality standard billets were chemically analyzed. The chemical compositions of the samples were examined and the heats chosen for further work was based on carbon equivalent factor. The sampling procedure of any heterogeneous material is of great importance. Two methods of sampling are advocated random sampling and representative sampling. Representative sampling is best achieved by taking samples equally spaced throughout the bulk. This method of sampling is perfectly satisfactory.

Inclusion content may be determined either by a macroscopic or a microscopic method. The advantages of microscopic method are that, the character or type of inclusions may be determined and extremely small inclusions are revealed. Specimens or metallographic assessment of inclusions were prepared by using standard techniques of polishing. Extreme care was used to ensure that the inclusions are retained. It was not always possible to retain all the inclusions. However, this did not affect the result because the cavities in the samples were counted as inclusions. Many investigators have preferred to estimate the inclusion content in steels without recourses to arbitrary standards, primarily because the personal factor in these methods is reduced to as rational a basis as possible. Several methods have been suggested for assessing the inclusion content in steel. Inclusion content was estimated by the method of direct counting and measurement of inclusions on metallographic samples (Kjerrmann and Jernkont, 1929).Both longitudinal and transverse sections were examined. The locations of inclusion analysis were selected randomly. For understanding the deformation behavior, the SEM with EDX analysis was performed on the finished rolled reinforced bars. The chemical compositions (as determined by optical emission spectroscopy) of ingot, normal standard billet and quality standard billet are listed in Table1.

Table 1: Chemical compositions of the ingots/billets

Heat No	Chemical Composition						Carbon Equivalent = %C + % Mn/6
	%C	%Mn	%Si	%P	%S	%N	
PI	0.33	1.12	0.24	0.04	0.04	0.03	0.52
NB	0.32	1.15	0.25	0.04	0.04	0.03	0.51
QB	0.31	1.14	0.31	0.03	0.04	0.04	0.50

Note: PI=Pencil Ingot, NB=Normal Standard Billet and QB=Quality Standard Billet

RESULTS AND DISCUSSION

Inclusion Distributions

Steel ingots or billets produced commercially are heterogeneous in nature. The exact distribution of the non-metallic inclusions in an ingot or billet is not known, but experience suggests that it could vary from top to the bottom or first to the end and also centre to the outside of an ingot or billet. Differences between ingots or billets in the same cast have also been observed. The magnitude of these differences is largely dependent on steel making and casting conditions.

The results of inclusion contents are given in Table 2. During the assessment, different particle sizes were measured and monitored. The inclusion sizes and distributions were found to be affected by the melting, handling and/or processing technique. The casting quality requirements were met regardless of the particle size ranges detected in the molten metal just before the pouring operation. The pencil ingot contains higher content inclusions than casting billets and gives inferior mechanical properties. Proper liquid metal treatment (ladle refining) with synthetic slag ensured lower number inclusions in the quality billets and reinforcing bars produced from these billets give better mechanical properties.

Table 2: Inclusion distributions in ingot/billet

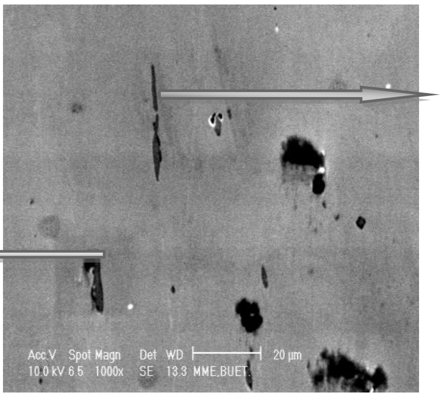
Heat No	Inclusions size distribution, µm					Total Number of Inclusions /cm^2
	3-10	10-20	20-30	30-40	>40	
PI	22150	784	890	252	16	24092
NB	11895	458	334	24	3	12714
QB	10125	451	22	7	00	10605

Metallurgical Observations

Samples polished in the rolling direction were taken from each reinforcing bars. These are examined under the optical microscope and scanning electron microscope. All the reinforcing bars had a ferrite/pearlite matrix typical of C/Mn steels with a carbon content of about 0.3%. All the steels contained inclusions of the oxide, carbide, sulphide or complex types.

EDX Analysis:

Element	% of wt	Comments
Fe	23.84	Mainly Sulphides (FeS, MnS) and some oxides
Mn	35.46	
Si	0.39	
Al	0.32	
O	1.94	
S	26.17	
C	11.88	



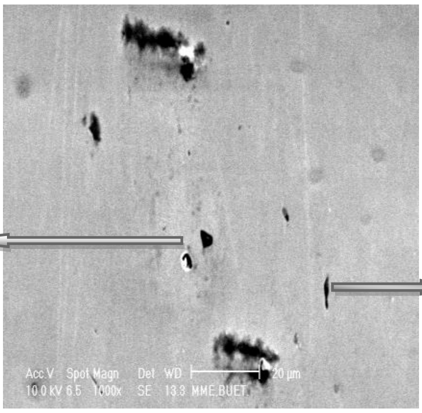
EDX Analysis:

