Weldability Characteristics of Torr and Corrosion-Resistant TMT Bars Using SMAW Process

Ramen Datta, R. Veeraraghavan, and K.L. Rohira

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Torr steel rebars, also known as cold twisted deformed (CTD) rebars, are used extensively for the construction of reinforced cement concrete (RCC) structures. These steels, which are characterized by a high carbon content and are subjected to a cold twisting operation to attain the desired strength level and bond strength, suffer from low ductility and poor bendability properties. Furthermore, these rebars are not suitable for coastal, humid, and industrial conditions where corrosion rates are very high. To combat these problems, recent efforts at the Steel Authority of India Limited (SAIL) have led to the successful development of corrosion-resistant thermomechanically treated (TMT) rebars with a minimum yield strength of 500 MPa. These rebars are characterized by a low carbon content, exhibit excellent strength-ductility-corrosion properties,[1] and are rapidly replacing traditional torr rebars in corrosion-prone areas for a wide range of applications, namely, concrete reinforcement structures, bridges, flyovers on dams, etc. A comprehensive evaluation of the weldability properties of corrosion-resistant Cu-TMT rebars was carried out, and they were compared with those made of torr steel in order to assess their suitability for various structural applications. Implant and restraint cracking (RC) tests were carried out to assess the cold-cracking resistance of the weld joint under different welding conditions. The static fatigue limit (SFL) values were found to be similar, namely, 640 MPa (torr steel) and 625 MPa (Cu-TMT steel) under condition of no preheating and no rebaking using a heat input of 7.5 KJ/cm, indicating adequate cold-cracking resistance for both the steels. Restraint cracking tests yielded critical restraint intensities (Kcr) in excess of 16,800 MPa for both of the steels. Based on the weldability tests, the optimized conditions for welding were formulated and extensive tests were carried out on the welded joints. Both of the steels exhibited adequate strength levels (tensile strength (TS): torr rebars, 524 Mpa; Cu-TMT rebars, 630 MPa) and adequate low-temperature impact toughness properties, ensuring a high integrity of the fabricated products.

Keywords cold cracking, shielded metal arc welding, thermomechanically treated rebars, torr steel, weldability

1. Introduction

The deterioration of concrete construction contributes greatly to the decay of infrastructural facilities such as bridges, dams, and flyovers, and accounts for the enormous rehabilitation costs incurred annually by the government of India. The majority of this damage is related to two major metallurgical phenomena, namely, corrosion and the weldability of the reinforcing steel embedded within the concrete. The severity of this problem has prompted worldwide attention to the design and development of steels with superior corrosion and weldability properties.[2]

The Steel Authority of India Limited (SAIL) has successfully developed a corrosion-resistant variety of rebar for the construction industry. This grade of steel, called Cu- thermomechanically treated (TMT), contains copper, which imparts adequate atmospheric corrosion resistance.[3-5] A high yield strength of 500 MPa and above is achieved through a state-of-the-art TMT process, in which the hot rebars emerging out of the final rolling stand are subjected to rapid on-line cooling through a series of water jackets. Direct water quenching results in the formation of martensite at the surface layers of the rebars, while the core remains austenitic. As the bar emerges from the quenching zone, the thermal gradient existing across the rebar section causes heat to flow from the hot austenitic core toward the rebar surface. This results in the tempering of the surface martensite, and an equalization of the surface and core temperatures takes place. Lower equalization temperatures result in higher yield strengths. During subsequent atmospheric cooling of the rebar on the cooling bed, the hot austenitic core gradually transforms to a ferrite-pearlite microstructure. This composite structure, in which the rim of the tempered martensite acts as the load-bearing constituent and the relatively soft ferrite-pearlite core provides the rebars with ductility and cold formability, helps in imparting superior mechanical properties to TMT rebars compared to the conventionally used torr steel rebars.

The weldability of a steel is related to its carbon equivalent (CE) and its position in the Graville diagram. The CE is determined by the carbon content and the CE of alloying elements (CEA) and is given as follows.[6]

$$CE = C + (Mn + Si)/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15 \quad \text{(Eq 1)}$$

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Graville[7] has classified a wide range of steels into three categories, namely, easy to weld, weldable, and difficult to weld, based on their carbon content and CE (Fig. 1). Steels having high carbon levels and high alloy content are highly susceptible to cracking and are categorized under zone III. Steels falling under zone II (moderate carbon level but low CE) are weldable, but only with certain basic precautions. A low-carbon steel (<0.13%) with low CE (<0.45) falls under zone I and ensures the highest safety to cracking under all welding conditions. Torr steel and Cu-TMT rebars having a carbon content of ~0.20% and a CE of 0.30-0.35 fall under zone II and need careful selection of welding parameters to ensure a defect-free weld joint.

