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The Morphology of Impact Fracture Surfaces in Manganese Cast Steel Modified by Rare Earth Elements

J. Kasińska *
Kielce University of Technology,
al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
* Corresponding author. E-mail: kasinska@tu.kielce.pl

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Abstract

The morphology of G20Mn5 specimens made of non-modified and rare earth metals (REM) modified cast steel was investigated. Molten metal was treated with a cerium-rich mischmetal contain 49.8% Ce, 21.8% La, 17.1% Nd, 5.5% Pr and 5.35% other rare earth metals making up the balance. The melting, quenching (920°C/water) and tempering (720°C/air) were performed under industrial conditions. Analysis included G20Mn5 cast steel fracture specimens subjected to Charpy V-notch impact testing at 20°C, -30°C and -40°C. The purpose of the analysis was to determine the influence of REM on the microstructure and mechanical properties of G20Mn5 cast steel and the REM effect on the morphology, impact strength and character of the fracture surfaces. In addition, a description of the mechanism by which fracture occurred in the two materials was proposed. The author demonstrated the beneficial effects of adding REM to molten steel, manifested by a 20 - 40% increase in impact toughness, depending on test temperature, as compared to the non-modified cast steel. Important findings included more than 100% increase in impact strength in comparison with the required impact toughness of 27J at -40C for heat treated steels (EN 10213).

Keywords: Cast steel, Modification, REM, Impact strength, Fracture analysis

1. Introduction

Low-alloy cast steel is widely used in modern technologies for its relatively low production costs. In addition to micro additions such as Nb, V, Ti [1], rare earth metals (REM) are applied to improve cast steel properties. Although the use of REM as additives is not new, they have become a highly sought-after global commodity over the last decade [2-5]. Special characteristics inherent in the REM make them suitable for application in the production of non-ferrous metal alloys [6]. Ultimate applications depend on the unique properties of individual metals in the REM group [7 - 11]. In metallurgical processes, the influence of REM on crystallization through microstructural refinement and improvement of mechanical properties, and correspondingly, overall performance plays an important role.

The influence of additions or microalloys on the properties of steel, cast steel and alloys is typically investigated through tests, including strength testing. Fractographic analysis of fracture specimens reveals the mechanisms that operated to produce the fracture. Fracture surfaces are a valuable source of cognitive and functional information, especially useful in the analysis of structural damage and failure of machine parts or equipment. Fractographic analysis provides information about the crack growth, growth rate or arrest and factors, both external and internal, that need to be considered. The Charpy V-notch impact testing is an inexpensive and fast method used for the assessment of resistance of materials and weldments to fracture, conducted on notched specimens subjected to dynamic loading. The Charpy test is not definitive in character. The quantities determined during the tests are not material constants and cannot be the basis for any fracture toughness calculations. They can only be compared with the results obtained from other tests performed on the same specimens under the same conditions. Nevertheless, the amount of comparative data obtained from the tests allows determining the brittleness of parent materials and welds and evaluating various factors which affect the amount of brittle fracture [12]. Assessment of particular fracture surface areas provides an approximation of the mode and distribution of stress and the type and magnitude of overload [11]. The test also indicates whether a given component deteriorated over a long time (fatigue fracture) or the fracture occurred rapidly.

Microscopic techniques (optical, scanning, stereoscopic, etc.) are used to assess the surface of fractures. The beginning of the micro fractography dates back to the 1940s, where a number of works by C. A. Zapffe and co-authors were published [13].

Several classification rules have been adopted for examining fracture surfaces, but most often the surfaces are classified according to their structure, load mode and crack growth mechanism. The primary division is based on identifying a fracture as brittle or ductile. A brittle fracture is identified when no macroscopic plastic deformation is observed. It is generated by loads in the elastic range that exceed the cohesion of the material in the lattice planes and develops at high velocities (the speed of sound in a given material) along the defined crystallographic planes of the grain - along the planes of cleavage. As a result, cleavage fracture occurs, either passing through grains (transgranular/transcrystalline fracture) or along grain boundaries (intergranular/intercrystalline fracture) [14].

