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The Role of Non-Metallic Inclusions in Steel Failure

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Abstract: The role of non- metallic inclusions in steel failure using an auger scanning electron microscope (SEM) with an in-built analyzer was undertaken in this study. Sample for investigation was removed from microalloyed steel and machined to a diameter and length of 3mm and 30mm respectively. It was then necked to 2mm at the middle and cleansed using water and ethanol. It was thereafter soaked in liquid nitrogen at -196°C for 15 minutes so as to render it brittle and was fractured manually at the neck. It was then mounted on a bracket and placed inside the experimental chamber of the microscope for investigation. The fractured surface was subjected to sectional observation at a magnification of 500-2000 and microphotographs of inclusion sites were taken. Chemical analysis of inclusions found at the sites was also carried out and used to determine their structures and relevant physical properties. The results obtained reveal the presence of inclusions that have different coefficients of thermal expansion from that of steel leading to cavity formation (sulphides) or stress concentration (oxides) at the inclusions. Also revealed are inclusions spaced close together in dimples and those that fractured in bits. These defects at inclusion sites are crack initiators in steel, some of which are propagated and extended leading to eventual failure of the part in service.

Key words: Microalloyed steel · Inclusions · Inclusion sites · Cavity · Crack

INTRODUCTION

The influence of non-metallic inclusions on steel properties of technical importance (such as machinability, fatigue life, red shortness) and mechanical properties has many research works dedicated to it. Studies conducted on the effects of inclusions on the machinability of steel show that sulphides don't impair this property but plastically undeforming oxides do [1, 2].

Results of research work conducted on the effects of inclusions on the fatigue life of steel have shown that certain inclusion parameters, such as number, composition, size, shape and their position in steel play key roles [3, 4]. Findings show that inclusions that have a low index of deformability may cause the introduction of microcracks at the steel/inclusion interface during hot or cold working. These cracks which are thus present in the steel from the beginning of service may then be the origin of later fatigue failure. It has equally been observed that angular inclusions with sharp edges and spherical inclusions that have cavities around them are nuclei of crack in the steel matrix. Iron sulphides, which precipitates at grain boundaries of steel have also been reported to promote hot- shortness due mainly to its low melting point ~ 1190°C [5, 6].

With regards to mechanical properties, it has been revealed that inclusions which fracture into stringers or plates during rolling promote differences in tensile properties in transverse and longitudinal directions [7- 9]. Tensile fracture in a reasonably ductile material initiates internally at inclusions or voids and ultimately fails by shear on 45° planes at the surface [10-12]. When a metal is deformed, not only is the matrix deformed, but also the inclusions, which may become elongated strings thus initiating microcracks that propagates during service and through connection with other microcracks [13-14]. Indirect correlation between inclusion amount and impact toughness have been reported by several authors. Studies support the fact that impact resistance of steel decreases with an increasing amount of inclusions [7]. This work aims at revealing how non metallic inclusions, depending on the type, lead to steel failure.

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Experimental

Materials/Equipment: Calcium treated micro-alloy steel [15], liquid nitrogen, Computerized Auger Scanning Electronic Microscope (SEM).

Procedure: Specimen removed from cast billet was machined to 3mm diameter and 30mm length, the specimen was necked at the middle to 2mm diameter. The specimen was thereafter washed with water and cleaned using ethanol to avoid contamination. It was then soaked in liquid nitrogen at a temperature of -196°C for 15 minutes in order to freeze it and render it sufficiently brittle. The specimen was then manually fractured at the neck. Thereafter, it was mounted on a bracket and placed in the experimental chamber of the microscope for investigation. The fractured surface was subjected to section by section observation under the auger scanning electron microscope at a magnification of 500 to 2000 in order to locate inclusions at fractured sites and analyze their composition.

RESULTS AND DISCUSSION

Results: The monograph of the fractured specimen is presented in Figure 1. Figures 2a-2f show the monographs of different inclusions observed on the surface of the fractured specimen. The compositions of inclusions analysed are presented in Table 1.

Discussion: Inclusions observed during investigation can be categorized as follows: those that retain their shapes but have voids or cavities of different sizes around them (Figs.2a-2c); inclusions spaced close together and arranged linearly or scatteredly (Figs. 2d and 2e) and inclusion that fractured into parts (Fig 2f).

Cavities around inclusions cause discontinuity in the interior or surface of the steel, which is very detrimental to its properties as these cavities are sites for micro crack initiation. The larger the cavity is, the higher the possibility of an early failure. The result of the chemical analysis conducted on the inclusions revealed that they contained high amounts of sulphur in their compositions (Table 1). Sulphide inclusions are known to have higher coefficient of thermal expansion than steel (Table 2), hence upon solidification they shrink much more than steel leading to the formation of cavities around them. This defect is particularly harmful because it creates localized internal weak points which eventually lead to fatigue damage.

Table 1: Chemical compositions of selected inclusions, %

Inclusion (Figure)	Chemical composition, %					
	Al	Ca	Mg	Mn	S	Si
2a-2c	16-29	30-38	~2	9-19	20-35	-
2d	43.0	51.2	2.3	0.9	0.9	1.7
2f	43.7	41.2	11.7	0.3	0.9	2.2

Table 2: Coefficients of thermal expansion (α) for steel and selected inclusions [5]

Material	Composition	α x 10^{-6} ($^{\circ}C^{-1}$)
Steel	-	12.5
Sulphides	CaS	14.7
	MnS	18.1
Aluminate	12CaO.7Al2O3	7.6

The ability of these inclusions in creating localized fracture is enhanced when they are spaced close to one another as in Figure 2d and 2e. In this case, the micro cracks, which resulted from the cavities around each of the inclusions, can extend and get connected together during steel working or in service. This of course will lead to a shorter fatigue life of the steel.

