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Effect of MnS inclusion and crystallographic texture on anisotropy in Charpy impact toughness of low carbon ferritic steel

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ABSTRACT

The combined effect of microstructure and crystallographic texture on the anisotropy in Charpy impact toughness has been studied in two hot-rolled low-carbon steel plates having different sulphur contents: 0.03 wt% S in high-sulphur, HS, steel and 0.01 wt% S in low-sulphur, LS, steel. Sub-size Charpy impact specimens were prepared from the rolled plates along 0°, 30°, 60° and 90° to the rolling direction and tested over the temperature range of +40 °C to −196 °C. Microstructure, inclusions and crystallographic texture have been characterized on the plane parallel to the fracture plane of each sample. The variation in upper shelf energy (USE) was more severe (~69%) in HS steel due to the presence of coarse and elongated MnS inclusions. Crystallographic texture, especially, higher fraction of alpha- to gamma-fibre texture and stronger cube texture resulted in stronger variation in ductile to brittle transition temperature (DBTT) in LS steel (by ~26 °C). Increase in the fraction of {001} planes of the crystals on the fracture plane of the sample increased the DBTT by helping the cleavage crack propagation. On the other hand, increase in the fraction of {110} planes of the crystals on the shear planes (inclined at 45° to fracture plane) increased the USE by promoting the plastic deformation.

1. Introduction

Anisotropy refers to the directionality in property, i.e. the variation in property with the change in orientation of the sample with respect to the rolling direction [1]. Anisotropy in the mechanical property can arise from several factors such as, chemical segregation, variation in shape and size of grains, inclusions and finally crystallographic texture [1].

Interdendritic segregation and the resultant pearlite banding is known to cause anisotropy in rolled steel plate [2,3]. High S content (> 0.01 wt%) in steel results in the formation of MnS inclusions in high fraction and large size, which deform during hot-rolling and becomes elongated along the rolling direction. Such stringer shaped inclusions are known to cause anisotropy in mechanical properties such as, tensile ductility and fracture toughness [4–6]. Variation in grain size and grain shape along different directions can also cause anisotropy in property [7]. Rolling below the lower critical temperature leads to the formation of elongated ferrite grains along the rolling direction. Therefore, the ferrite grain size varies along different directions resulting in the anisotropy in mechanical property [7,8].

A number of studies have been reported on the role of crystallographic texture on Charpy impact properties [9–13]. Kotrechko et al. [9] demonstrated that the non-uniform distribution of crystallographic planes due to the presence of strong crystallographic texture can cause anisotropy in Charpy impact properties. High intensity of {112}⟨110⟩ texture component has been reported to induce anisotropy [12]. Mintz et al. [10] reported that the presence of crystallographic texture mainly contributes to the anisotropy in ductile fracture whereas it has no role on the cleavage fracture. In a recent study Physhmintsev et al. [14] have shown that crystallographic texture might have no role even on the ductile fracture arrest. In contrast, Joo et al. [15] indicated that the increase in intensity of {001} planes of the crystals parallel to the fracture plane of the sample promotes cleavage crack propagation and hampers low-temperature impact toughness.

The present work aims to investigate the combined effect of microstructure and texture on the anisotropy in Charpy impact toughness and impact transition behaviour of low-carbon ferritic steel.

2. Experimental details

Two steels having different sulphur contents (high-sulphur, HS, and low-sulphur, LS) were prepared in air induction furnace, with

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Nomenclature

HS	high sulphur
LS	low sulphur
USE	upper shelf energy
LSE	lower shelf energy
DBTT	ductile to brittle transition temperature
SEM	Scanning electron microscope
EBSD	electron backscattered diffraction analysis
ECD	equivalent circle diameter
IPF	inverse pole figure
BCC	body centred cubic
RD	rolling direction
TD	transverse direction
ND	normal direction

Table 1
Chemical composition of the investigated samples (wt%).

Sample code	C	Mn	Si	Al	Ti	V	Nb	S	P	N
HS	0.08	1.2	0.3	0.013	–	0.08	0.05	0.03	0.02	0.007
LS	0.1	1.25	0.15	0.014	0.01	–	0.06	0.01	0.01	0.007

the composition given in Table 1. The cast ingots (100 mm thick) were soaked at 1200 °C for one hour followed by laboratory rolling, down to 8 mm thick plate using finish rolling temperature of 800 °C.