The present study was conducted to assess the weldability properties of indigenously developed Cu-TMT rebars and to compare them with the traditionally used torr cold twisted deformed (CTD) rebars using the Shielded Metal Arc Welding (SMAW) process. This article discusses the results obtained and its influence on the application of these rebars for conventional construction applications. Based on these results, the safe welding procedures for these steels were formulated.

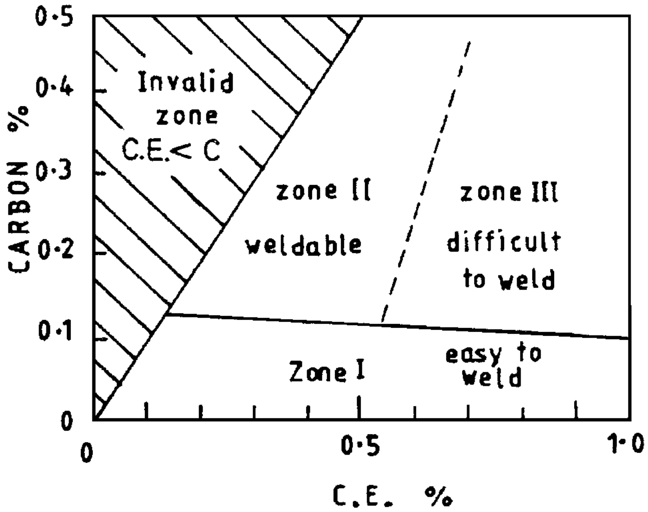

Fig. 1 Weldability assessment of steels using the Graville diagram

2. Experimental

2.1 Material Composition and Properties

The starting material used for the present study was 20 mm diameter rebars of torr and Cu-TMT steels. The chemical composition and typical mechanical properties of the two steels are presented in Table 1. It may be noted that despite the similar C and Mn levels, the strength and Charpy impact energy (CIE) values of the Cu-TMT rebars are substantially higher than those of torr steel rebars. To ensure good weldability, the CE levels of the two grades were restricted to 0.31 and 0.35, respectively. This is well below 0.55%, which is prescribed as the upper limit for such rebars in ASTM A706/706M–90, which relates to the "Standard Specification for Low Alloy Steel Deformed Bars and Concrete Reinforcement," from the American Society for Testing of Materials.

Table 1 Chemical Composition and Mechanical Properties of Torr and Cu-TMT Rebars (a)

	Chemical Composition, wt.%						
	C	Mn	Si	S	P	Cu	CE
Chemical composition							
Torr	0.21	0.56	0.05	0.033	0.03	…	0.31
Cu-TMT	0.18	0.90	0.06	0.04	0.03	0.20	0.35

				CIE, J	
	YS, MPa	TS, MPa	% EL, $5.65\sqrt{Ao}$*	RT	0 °C
Mechanical properties					
Torr	423	523	28.0	117	7.8
Cu-TMT	519	624	26.0	165	156.0

(a) Ao: cross-sectional area of the test piece; Ys: yield strength.

2.2 Metallography and Property Evaluation

Optical microscopy was carried out using an MeF_2 model microscope (Reichert, Austria). The longitudinal sections of weld joints were polished and etched with 2% nital. Tensile samples were prepared as per the ASTM 10 (PA-370) specification and were tested on a 10 ton static universal testing machine (Instron-1195 model, Instron Ltd, High Wycombe, Buckinghamshire, UK) at a strain rate of 6.6×10^{-4}/s. Standard Charpy V-notch samples were prepared and tested at room temperature (RT) and at 0 °C. An average of two tests was taken to calculate the tensile properties, and three tests to calculate the CIE at a given test temperature.

