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Impact Toughness of Concrete Reinforcement Bars Produced by the THERMEX Process and Ordinary Rolling Process

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*Abstract— **The impact toughness of rebars produced by the THERMEX process and ordinary rolling process was investigated by the Charpy impact test at temperatures between -40^{0}C and 100^{0}C. The THERMEX process utilizes quenching and self-tempering technology during the final stages of rolling, whereas the ordinary rolling process does not. The rebars produced by the THERMEX process are known as quenched and self tempered rebars or QST rebars. A novel approach for testing impact toughness of QST rebars was implemented. The impact properties that were investigated comprised the total impact energy, ductile to brittle transition temperature (DBTT), transition temperature at 100% ductile fracture and transition temperature at 100% brittle/cleavage fracture. The QST rebars displayed much higher resistance to ductile fracture at high test temperatures, while its resistance to brittle fracture at low test temperatures was only a little higher than that of the ordinary hot rolled rebars. The QST rebars also displayed lower ductile to brittle transition temperature than the ordinary hot rolled rebar. This increase in the impact toughness of QST rebars can mostly be attributed to its composite microstructure consisting of a strong tempered martensite periphery/case and ductile ferrite-pearlite core.***

*Keywords— **ductile to brittle transition temperature (DBTT), impact toughness, quench and self-tempering, THERMEX process.***

I. Introduction

THERMEX is a patented technology that utilizes rapid water quenching system for the production of thermoprocessed rebars [1]. The THERMEX cooling technology involves subjecting the bar to predetermined quantity of high-pressure water after the last rolling mill stand. This treatment converts the bar surface to a hardened structure and subsequently the phase evolves by cooling at ambient temperature to allow the hot core to temper the surface through thermal exchange. This results in a unique composite microstructure comprised of tempered martensite in the peripheral zone/case, transition zone of pearlite and bainite just after the martensite periphery and a fine grain ferrite-pearlite at the central zone/core.

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Due to the quenching and self-tempering method, rebars produced by the THERMEX process are called Quenched and Self-Tempered (QST) rebars [2]. QST high strength rebars are low carbon structural steels containing less than 0.30 % carbon and lower alloy content than ordinary hot rolled rebar [2], [3], [4]. It is widely used in the construction of buildings, bridges, flyovers, dams, load bearing machine components, concrete roads etc. High strength (yield strength≥450 MPa, ultimate strength≥500 MPa) and ductility, good weldability, earthquake resistance and cost effectiveness make it viable as a construction material for reinforcement of concrete [4]. Ordinary hot rolled and normalized rebars had formerly been the main structural materials used for construction and various other purposes. These steels have a carbon level of 0.2%-0.4% with a minimum of 1.4% Manganese [5] which is considered optimum when high strength with good ductility is required. The microstructure of ordinary hot rolled carbon steels normally comprises a mixture of ferrite and pearlite. Impact toughness of steels is fundamentally dependent on the microstructure [5]. Microstructure of steels is determined by the chemical composition of the steel and the heat treatment procedure through which it was processed. These parameters associated with the microstructure of steel mainly controls dislocation density, grain size and the volume fraction and size of second phase particles. Production of steel with the same raw material (Iron, Carbon and other alloying elements) did not change much with time but modification in processing has significantly improved the quality of steel. In the present study, a comparison has been made between the impact properties of QST rebars and ordinary hot rolled rebars. The impact properties were determined by the Charpy impact test. Although there are specified details of Charpy testing but there is hardly any established procedure for testing the impact toughness of QST ribbed bar product [6]–[8]. A novel approach was taken to machine subsize specimens out of the QST rebars for impact testing of rebars by the Charpy test method. The determined properties were then correlated to the composition and microstructure of the rebars. The advantages of Charpy testing are that it is a rapid test method requiring small investment, test specimens are of small size and simpler to machine. The Charpy test data can be used to predict the performance of material in service condition. It reproduces the ductile to brittle transition of steel in about the same temperature range as it is actually observed in engineering structures. Through Charpy test important data such as, impact energy, ductile to brittle transition temperature (DBTT) can be determined.