In ductile fracture (plastic fracture), plastic deformation takes place prior to the fracture due to shear stress (sliding in slip planes). High resistance to decohesion occurs in cleavage planes and at grain boundaries. The fracture surface is inclined about 45° to the maximum stress direction [15]. These fractures are often termed ductile plus brittle fractures.

Brittle fractures occur in cleavage planes regardless of the mode and conditions of loading. Regular spatially face-centred cubic lattices (FCC) typically cleave on (100) or (110) planes [16]. In body-centred cubic metals (BCC), cleavage occurs on (100), (112) and (111) in chromium, on (100) and (110) in molybdenum, tantalum, and tungsten, and on (100) in iron and vanadium. The mode of brittle fracture is described by features such as ridged patterns, river patterns, tongues, secondary cracks, or quasi-cleavage. An example of the surface with the brittle fracture characteristics is shown in Fig. 1 [16]. Cleavage steps form as a result of the crack front meeting screw dislocations cutting across cleavage planes, Fig. 2 [11, 18]. As approaching ridges meet, the previous one can increase or be reduced. The schematic view of a ridged pattern in the cleavage plane is shown in Fig. 3[11]. A crack dislocating from grain A to grain B adapts its direction to the new orientation. The appearance of river patterns helps identify the direction of crack propagation.

Cleavage fracture ranges represent the grain size in the crystalline material. Grain boundaries of different crystallographic orientations impede the development of cleavage cracks by forming ridges. Precipitated second phases have a similar effect of temporarily arresting the crack inside the grain and forming new river lines.

Plastic (ductile) fractures have characteristic cavities – dimples. Dimples form when micropores in the material grow under loading and coalesce (converge) as a result of plastic strain (decohesion). Microvoids generally nucleate in the interfaces/boundaries between the matrix and second phase particles or precipitates. Fracture surfaces may thus exhibit precipitates in the cavities or the voids left by pulled out inclusions. The number of dimples depends on the number and type of precipitates (or phases) and their distribution in the matrix. The grain size and plastic properties of the material also play a role. The size of the dimples corresponds to the distance between inclusions or precipitates [19]. In ductile fracture, the dimples are classified as equiaxed (uniaxial tension) and elongated ("scales") by shear or eccentric (non-uniform) tension.

Quasi-cleavage is generally found in technical alloys (quenched and tempered). This is not a precise definition of the mode of fracture, but provides some general information. Supporting evidence can be obtained by subjecting fatigue fracture surfaces to long-term loads under various conditions (environmental or temperature-related variables). Observation of such surfaces helps identify the causes of damage and, to a large extent, supports the evidence in expert reports on materials failure [20]. Analysis of the morphology of fracture surfaces and the material itself (metallography, X-ray fractography, etc.) determines the microstructural factors that have had a significant impact on the damage process [21]. In light of the above considerations, proper handling and preparation of fracture surfaces for observation should not be underestimated [22].

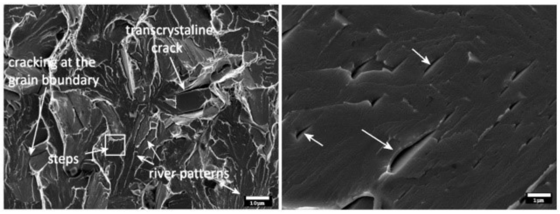

Fig. 1. Fracture surfaces from three-point bend testing of G17CrMo5-5; a – characteristic fracture features, b – tongues.