The inclusion in Figure 2d marked ‘ * ‘ is not inside a dimple, analysis shows that it is an oxide inclusion whose composition approximates to$12CaO\cdot7Al_2O_3$. Oxide inclusions generally have lower coefficient of thermal expansion than steel and upon cooling, tensile stress is created at the matrix- inclusion interface in place of cavity as is the case with sulphides. This stress concentration can significantly change the property of the surrounding steel matrix and actually causes localized plastic deformation [5]. The extent of the stress generated and the accompanying plastic deformation depend on the number of this type of inclusions within the locality.

Also observed is the inclusion presented in Figure 2f, which is comparatively large (~ 40 microns) and appears to have fractured. This signifies that the inclusion is highly brittle. SEM result shows that it is composed of CaO, MgO and Al_2O_3 (see table 1). The size and composition of the inclusion indicate that it is likely to be an entrapped exogenous inclusion whose origin is likely to be ladle glaze. Large and brittle inclusions are good initiators of most of the ductile fractures in steel. During metal working or in service, they easily fragment into pieces resulting in internal fissures which, ultimately leads to failure in service.

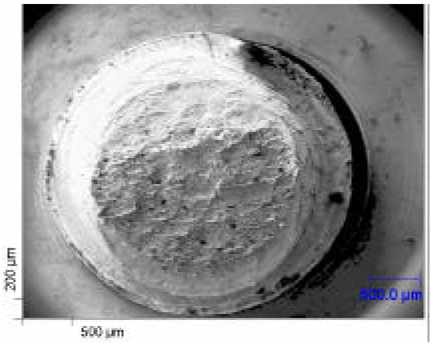

Fig. 1: Micrograph of fractured surface of the specimen

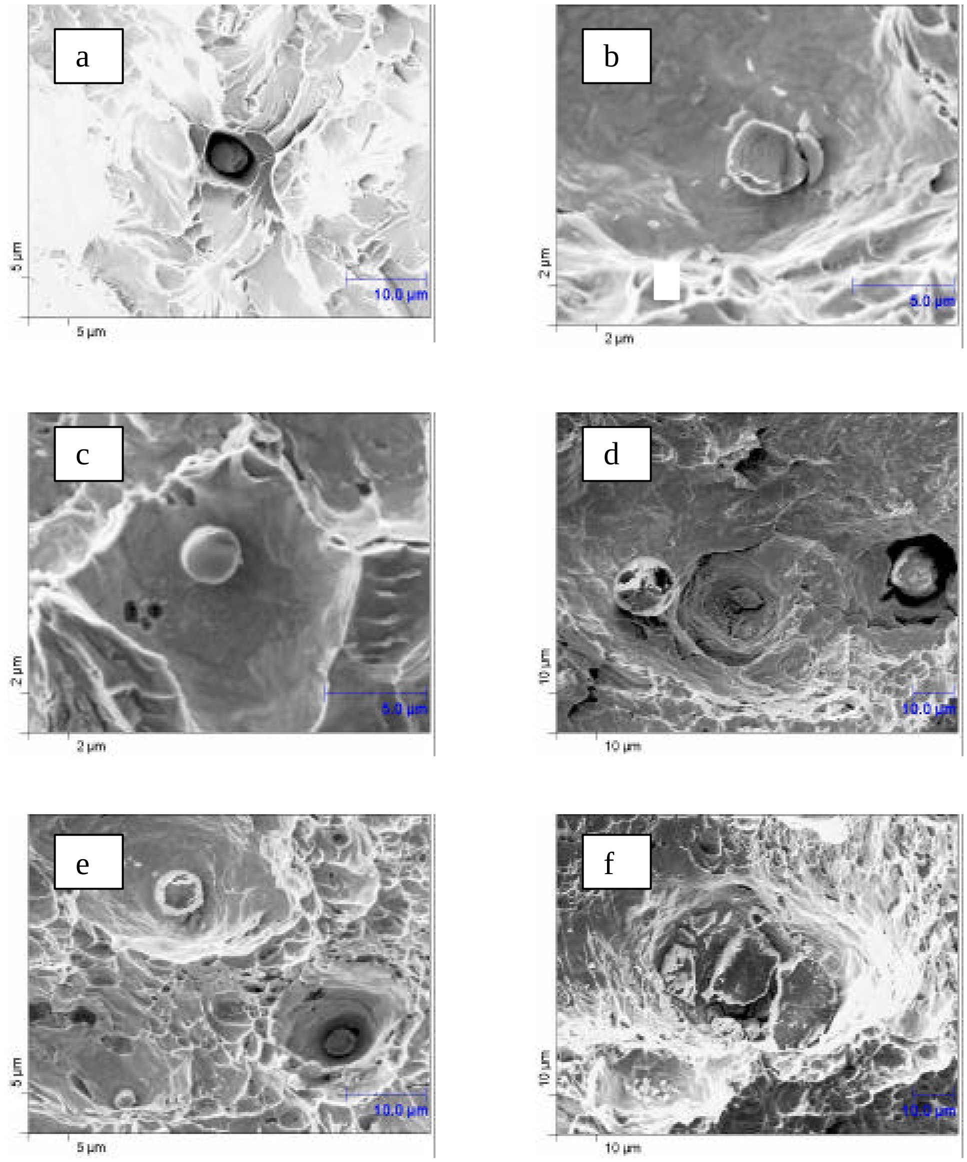

Fig. 2: Micrographs of inclusions observed in fractured steel

CONCLUSION

In the steel grade investigated for this work, sulphide inclusions, $12CaO{\cdot}7Al_2O_3$ type calcium aluminate and ladle glaze were observed. The analysis conducted on them showed that they have the tendency of initiating cracks in the steel matrix.

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