II. MATERIALS AND METHODS

A. *Production and Selection of Rebars*

The THERMEX cooling technology is designed to be installed in-line with the rolling process [3], [6], [7]. After leaving the finish rolling mill at about 1000^{0}C as seen in Fig. 1(8), the hot rolled bar is quenched by rapid water sprays in the finish cooling zone as seen in Fig. 2(a) in order to rapidly cool the surface of the bar below the martensitic transformation temperature, M_s according to Fig. 2(b) [3], [6].This phase of the process creates a hardened "case" or "periphery". The central zone/core of the bar still remains austenitic. The residual heat in the core of the rebar radiates out to the rim of the rebar, [3] tempering (self) the newly formed martensite [2]–[6]. This tempering temperature or equalization temperature is the maximum temperature attained by the rebar surface after quenching. Tempering enables partial diffusion of carbon out of the extremely brittle but strong martensite which relieves inherent stresses locked in during quenching. During this time, the surface of the bar reheats to approximately 600-700°C from the heat radiated from the core according to Fig 2(b). After the bar reaches its peak reheat temperature, it cools naturally until reaching ambient temperatures as seen in Fig 2(b). After the bar has reached ambient temperature, it behaves more like a composite material than a single, solid material [2],

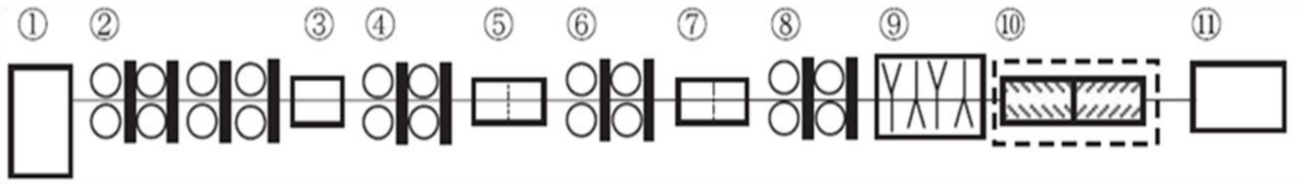

Fig. 1 Layout of Rolling Mill and Cooling Zone in Bar Product Line: (1) Reheating Furnace, (2) Roughing Mill, (3) Rough Cooling Zone, (4-6) Intermediate Rolling Mill, (7) Intermediate Cooling Zone, (8) Finish Rolling Mill, (9) Finish Rolling Mill (SCFM), (10) Finish Cooling Zone, (11) Cooling Bed [7]