2.3 Weldability Evaluation

The cold cracking susceptibility was determined by an implant test using the SMAW process. The implant test was originally proposed by Granjon.[8] The standard procedure for conducting the test has been outlined by International Institute of Welding (IIW) in 1973.[9] Essentially, it is a constant load rupture test of a real heat-affected zone (HAZ) immediately after welding, in which the combined effect of diffusible hydrogen, the hardening of the HAZ due to the weld thermal cycle, and the residual stress developed due to welding on cold-cracking susceptibility is studied. The implant specimen is a 6 mm diameter cylindrical test piece with a circular notch. The notch is positioned such that it is located in the HAZ to maximize the sensitivity of the test. In this test, one end of the specimen was inserted with a sliding fit into a hole bored into a plate called the "host plate." The other end of the specimen was threaded to facilitate the application of the load through a loading bar. A weld bead was laid under conditions of investigation on the host plate across the implant specimen. The set-up was allowed to cool to a preselected temperature, usually 100 °C, before the application of a static tensile load through a constant load system until failure occurred or the lapse of 24 h, whichever was earlier. The maximum stress that the material could withstand without failure was determined by testing at different stress levels. This critical stress level for cracking is known as the static fatigue limit (SFL).

In the restraint-cracking test, a set of restraining devices were employed to impose different levels of restraint intensity (*K*) values on a cylindrical bar material. The cracking tendency increased with an increase in the *K* values of the assembly. Weld cracking occurred for a specified welding condition when the *K* value increased to a critical level called the critical restraint intensity (Kcr). It is recommended that for safe structural applications, the Kcr value should be higher than the actual *K* values observed for different structural applications. Table 2 provides a list of restraint levels for various applications.

3. Results and Discussion

3.1 Implant Test

The implant test results for torr and Cu-TMT rebars are presented in Table 3. The SFL values obtained for torr steel using AWS-E7018 electrodes without preheating or baking of electrodes were found to be 640 and 644 MPa for heat inputs of 7.5 and 10.5 KJ/cm, respectively. The SFL values are well in excess of the minimum specified yield strength (MSYS) of 415 MPa, indicating adequate resistance to cold cracking. A typical plot for determining the SFL values for the above steel using a heat input of 7.5 KJ/cm is shown in Fig. 2. It may be noted that the SFL values are based on a series of tests at different stress levels, with the symbol (■) indicating failure and the symbol (♦) representing success (i.e., no failure).

The type of heat flow encountered for the implant tests and butt welding of the bars for the chosen heat input (7.5 and 10.5 KJ/cm) using the SMAW process corresponds to three-dimensional (3D) flow. Based on 3D heat flow conditions, the cooling time from 800–500 °C ($\Delta t_{8/5}$) for heat inputs of 7.5 and 10.5 KJ/cm were estimated to be 3 and 4 s, respectively. Despite the high cooling rate associated with the weld thermal cycle, the steel was not susceptible to cold cracking for the welding conditions investigated.

The implant test results for Cu-TMT rebars are presented in Table 3. The SFL values using AWS-E 8018 W electrodes without preheating and rebaking were determined to be 625 and 618 Mpa, respectively, for heat inputs of 7.5 and 10.5 KJ/cm. The above values (625 and 618 MPa) are well above the MSYS (500 MPa), indicating adequate cold-cracking resistance. It was concluded that the weld joints of both the steels (i.e., torr and Cu-TMT) possess adequate strength and integrity even under high hydrogen level (i.e., no rebaking) welding conditions.

3.2 Restraint Cracking

The sensitivity of cracking of the root layer in butt welding was tested by imposing different levels of restraint intensities, varying between 7700 and 16 800 MPa. The welding conditions used and the results obtained for torr and Cu-TMT rebars are shown in Table 4. Figure 3 shows the photomacrograph of a torr steel restraint specimen exhibiting a sound weld joint at a restraint intensity of 16 800 MPa. A critical restraint intensity in excess of 16 800 MPa was achieved for both the steels without preheating and rebaking (high hydrogen level) conditions, which is considered to be safe for most end applications (see Table 2).

Table 2 Restraint Intensities for Different Structural Applications

Application	Location	Thickness, mm	*K*, MPa
Ship	Transverse bulk head	16	16 400
	Longitudinal bulk head	14	12 600
	Bottom shell	28	7 800
	Upper deck	32	12 800
Bridge	Diaphragm and web plate	19–38	2 000
	Diaphragm and flange plate	40–60	18 000
Building frame	Beam-column construction	28	10 900

Table 3 SFL Values Obtained Under Different Welding Conditions for Torr and Cu-TMT Steel

			Welding condition, °C			
Grade	Electrode	Electrodes diameter, mm	Rebake	Preheat	Heat input, KJ/cm	SFL, MPa
Torr	E7108	2.5	Nil	Nil	7.5	640
	SFA 5.1	3.15	Nil	Nil	10.5	644
Cu-TMT	E8018W	2.5	Nil	Nil	7.5	625
	SFA5.5	3.15	Nil	Nil	10.5	618