Element	% of wt	Comments
Fe	65.89	Mainly carbides(Fe_3C , Mn_3C)and some oxides
Mn	23.74	
Si	0.52	
Al	0.45	
O	1.98	
S	0.38	
C	7.11	

Fig 2: SE image sulphide and carbide type's inclusions; chemical composition (mass %) of the inclusions, inclusions detected by EDX microanalysis in the deformed bars and shapes after rolling

EDX Analysis:

Element	% of wt	Comments
Fe	53.3	carbides (Fe_3C,Mn_3C) , silicate and oxides(FeO, MnO, SiO_2 , Al_2O_3)
Mn	24.26	
Si	1.10	
Al	0.91	
O	7.51	
S	0.00	
C	12.92	



EDX Analysis:

Element	% of wt	Comments
Fe	52.18	Mainly carbides
Mn	19.04	
Si	7.12	
Al	3.69	
O	0.00	
S	0.00	
C	17.94	

Fig 3: SE image oxides and carbides type inclusions, inclusions distinguished by EDX and depending on their shapes after rolling

The shape change of inclusions after multi-pass hot rolling and EDX results are showed in Fig. 2 and Fig.3. During rolling the plastic inclusions change shape and therefore their size, whilst the harder types of inclusions are not affected by reduction. Inclusions in the form of thin films located on grain boundaries are especially dangerous for steel quality. These are usually low-melting oxysulphide inclusions precipitated in liquid state during steel solidification. They weaken the intergranular bonds, especially at elevated temperatures (red shortness). After rolling or forging the sulphide type inclusions are elongated and rolled out to some extent with the working/rolling direction (Fig.2). Elongated MnS found in the deformed bars. Inclusion particles with sharp edges may be quite dangerous; these are usually high melting inclusions (Malkiewicz and Rudnik, 1963; Baker, et al., 1976; Belchenko and Gubenko, 1983). Rounded off inclusion particles are considered less harmful. They are formed by substances which have low melting point and are poorly wettable by the metal.

Small carbide type inclusions are retaining their shape (Fig.3) and particle size, refractory and brittle one breaks up. A low concentration of inclusions in steel is not, by itself, the guarantee of high quality because the inclusions may be concentrated in particular places of an ingot or billet.

Fig.4.a shows the Optical micrograph of elongated inclusion. The size of the elongated sample indicates the degree of reduction of the material from ingot or billet to deformed bars. With increasing reduction, the plastic inclusions change shape and therefore their size, whilst the harder types of inclusions are not affected by reduction. Inclusion particles with sharp edges (Fig. 4.b) may be also quite dangerous; these are usually high-melting inclusions, i.e. with the melting point above the temperature of molten metal. They often serve as stress concentrators in the metal and as sites for the beginning of fracture. If such an inclusion passes onto the surface of an article (a ball bearing, rail, etc.) it will crumble out soon and cause premature failure of the article. Rounded off inclusion

particles (Fig.4.c) are considered less harmful. They are formed by substances which have a low melting point and are poorly wettable by the metal.

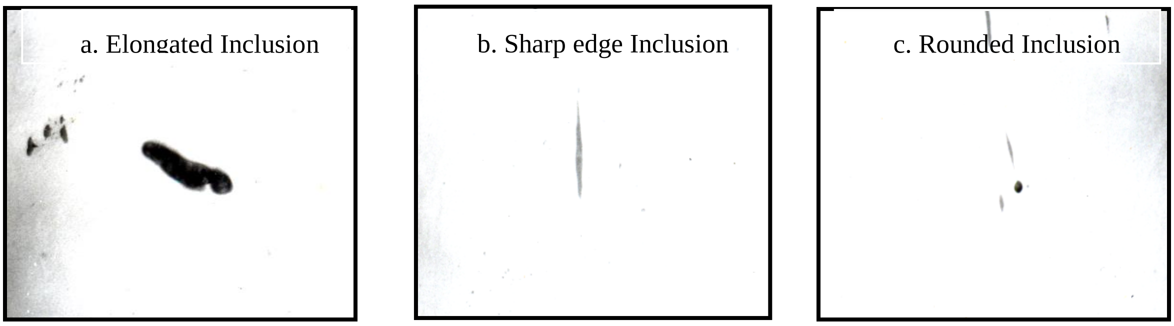


Fig. 4: Optical micrographs showing (a) elongated, (b) sharp edge and (c) rounded off inclusion after hot rolling

CONCLUSIONS

The nature, size, shape and distribution of inclusions have been studied. It was found that most of the inclusions were Mn, Al and Si based complex silicate or oxide or carbide precipitates. Structural steel from pencil ingot contain larger size (>40 μm) and higher number (24092/cm^2) inclusions. Deformed bars produced from normal casting billets (without treatment) content lower size and number inclusions. Inclusions level in the reinforced bars produced from quality standard billet (ladle refining) are lower number and size (<40 μm) than pencil ingots or normal standard billets. During deformation (hot rolling) sulphide type inclusions are elongated and rolled out and elongated MnS found in the deformed bars. Small carbide type inclusions are retaining their shape and particle size, refractory and brittle one breaks up.

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