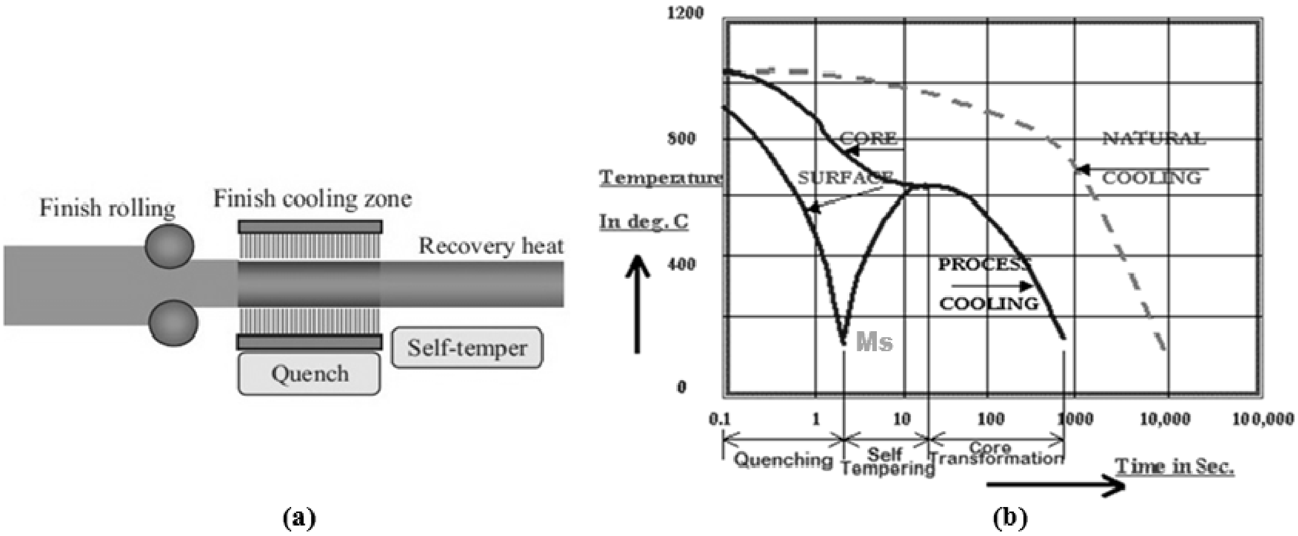

Fig. 2 (A) Finish Cooling Zone [7], (B) Schematic Diagram of the THERMEX Process on a Time-Temperature Curve [8]

On the other hand an ordinary hot rolled rebar simply moves forwards from the finishing rolling mill to the cooling bed and hence cools down by the ambient temperature (normalization). The major difference lies in the exit temperature of the rebars. The QST rebar leaves the final stages of rolling with lower temperature than the ordinary rebar. A QST rebar has the ductility from the core of the bar and the strength from the case of the bar [2], [3]. By reducing the alloy additions, the core of the bar is softer and more ductile than the fully alloyed counterpart [2]. The selection and procurement of rebars was done randomly from two different rolling mills producing QST rebars by THERMEX process and ordinary hot rolled rebars. Rebar diameter of 32 mm was selected for impact testing, as it provides sufficient martensite layer for analysis.

B. *Chemical and Microstructural Analysis*

Optical emission spectroscopy (OES) has been done to determine chemical composition of the rebars. For microstructural analysis, small cylindrical sections were cut from the rebars and then mounted for coarse grinding. Standard techniques were followed to prepare sample for optical microscopic observation [9]. After the final stages, the surfaces of the specimens were dried with acetone and etched in 2% Nital solution [2 ml concentrated nitric acid (HNO_3)+ 98 ml ethanol (C_2H_5OH] to observe the microstructure of QST and ordinary hot rolled rebars.

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C. Specimen Preparation and Impact Testing

In order to evaluate the impact toughness, Charpy specimens were machined from the rebars as shown in Fig. 3(a). The dimensions of a standard Charpy specimen cut from a QST rebar is shown in Fig. 3(b). The preparation of subsize specimen by this method enabled preservation of the outer martensite periphery/layer to a large extent so that after cutting the V-notch, about 2 mm layer of tempered martensite remained beneath the notch [10]. The V-notch contained a root radius of 0.25mm. Triplicate Specimens were tested at 100°C, 60°C, RT (28°C), 0°C, –10°C, –20°C, –30°C and –40°C according to ASTM standards (ASTM-E2248) for accuracy. After testing, the averages of the absorbed impact energy values were calculated.