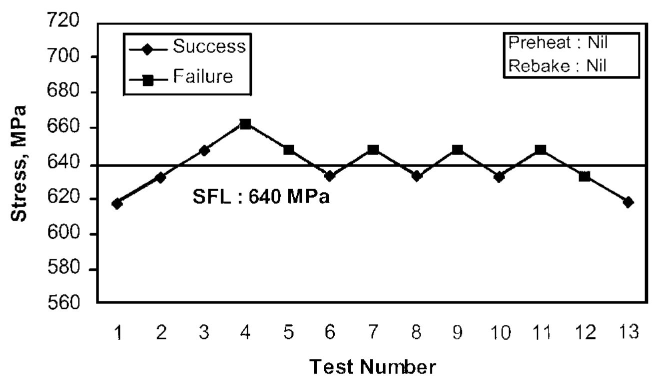

Fig. 2 SFL plot for torr steel at a heat input level of 7.5 KJ/cm

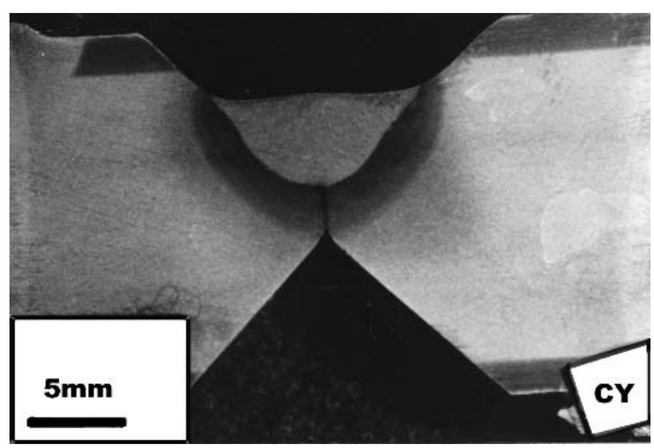

Fig. 3 Macrophotograph of a sound weld joint for torr steel obtained at a restraint intensity of 16 800 MPa

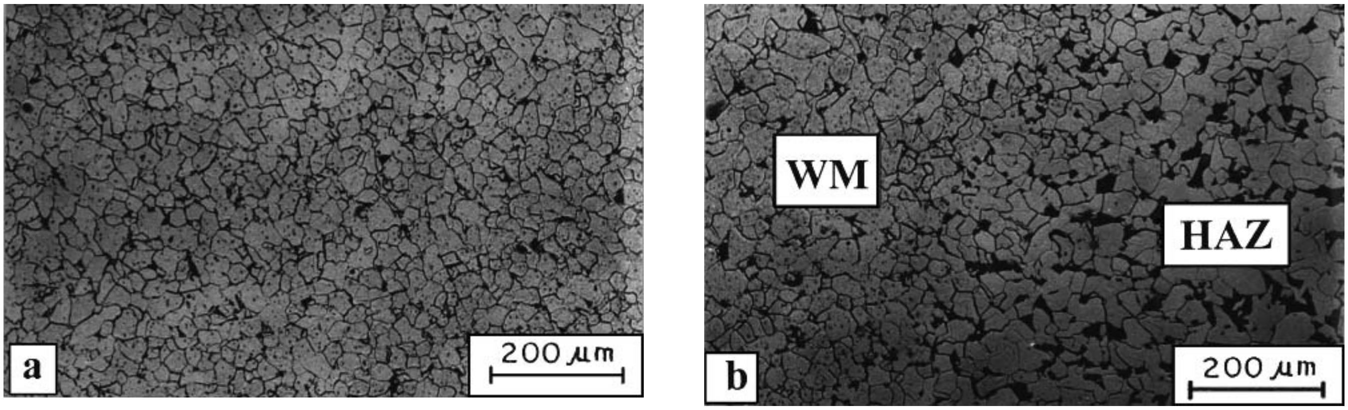

Fig. 4 Optical photomicrographs of WM and HAZ for torr steel exhibiting (**a**) a refined ferrite-pearlite structure and (**b**) a coarse ferrite-pearlite structure with a higher volume fraction of pearlite

Table 4 Restraint Cracking Test Results for Torr Steel and Cu-TMT Rebars (a)

			Torr		Cu-TMT	
Serial No.	Restraint Length, mm	Restraint Intensity, MPa	LPI and MPI	Macroexamination of 3 Sections	LPI and MPI	Macroexamination of 3 Sections
1	150	7 700	NSD	No cracks	NSD	No cracks
2	100	10 500	NSD	No cracks	NSD	No cracks
3	75	13 700	NSD	No cracks	NSD	No cracks
4	50	16 800	NSD	No cracks	NSD	No cracks

(a) NSD: no significant defects. Bar diameter, 20 mm; preheat, Nil; rebake, Nil; heat input, 7.5 KJ/cm.