Specimens were mounted and polished following standard metallographic techniques and etched in 2% nital solution. Leica DM600M model optical microscope and Zeiss Auriga compact scanning electron microscope (SEM) were used for microstructural and inclusion study and Leica M.W and L.A.S software were used for the image analysis (phase identification and measurement of the phase fraction). The average ferrite grain size was measured through equivalent circle diameter (ECD) method based on the determination of grain area (by image analysis) of more than 500 grains from each sample [16]. Sample preparation for EBSD consists of standard mechanical polishing (down to 0.25-μm grit), followed by electro-polishing with the solution containing 5 vol% perchloric acid and 95 vol% acetic acid. The electro-polishing has been carried out in Buehler Electromet4® for 15 s at 20 V. Electron backscattered diffraction analysis, EBSD, was carried out using HKL channel 5 system (oxford Instruments, Abington, Oxfordshire. UK) attached to Zeiss Auriga compact SEM at a step size of 1 μm. For macro-texture study, specimens were collected from the plane parallel to RD–TD plane at quarter-thickness.

Standard tensile specimens and sub-size Charpy impact specimens (cross-section 8 mm × 10 mm) were fabricated from the rolled plates along four (4) different directions, at an angle of 0° (sample code R0), 30° (sample code R30), 60° (sample code R60) and 90° (sample code R90) with respect to the rolling direction following ASTM E-8 standard [17] and ASTM E-23 standard [18], respectively, Table 2. Tensile specimens were tested at room temperature (+25 °C) at cross-head velocity of 1 mm/min using Instron 8862 servo-electric test system (10 t capacity). Charpy impact testing has been carried out using an Instron® SI-1C3 model instrumented impact testing machine (400 J capacity),

Table 2
Sample codes and the details of the investigated samples.

No.	Abbreviation	Full form
1	LSR0	Low sulphur steel, 0° with respect to RD
2	LSR30	Low sulphur steel, 30° with respect to RD
3	LSR60	Low sulphur steel, 60° with respect to RD
4	LSR90	Low sulphur steel, 90° with respect to RD
5	HSR0	High sulphur steel, 0° with respect to RD
6	HSR30	High sulphur steel, 30° with respect to RD
7	HSR60	High sulphur steel, 60° with respect to RD
8	HSR90	High sulphur steel, 90° with respect to RD

attached with Instron Dynatup Impulse data acquisition system, over the temperature range of +40 °C to −196 °C. The Charpy impact transition curves were drawn within the scattered data points of Charpy impact energy vs. temperature plot by fitting a "tanh" function, following the procedure given by Sakai et al. 1989 [19]. The specimen temperature was maintained within ±2 °C using a medium of methanol and liquid nitrogen. Detailed fractographic study has been carried out on the broken Charpy impact specimens.

3. Results and discussions

3.1. Microstructural characterisation

Microstructural characterisation has been carried out on the plane parallel to the main fracture plane of Charpy impact samples, having different orientations with respect to the rolling direction, Fig. 1. That means TD–ND plane was studied in R0 sample and on RD–ND plane was studied in R90 sample. Optical micrographs of HS and LS steel samples showed ferrite–pearlite microstrcrutures in both the steels, with higher pearlite fraction in HS (~13%) than that in LS (~7%), Fig. 2 and Fig. 3. The average ferrite grain size was much higher in HS steel samples (22–24 μm) than that in LS steel samples (6–8 μm). The ferrite grain size distributions measured in HS and LS steel samples are presented in Fig. 4. The grain size distributions were unimodal in nature in both the steels and did not show much variation with respect to the sample orientation, Fig. 4. The distribution clearly shows that much larger grains were present in HS steel (up to ~47 μm size), than that in LS steel (up to ~25 μm size), Fig. 4. The ferrite grains were slightly more elongated in LS steel samples (having average aspect ratio of 2.0–2.2), as compared to HS steel samples (having average aspect ratio of 1.2–1.4). The grain aspect ratio did not show any significant

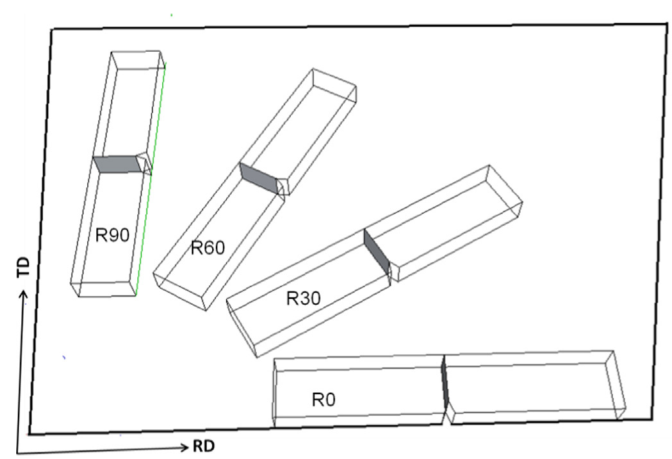

Fig. 1. Schematic diagram showing the orientation of Charpy impact specimens with respect to the rolling direction, RD. Grey coloured planes are the macroscopic fracture plane of Charpy impact specimens at different orientations.