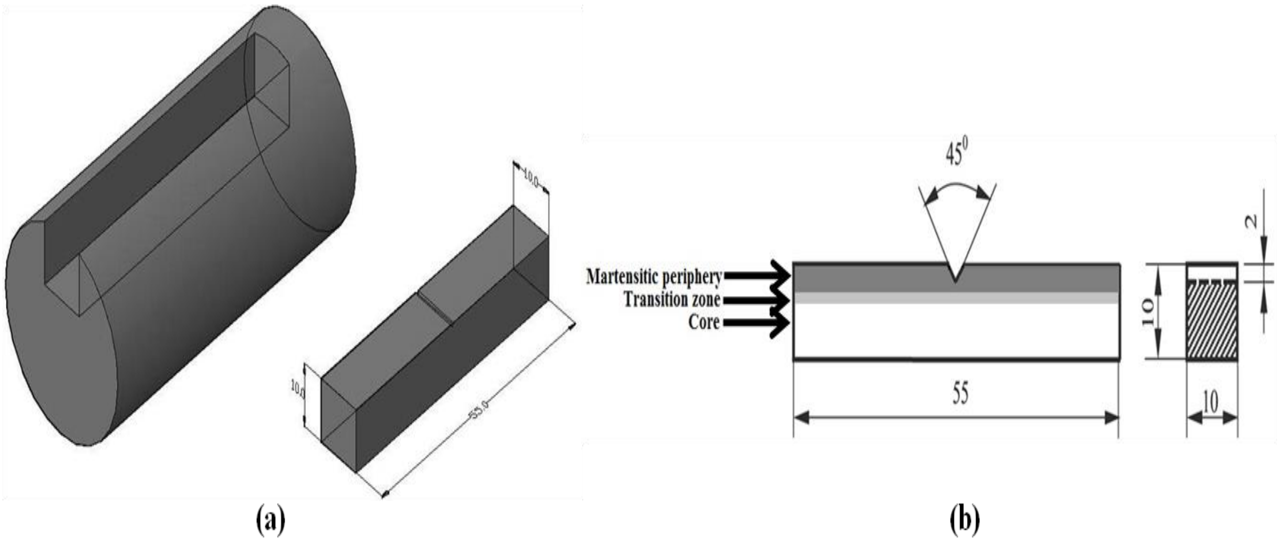

Fig. 3 (A) Location of Charpy Specimens, (B) Dimensions of Standard Charpy Specimen (all Dimensions in mm)

III. RESULTS AND DISCUSSIONS

A. Chemical Composition Evaluation

The chemical composition of the QST and ordinary hot rolled rebar is given in Table I. It is clearly noted that the QST rebars have less %C than the ordinary hot rolled rebar. The QST rebars also have less alloying elements than the ordinary hot rolled rebar. The main principle behind the THERMEX process is to impart better properties to the rebar without additional alloying elements. The ordinary hot rolled rebar has higher %C and alloying elements to maintain high strength required for structural applications. The THERMEX process produces a rebar with a composite microstructure that compensates addition of alloying elements for high strength. Generally, carbon required for a typical QST rebar application is between 0.25 and 0.30%. As a result, carbide-forming residuals have a lessened effect compared to when they are found in fully alloyed steel. Also, when using QST rebar, the mechanical properties are not determined by chemistry alone, the final quenching phases of the process also play a major role. The process is able to absorb a wider range of residuals in the steel scrap compared to a more traditional process, while still achieving the desired properties.

Table I. Chemical Composition (wt %) of QST and Traditional Hot Rolled Rebar

Type of rebar	Composition							
	%C	%Si	%Mn	%P	%S	%Cu	%Ni	%Cr
QST rebar 1	0.17	0.13	0.72	0.03	0.01	0.32	0.06	0.07
QST rebar 2	0.27	0.16	0.74	0.03	0.04	0.3	0.14	0.17
Ordinary hot rolled rebar 1	0.33	0.28	1.71	0.05	0.05	0.3	0.10	0.11
Ordinary hot rolled rebar 2	0.36	0.29	0.78	0.04	0.04	0.35	0.05	0.06

A. Microstructural Evaluation

The macrostructure of the investigated QST rebar revealed three distinct layers namely a martensitic periphery, transition zone and a central zone/core according to Fig. 4. Tempering the martensite is necessary to reduce internal stresses to the newly formed martensite and to eliminate brittleness in the final bar.