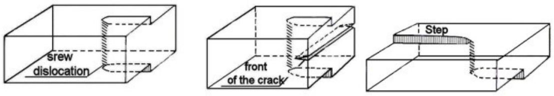

Fig. 2. Fracture model showing a cleavage ridge/step forming by screw dislocations cutting across the cleavage plane (based on [11])

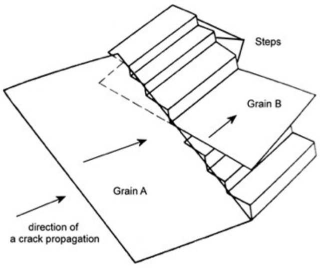

Fig. 3. Schematic representation of ridges/steps forming in the cleavage plane (based on [11])

2. Materials and experimental procedure

Manganese cast steel G20Mn5 was melted under industrial conditions in an induction furnace with a capacity of 300 kg. The chemical composition of the mischmetal used for the modification was as follows: 49.8% Ce, 21.8% La, 17.1% Nd, 5.5% Pr and 5.35% other REM. Two series of melts with the chemical composition given in Table 1 were made, which after cutting off the deadheads were subjected to heat treatment (quenching (920°C/water) and tempering (720°C/air)). The addition of mischmetal resulted in significant grain refinement (Fig. 4) and change in the morphology and size of non-metallic inclusions (Fig.5) [23].

Table 1
Chemical composition of the cast steel

	Cast steel without REM	Cast steel with REM
Element	% mass	
C	0.19	
Mn	1.14	
Si	0.41	
P	0.02	
S	0.018	
Cr	0.15	
Mo	0.15	
Fe	97.80	
Ce	<0.00500	0.0288
La	<0.00100	0.0176

Tensile test was carried out at the room temperature using an INSTRON testing machine The introduction of mischmetal into cast steel did not cause a clear change in the yield point/strength or tensile strength, which on average amounted to approximately 348 MPa and 550 MPa for both variants of melts, respectively. Significant impact resistance changes in the cast steel under analysis were recorded (Table 2) [23].

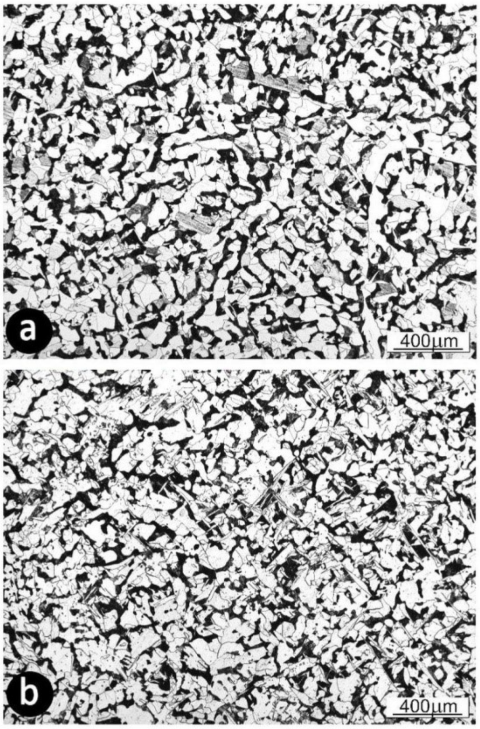

Fig. 4. Microstructure of G20Mn5 cast steel without heat treatment, a – non-modified, b – modified with REM

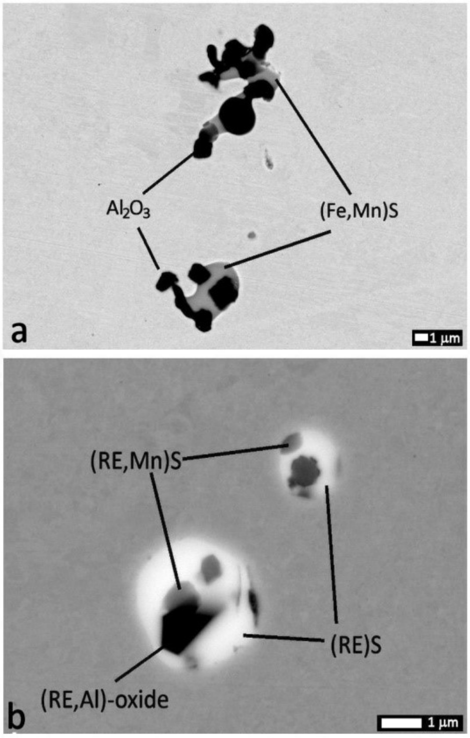

Fig. 5. SEM micrographs of inclusions in BSE modes, a – non-modified, b – modified with REM