3.3 Weld Joint Properties

Based on the weldability test results, the butt welding procedure and welding conditions chosen for torr steel were as follows: rebake, nil; preheat, nil; interpass temperature, 250 °C max; number of passes, 11; heat input, 7.1-18 KJ/cm; and welding speed, 120-150 mm/min. Butt welding was carried out, and the weld joint was subjected to extensive tests to characterize the microstructure and mechanical properties.

Optical photomicrographs of the weld metal and HAZ for the torr steel are shown in Fig. 4(a) and (b). While the weld metal exhibited a refined polygonal ferrite-pearlite structure, the HAZ revealed a transition to a coarse ferrite pearlite structure with a higher volume fraction of pearlite (Fig. 4b). A macroexamination of the weld joint revealed no significant defects (Fig. 5). Various tests were conducted to characterize the weld joint properties. The transverse tensile strength of the weld joint was 524 MPa, which is comparable to the typical strength level of the parent metal (523 Mpa; Table 1B) and higher than the minimum specified tensile strength (MSTS) of 485 MPa. The Charpy impact test results at RT and 0 °C are presented in Fig. 6. The CIE levels for the weld metal (WM) and HAZ were superior to that of the parent metal (PM) at 25 and 0 °C, indicating adequate soundness of the weld joint. This also means that the PM is the likely zone for crack initiation and propagation. Furthermore, the sharp drop in the CIE for the PM from 117 J at 25 °C–7.8 J at 0 °C reflects a high ductile-brittle transition temperature in the temperature range of 25-0 °C. Figure 7 represents the hardness profile across the PM, HAZ, and WM. The hardness measured with a 10 kg load varied within a range of 146-236 hardness in Vickers scale (HV). The hardness ranges of PM, WM, and HAZ were as follows: PM, 187-230; HAZ, 194-236; and WM, 146-186. A higher hardness level in the PM and HAZ may be attributed to a higher volume fraction of pearlite compared to the WM. It also indicates lower impact toughness values for the PM and HAZ, which agrees very well with the impact test results described earlier.

Based on the above test results, it was concluded that the weld joint possessed satisfactory internal soundness, strength, and toughness properties and that it conformed to the stipulated requirements of Indian Standard (IS): 1786/85 specification (yield strength (YS), 415 MPa minimum; Elongation (El), 14.5% minimum). However, the poor impact toughness properties of the torr rebars (PM) at 0 °C make the steel susceptible to brittle failure in cold climatic regions where the temperature dips below 0 °C.

The welding conditions and parameters chosen for Cu-TMT rebars were as follows: rebake, nil; preheat, nil; number of passes, 7; interpass temperature, 250 °C maximum; heat input, 7.5–18.6 KJ/cm; and welding speed, 120–150 mm/min. Nondestructive tests (liquid penetrant inspection (LPI), magnetic particle inspection (MPI), and radiography) indicated no significant defects in the weld joint. Microstructural studies of the weld metal and the HAZ were carried out. The weld metal exhibited a typical polygonal ferrite-pearlite structure, while the HAZ revealed a predominantly Widmanstatten ferrite structure with small amount of bainite (Fig. 8). A macroexamination of the weld joint revealed no evidence of cracks. The weld joint was subjected to various mechanical tests to establish its properties. The transverse tensile strength of the weld joint was