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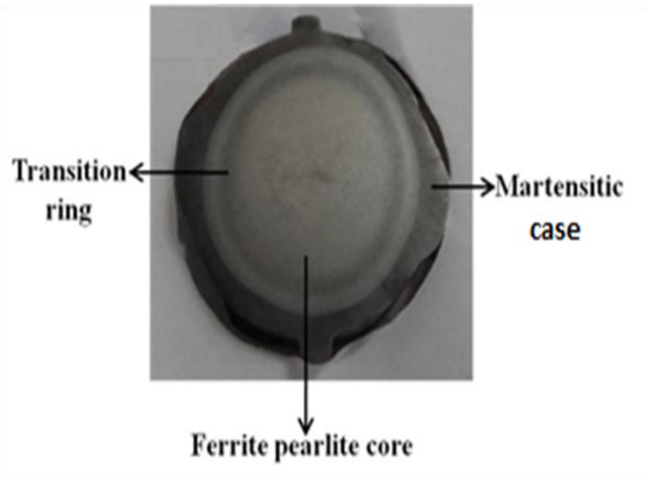
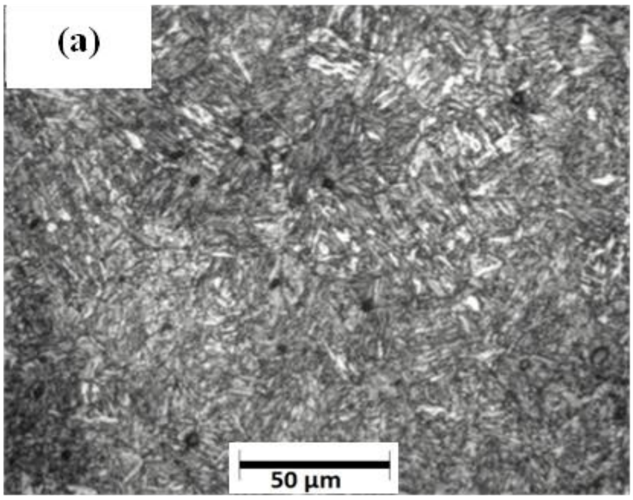


Fig. 4 Macrostructure of QST Rebar

The core of the QST rebar is ferritic-pearlitic as seen in Fig. 5(c). Grain refinement of the core of the bar is observed compared with ordinary hot rolled rebar. This grain refinement contributes to the generally improved elongations of QST rebar compared to the fully alloyed rebar. This characteristic of the QST rebar allows the manufacturer to increase the strength of the bar without sacrificing ductility of the bar. Starting at the surface of the bar, the microstructure is tempered martensite as seen in Fig. 5(a). Moving toward the center of the bar, the tempering becomes more pronounced, which is viewed as a "softening" of the microstructure. At the transition zone as seen in Fig. 5(b) from martensite to ferrite, there is some evidence of mixed bainite. The ferritic-pearlitic structure begins from this point through to the center of the bar.



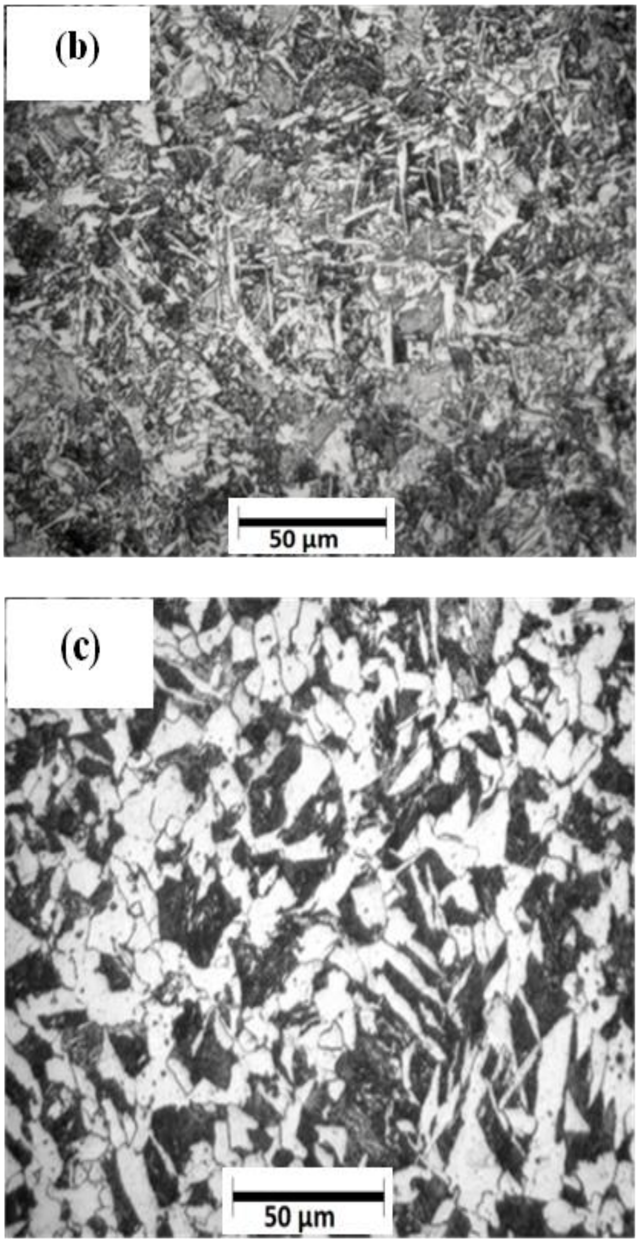


Fig. 5 Microstructure [Magnification: 200X] of (A) Martensitic Case/Periphery, (B) Transition Zone, (C) Ferrite-Pearlite Core