Table 2
Impact energy of modified and non-modified cast steel

Temperature of test, °C	without REM	with REM
	Impact toughness, J	
-40	48, 48,54	76, 60, 61
-30	58, 67, 66	62, 53, 102
+20	113, 113, 123	140, 151, 134

3. Morphology of impact fracture surfaces

Impact fracture surfaces of specimens broken at ambient temperature showed a ductile character in both cases. The differences included the size of non-metallic inclusions observed on the fracture surface, and thus the size of dimples around them (Fig.6).

At the test temperature lowered to -30°C, the mode of fracture changed to brittle with locally occurring ductile fracture bands. In the case of modified cast steel, the bands were more frequent (they represented a larger portion on the fracture surface). The dimples in these areas in the cast steel with mischmetal were smaller. The grain refinement after modification also affected the cracking process. This was reflected in the increase in the number of ridges/steps, which then merged into the river patterns. Brittle fracture at grain boundaries and transcrystalline cracks were observed to a much lesser extent (Fig 7).

At the test temperature lowered to -40°C for cast steel with the REM addition, markedly fewer transcrystalline cracks or cracks along grain boundaries were observed. As in the previous cases, numerous ridges/steps and river patterns were observed on the fracture surface, indicating a greater grain refinement in the case of modified cast steel. Areas of ductile fracture were observed locally in both modified and unmodified cast steel. As in previous tests, more such areas were observed in modified cast steel specimens (Fig.8).

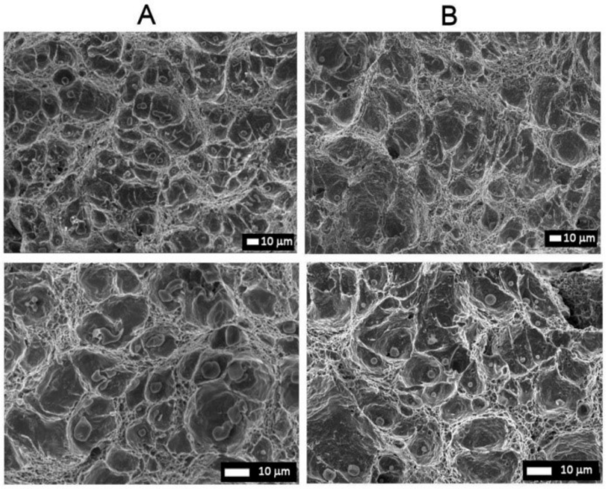

Fig. 6. Morphology of fracture surfaces of non-modified cast steel A and modified cast steel B. Test temperature: +20°C

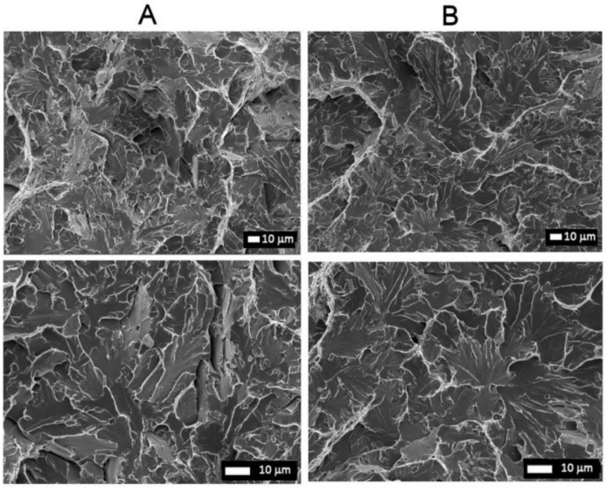

Fig. 7. Morphology of fracture surfaces of non-modified cast steel A and modified cast steel B. Test temperature: -30°C