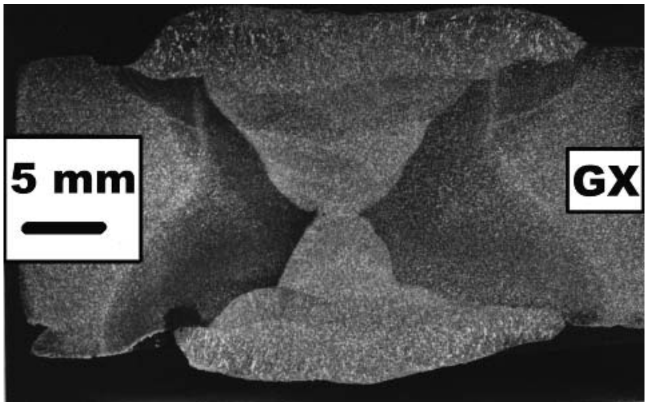

Fig. 5 Macrophotograph of torr steel weld joint revealing no cracks

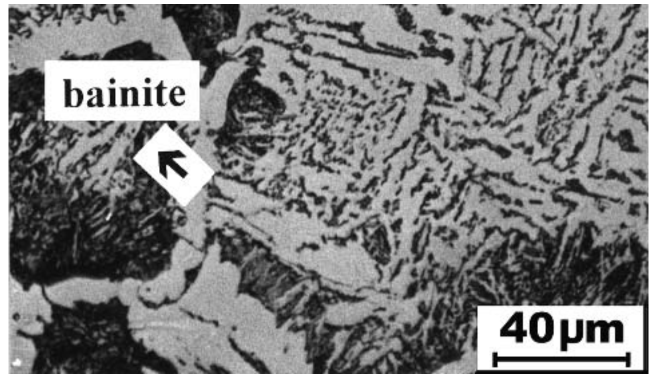

Fig. 8 Optical micrograph of HAZ for Cu-TMT rebars revealing a Widmanstatten ferrite structure with small amounts of bainite

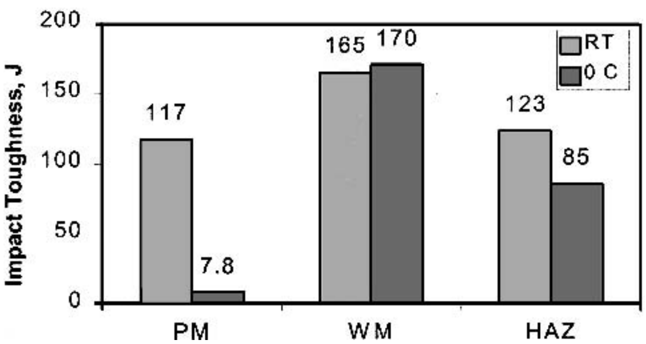

Fig. 6 CIE values of PM, WM, and HAZ at RT and 0 °C for Cu-TMT rebars

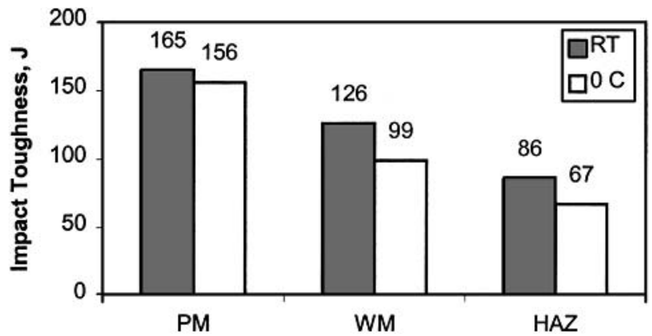

Fig. 9 CIE values of PM, WM, and HAZ at RT and 0 °C for Cu-TMT rebars

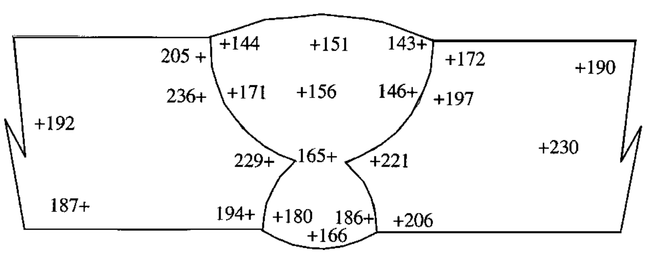

Fig. 7 Hardness profile across the weld joint for torr steel

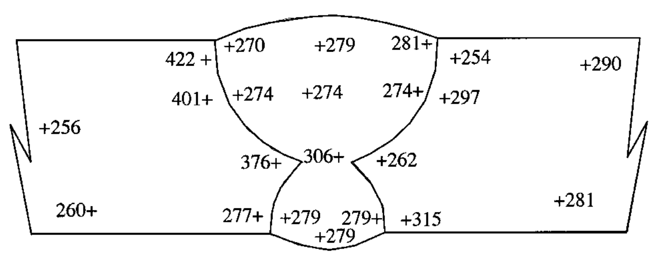

Fig. 10 Hardness profile across the weld joint for a Cu-TMT steel

determined to be 600 MPa, which is well above the MSTS of 580 MPa. Figure 9 shows that the Charpy impact properties of the PM for the Cu-TMT rebars were significantly higher than those of WM and HAZ, both at 25 and 0 °C. However, it may be noted that the CIE values of all three constituents (i.e., PM, WM, and HAZ) are adequate both at 25 and 0 °C, indicating good resistance to brittle failure. Figure 10 represents the hardness profile across the PM, HAZ, and WM. The hardness varied within a range of 256-422 HV, which is significantly higher than the hardness values obtained for torr steel (146-236 HV). The hardness range of the three constituents were as follows: PM, 256-290 HV; HAZ, 262-422 HV; and WM, 270-306 HV. The hardness of the PM and WM are similar, which is desirable. However, the hardness level of the HAZ is significantly higher in one or two locations (401 and 422 HV). This may be attributed to the localized formation of bainite, as is evident in Fig. 8.