The macrostructure of the ordinary hot rolled rebar as seen in Fig. 6(a) did not have any distinct layers like the QST rebar. The microstructure revealed a ferrite-pearlite structure characteristic of normalized rebars. The ferrite-pearlite grains are coarser than QST rebars as seen in Fig. 6(b) and 6(c). Depending on carbon content and cooling rate, the proportions of ferrite and pearlite vary [3]. Here it is to be mentioned that both ferrite and pearlite are stable phases at room temperature. The finer ferrite-pearlite core of QST rebars are a result of lower exit temperature after the quenching treatment [3], [4]. The lower temperature enables lower amount of grain growth. On the contrary, normalized rebars are simply guided on to the cooling bed after exiting from the final pass.

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Since the exit temperature of ordinary hot rolled rebars are much higher than QST rebars the grain sizes of both ferrite and pearlite tend to be coarser in nature.

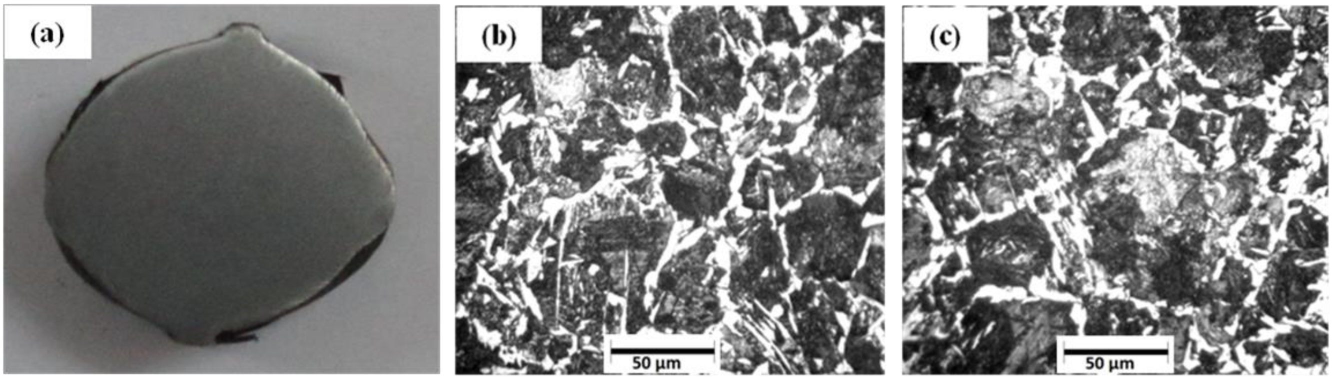

Fig. 6 (A) Macrostructure of Ordinary Hot Rolled Rebar; (B) and (C) Microstructure [Magnification: 200X] of Ordinary Hot Rolled Rebar

B. Evaluation of Impact Properties

The impact results for both steels showed typical ductile-to-brittle transition behaviour characteristic of ferritic steels giving a ductile to brittle transition temperature curve (DBTT curve). The variation of impact energy with testing temperature for both types of rebars is shown in Fig. 7. The curve represents a change in fracture behaviour from ductile at high temperature to brittle at lower temperature.