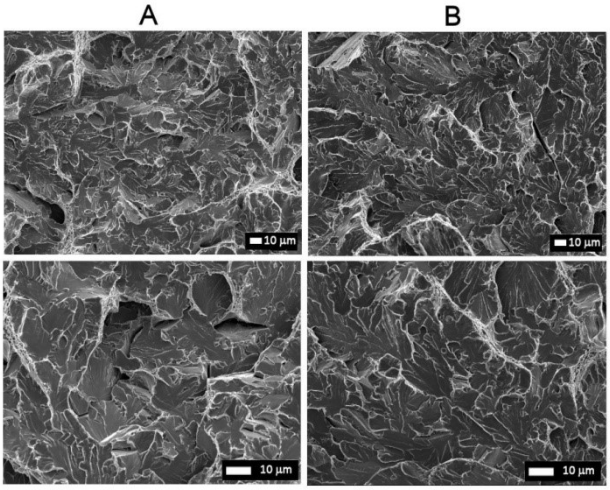

Fig. 8. Morphology of fracture surfaces of non-modified cast steel A and modified cast steel B. Test temperature: - 40°C

4. Study results and analysis

Analysis of the morphology of impact fracture surfaces provides information needed to assess the material. In the case of the analyzed variants of G20Mn5 cast steel, a number of positive changes were observed after introducing mischmetal in the form of a cerium mixture. These included grain refinement, morphological changes and size reduction of non-metallic inclusions, which directly affected the morphology of the impact fractures. Grain refinement and thus larger volume fraction of boundaries in the material causes the traveling crack to encounter more barriers (boundaries) to overcome. The number of ridges/steps also increased, which may indicate a change in the dislocation structure of the material after the addition of rare earth metals. This may have nothing to do with their growth or constraint, but may affect their distribution and correlations (position relative to each other or to other elements of microstructure such as grain boundaries or precipitates). An important element that improved the microstructure was the shape change and size reduction of non-metallic inclusions, thereby restraining the propagating crack front in the material. The shape change to spherical eliminated "notches", at which cracks initiate and grow. The crack front propagating around spherical inclusions has to use more energy as confirmed by the microscopic observations. Local deformations around the inclusions indicated the occurrence of stress (Fig. 9).

To properly describe the impact of REM on the crack process in the G20Mn5 cast steel, the research will be extended to include the analysis of dislocations with the use of transmission electron microscopy.

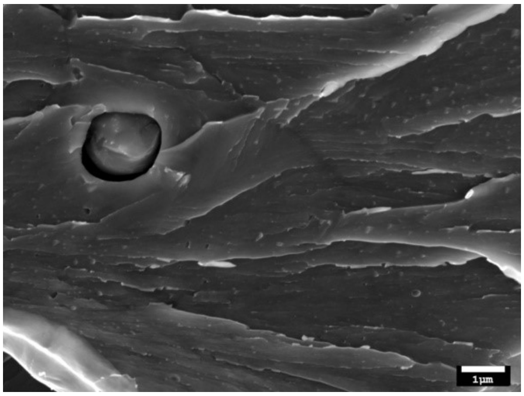

Fig. 9. Non-metallic inclusion in the modified cast steel

5. Conclusions

Modification of G20Mn5 cast steel can be carried out efficiently and repeatedly under industrial conditions. This is extremely important from a wider industrial perspective. The introduction of rare earth metals helps increase impact toughness, as compared to unmodified steel, in the temperature range from - 40 °C to+20° C. The effect of REM on the structure and morphology of non-metallic inclusions is reflected in the differences observed on the surfaces of impact fractures. The differences observed included the grain size as well as in the shape, size and dispersion of non-metallic inclusions, all of which affected the cracking process.

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