Based on the above tests, it was concluded that the Cu-TMT weld joint possessed satisfactory internal soundness, strength, and toughness properties. It was also established that the weld joint met all the requirements and that the weld procedure that had evolved was adequate and satisfactory.

3.4 Weld Joint Configurations

The welding of torr and Cu-TMT rebars for construction applications requires different joint configurations depending on the rebar diameter and welding process employed. Five weld joint configurations, namely, single lap joint, double lap joint, cruciform joint, socket joint, and bar-to-plate joint, were

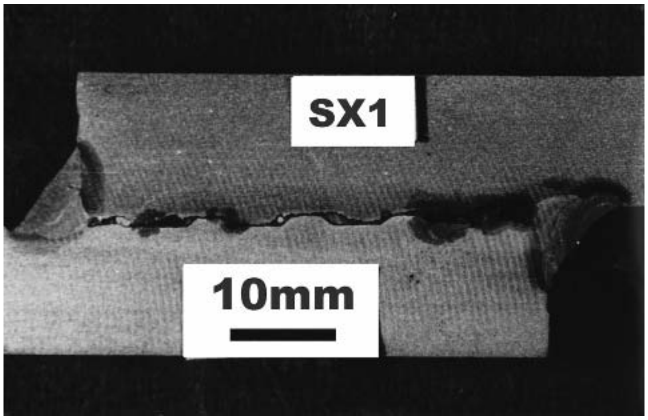

Fig. 11 Transverse section of a single lap joint for torr steel rebars

tried using the SMAW process. The welding of the bars was performed under conditions similar to those normally followed during fabrication. Figure 11 shows the transverse section of a typical single lap joint made using torr steel rebars. Figure 12 similarly shows the transverse section of a bar-to-plate joint for Cu-TMT rebars. The results of tensile shear tests carried out on the five weld joint types are presented in Table 5. All five weld joints meet the MSTS levels of 485 MPa for torr rebars and 580 MPa for Cu-TMT rebars.

It is evident, on the basis of the various tests conducted in the present study, that the weld joints for torr and Cu-TMT rebars possess the requisite internal soundness and exhibit an adequate combination of strength and toughness properties. Despite the higher strength level exhibited by the Cu-TMT rebars, the associated toughness properties are on par with those of torr rebars. Based on the above results, it may be concluded that welding procedures that have evolved for the two grades of steel are adequate.

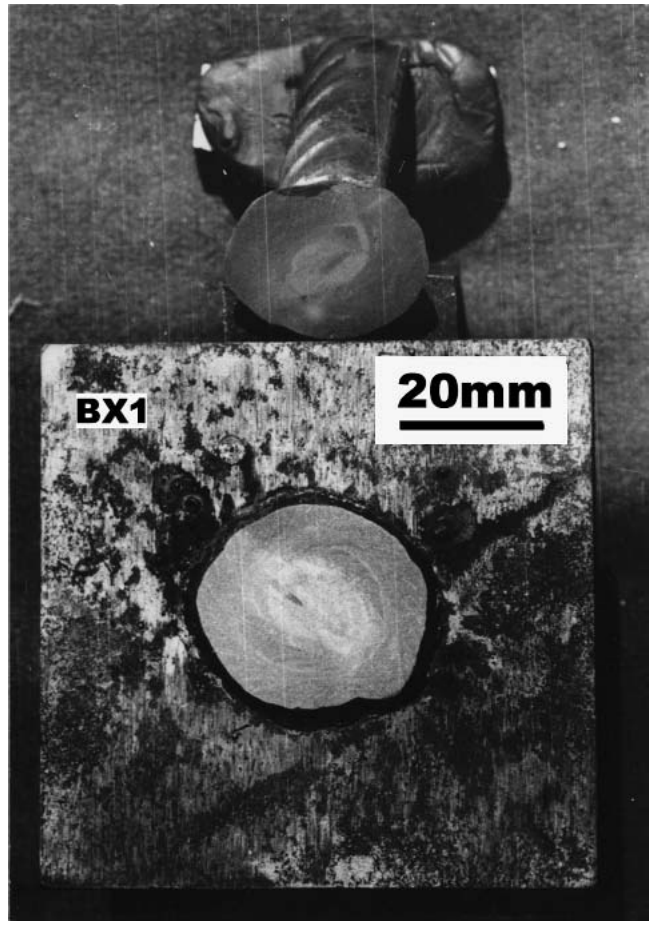

Fig. 12 Photograph showing a transverse section of a bar-to-plate joint for Cu-TMT rebars