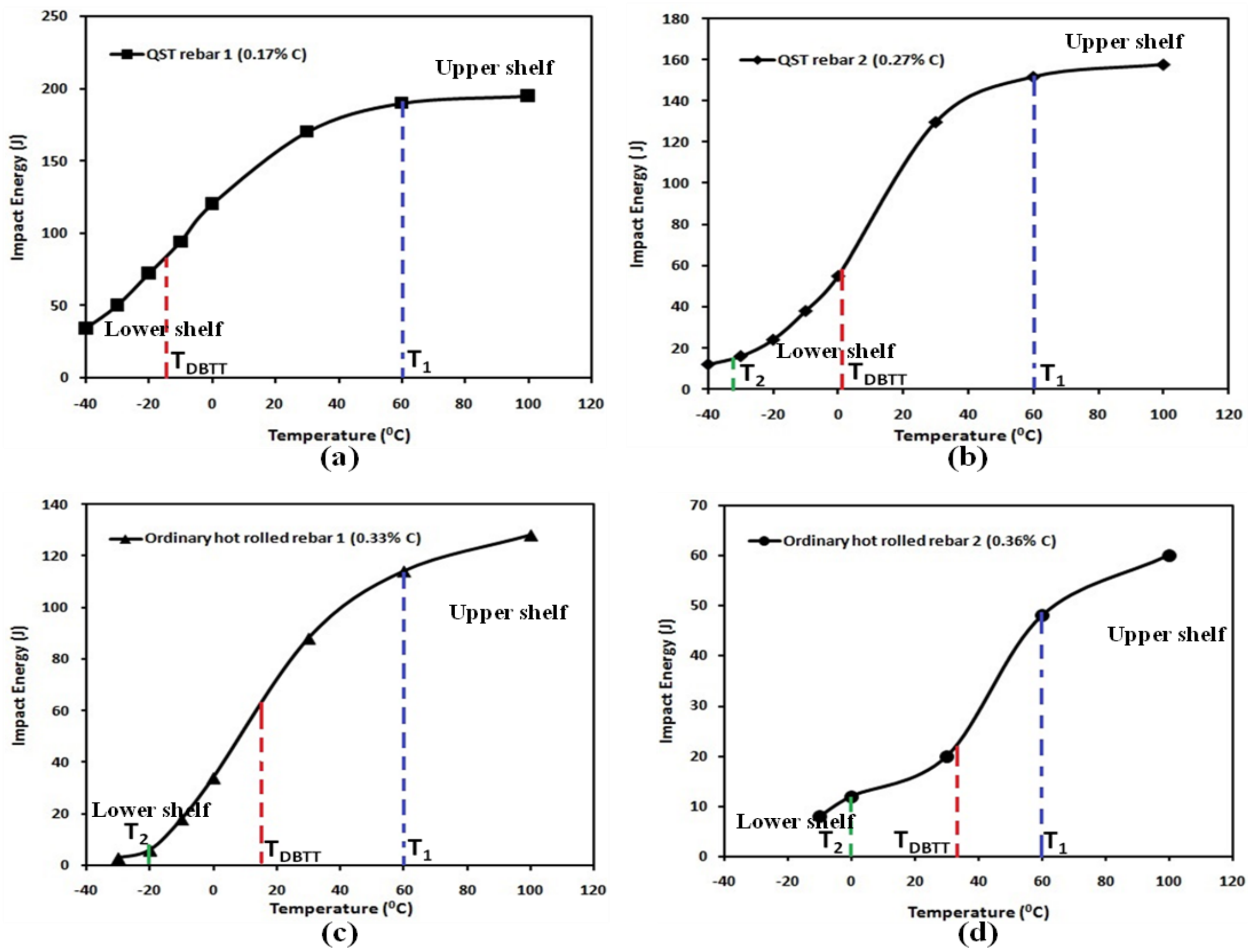

Fig. 7 DBTT Curves (A) QST Rebar 1, (B) QST Rebar 2, (C) Ordinary Hot Rolled Rebar 1, (D) Ordinary Hot Rolled Rebar 2

The temperature T_1 denotes transition temperature at which fracture is 100% ductile (fibrous). Temperature T_2 denotes temperature at which fracture is 100% brittle (cleavage). The temperature T_1 for all the rebars is 60^0C as seen in Fig. 7. On the contrary the temperature T_2 is different in all rebars. For the QST rebars, it can be said that 100% brittle fracture takes place below -20^0C as seen in Fig. 7(a) and 7(b). For the ordinary hot rolled rebar 100% brittle fracture takes place at and above -20^0C as seen in Fig. 7(c) and 7(d). T_{DBTT} is the ductile-to-brittle transition temperature determined at the average energy absorption of upper and lower shelves. The DBTT for QST rebars is the lowest with a temperature of -16^0C for QST rebar 1 and 5^0C for QST rebar 2 as shown in Fig. 7(a) and 7(b). The DBTT for ordinary hot rolled rebar is quite high with a temperature of 15^0C for ordinary hot rolled rebar 1 and 35^0C for ordinary hot rolled rebar 2 as seen in Fig. 7(c) and 7(d). Table II shows the impact test data for all the rebars.

Table II. Impact Test Values of QST and Traditional Hot Rolled Rebars

Temperature	-40^0C	-30^0C	-20^0C	-10^0C	0^0C	28^0C	60^0C	100^0C
Type of rebar	Impact energy (Joules)							
QST rebar 1	34	50	72	94	120	170	190	195
QST rebar 2	12	16	24	38	55	130	152	158
Ordinary hot rolled rebar 1	-	3	6	18	34	88	114	128
Ordinary hot rolled rebar 2	-	-	-	8	12	20	48	60

The QST rebars have much higher upper shelf energy (USE) than that of the ordinary hot rolled rebars as seen from Table II. The average upper shelf energy of QST rebars is almost twice that of the ordinary hot rolled rebars. The QST rebars also have higher lower shelf energy (LSE) than ordinary hot rolled rebars. The average LSE of QST rebars is above four times than that of ordinary hot rolled rebars. This indicates that QST rebars have superior resistance to ductile fracture and relatively better resistance to brittle fracture than ordinary hot rolled rebars. The results have shown that the low alloy QST rebars with its composite microstructure exhibits higher resistance to both ductile and brittle fracture than the ordinary hot rolled rebar with its ferritic-pearlitic microstructure. This difference in fracture behavior between these two investigated rebars can be related to the difference in their chemical composition and microstructure. The main microstructural parameters that would control the fracture properties of both steels are second phase particles (carbides and inclusions) and grain size. The higher upper shelf energy value of the low alloy QST rebars compared to that of the ordinary hot rolled rebars from Table II indicates higher energy expenditure during ductile crack initiation and propagation processes. As shown in Table I, the carbon content of the ordinary hot rolled rebars is twice as much as that of the QST rebars. Carbon and Sulphur have been known to have detrimental effect on toughness of steels through formation of carbides and inclusions. An increase in %C results in the transition occurring over wider temperature ranges [9] as is evident from Fig. 7(c) and 7(d) for ordinary hot rolled rebars. Since the ordinary hot rolled rebars contain higher carbon content than the QST rebars, it is then expected that it will form higher amount of carbide particles. The type of carbides formed in the hot rolled carbon steel is expected to be cementite (Fe_3C) which is incorporated in the pearlite structure. The cementite carbide particles would provide sites for easy nucleation of voids through cracking of these particles [10]. Compared to ordinary hot rolled rebars, the QST rebars showed lower ductile to brittle transition temperature. Furthermore, temperature T_2, was lower for QST rebars than ordinary hot rolled rebars. The smaller grain size of the QST rebars proposes higher resistance to cleavage brittle fracture since grain boundaries are effective barriers to the propagation of brittle cracks [11]. Reducing grain size shifts the DBTT curve to the left provides a wider range of service temperatures.

IV. Conclusion

At high test temperatures, the QST rebars exhibit much higher resistance to ductile fracture than the ordinary hot rolled rebars. At low test temperatures, the resistance to brittle fracture of QST rebars is only slightly higher than ordinary hot rolled rebars. The ductile-to-brittle transition temperature of QST rebars is lower than ordinary hot rolled rebars. The impact toughness of QST rebars is much higher than ordinary hot rolled rebars. This high toughness can be attributed to the composition and composite microstructure of the QST rebars. Owing to the THERMEX technology, QST rebars have fine grained structure and low amount of alloying elements which increase its impact toughness by several factors. Due to the slow cooling of ordinary hot rolled rebars i.e. normalization method; they develop coarse grained structure which lowers its impact toughness.

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