Table 5 Tensile Shear Test Results for Torr and Cu-TMT Rebars Using Five Weld Joint Configurations (a)

	TS, MPa		Position of Fracture	
Type of Joint	**Torr**	**Cu-TMT**	**Torr**	**Cu-TMT**
Single lap	521.0	659.2	HAZ	HAZ
Double lap	622.0	800.5	PM	HAZ
Cruciform joint	575.8	693.5	PM	PM
Socket joint	805.4	848.5	PM	PM
Bar-to-plate joint	570.9	715.1	PM	PM

(a) Welding conditions: preheat, nil; rebake, 350 °C for 2 h; heat input, 7.5 KJ/cm.

4. Conclusions

- Implant tests using the SMAW process yielded good cold-cracking resistance for torr and Cu-TMT rebars without preheating and rebaking (i.e., high hydrogen levels). The SFL values obtained were 640 and 644 MPa for torr steel and 625 and 618 MPa for Cu-TMT steel using heat input levels of 7.5 and 10.5 KJ/cm, respectively.
- The Kcr was found to be in excess of 16 800 MPa for torr and Cu-TMT rebars without preheating and rebaking. This is considered to be adequate for normal restraint levels in construction.
- The weld metal exhibited a fine polygonal ferrite-pearlite structure for the torr steel rebars. The HAZ revealed a coarse ferrite-pearlite structure with a higher volume fraction of pearlite. The weld joint exhibited adequate strength (TS, 524 MPa) and impact toughness properties (CIE at 0 °C: WM, 170 J; HAZ, 85 J). The toughness value of the parent metal, however, recorded a sharp drop from 117 J at 25 °C–7.8 J at 0 °C, reflecting a high ductile-brittle transition temperature.
- The microstructural evaluation of the Cu-TMT rebars revealed polygonal ferrite-pearlite and Widmanstatten ferrite-bainite structures for the WM and HAZ, respectively. The transverse tensile strength (600 MPa) of the weld joint was found to be higher than the MSTS (580 MPa). The impact toughness properties of the WM and HAZ (CIE, 99 and 67 J, respectively, at 0 °C) were relatively lower than those of PM (CIE, 156 J at 0 °C). However, even the lowest CIE observed (67 J at 0 °C) is considered to be adequate for most end applications.
- The results of tensile shear conducted on torr and Cu-TMT rebars using five commonly used joint configurations

showed that the weld joints possess adequate internal soundness and meet the MSTS requirements of 485 and 580 Mpa, respectively.

Acknowledgments

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References

1. S.A. Madatyan: *Steel USSR*, 1991, *21*(7), pp. 322-25.
2. G. Thomas: *Trans. IIM*, 1996, *49*(3), pp. 127-32.
3. S.L. Chawla and R.K. Gupta: *Material Selection for Corrosion Control*, ASM International, Materials Park, OH, 1993, pp.-29-63.
4. W.K. Boyd and F.W. Fink: "MCIC Report No. 74-23," Battele Columbus Laboratories, Columbus, OH, 1974, pp. 1-77.
5. A. Ray, D. Mukerjee, S.K. Sen, A. Bhattacharya, S.K. Dhua, M.S. Prasad, N. Banerjee, A.M. Popli, and A.K. Sahu: *J. Mater. Eng. Performance*, 1997, *6*(3), pp. 335-43.
6. F.N. Williams: *Welding J.*, 1995, *74*, 1995, p. 57.
7. B.A. Graville: *Proceedings of the International Conference on Welding of HSLA Structural Steels*, A.B. Rothwell and J.M. Gray, ed., ASM, Materials Park, OH, 1978, p. 85.
8. H. Granjon: "Soudage et Techniques Connexes," Report 22 (3/4) 1968 and IIW Doc.-1X 584-68, 1968.
9. Anon.: International Institute of Welding (IIW) document, 1993, pp. 830-73.