Study on notch tensile properties of Magnetically Impelled Arc Butt (MIAB) welded carbon steel tubes

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Abstract: Magnetically Impelled Arc Butt (MIAB) welding is a pressure welding process that uses the circumferential rotating arc to cause uniform heating of the faying surfaces. In this work, notched tensile testing of MIAB welded Carbon steel was carried out to determine the notch sensitivity of Thermo-Mechanically Affected Zones (TMAZ) and to compare the notch tensile property of these zones with the base metal property. In MIAB welding, after sufficient melting of the faying surface, a short pulse of high current is applied to expel the molten metal and impurities from the interface before welding. Insufficient expulsion and formation of Light Band (LB) zone at the weld interface resulted in lower Notch Tensile Strength (NTS). Incomplete expulsion with lower upset current at the weld interface contributes to lower Normalized Notch Strength Ratio. Instead, higher upset current contributed to higher NTS due to complete expulsion and stronger acicular ferrite formation. Other TMAZs away from the weld interface showed higher notch tensile strength with Notch Strength Ratio (NSR) and Normalized Notch Tensile Strength Ratio (NTS*) greater than unity.

Keywords: MIAB Welding, TMAZ, Carbon steel, Notch Tensile Strength, Notch Strength Ratio, Normalized Notch Strength Ratio.

1. Introduction
Magnetically Impelled Arc Butt (MIAB) Welding involves joining faying surfaces using a circumferential rotating electric arc and upset pressure [1,2]. Interaction of electric current and magnet field creates Lorentz force around the edges of faying surfaces aiding circumferential arc rotation [3,4]. Arc rotation plays a vital role in uniform heating and sufficient melting of the joining surface. After sufficient melting, the upset current applied ahead of upset pressure helps in removing the molten metal and joining happens between the plasticized metal at the interface [5].

Previous work on the characterization of the MIAB welded carbon steel reported the influence of welding parameters on the weld characteristics [6,7]. The upset current and arc rotation current significantly control the formation of the Light Band (LB) zone at the weld interface. The LB zone substantially affects...
the MIAB weld properties. With optimized welding parameters, MIAB weldments displayed higher joint efficiency with tougher microstructure without LB zone. In the un-notched tensile testing, the tensile properties of all Thermo-Mechanically Affected Zones (TMAZ) were not known as the specimen fails either at the base metal or the weld interface. To determine the tensile properties of all TMAZs, notched tension tests were carried out with the notch at the specific location of the TMAZ. In correlation to un-notched tensile testing, the LB zone had a similar effect on the Notch Tensile Strength (NTS) of the weld interface.

2. Materials and methods
Carbon steels tubes containing 0.27 wt% C was chosen for MIAB welding. Carbon steel had yield strength of 252 MPa, tensile strength of 455 MPa and hardness of 155 HV at 100g load. Steel tubes with 44 mm outer diameter and 4.5 mm thickness were used for MIAB welding trials. MIAB welding was carried out using a hydraulic MIAB welding machine available at Welding Research Institute, BHEL, Tiruchirappalli, India. MIAB welding trials were carried out in four stages with varying welding current and time intervals [8, 9]. Table 1 shows the MIAB welding trials for the carbon steel tubes. Arc rotation current, arc rotation time and upset current were varied in two levels. For all welding trials, the arc gap was maintained as 2 mm. After the application of upset current, upset pressure of 16 MPa was applied at the interface to cause solid-state bonding of faying surfaces.

Table 1. MIAB welding trials

| Sample ID | Arc initiation | Arc stabilization | Arc rotation | Upsetting |
|-----------|----------------|------------------|--------------|-----------|
|           | I1 (A) | t1 (s) | I2 (A) | t2 (s) | I3 (A) | t3 (s) | I4 (A) | t4 (s) |
| S/1       | 300    | 1      | 300    | 6      | 310    | 12     | 1000    | 0.3    |
| S/2       | 300    | 1      | 300    | 6      | 280    | 12     | 1000    | 0.3    |
| S/3       | 300    | 1      | 300    | 6      | 280    | 8      | 1000    | 0.3    |
| S/4       | 300    | 1      | 300    | 6      | 310    | 8      | 1000    | 0.3    |
| S/5       | 300    | 1      | 300    | 6      | 280    | 8      | 600     | 0.3    |
| S/6       | 300    | 1      | 300    | 6      | 310    | 8      | 600     | 0.3    |
| S/7       | 300    | 1      | 300    | 6      | 280    | 12     | 600     | 0.3    |
| S/8       | 300    | 1      | 300    | 6      | 310    | 12     | 600     | 0.3    |

The tensile test specimen with a double 'V' notch of 2 mm depth was used for the notched tension test. Using hardness analysis, the location of all TMAZs from the weld interface to base metal was determined and the notched tensile test was carried out with the notch at the required location of TMAZ. After testing, the samples were characterized with an optical microscope and scanning electron microscope for microstructural analysis and fractographic studies. 2% Nital solution was used as an etchant for microstructural characterization.

3. Results

3.1 Hardness testing of MIAB weldments
Variation in weld thermal cycle from the weld interface to unaffected base metal resulted in the formation of three distinct TMAZs (Figure 1). The zone along the weld interface is TMAZ I. Next to TMAZ I, two other adjoining TMAZs namely TMAZ II and TMAZ III were observed with decreasing peak temperature towards base metal. High strength acicular ferrite morphology along with pearlitic structure at the weld interface (TMAZ I) in samples with higher upset current (Sample S/1) displayed higher weld hardness. The presence of decarburized LB zone at the weld interface with a lower upset current (Sample S/8) exhibited lower weld hardness. The coarse-grained ferritic structure indicating loss of carbon from weld interface was evident in the optical micrograph. In all weldments, irrespective of upset current and...
other welding parameters, a similar microstructure with marginal variation in hardness was seen at TMAZ II and TMAZ III (Figure 2). Polygonal ferrite and pearlite with varying grain structures at TMAZ II and TMAZ III displayed higher hardness than unaffected base alloy.

Figure 1. Transverse hardness analysis result for sample S/1 and S/8 along with optical micrograph of TMAZ I

Figure 2. Hardness data for all samples at TMAZ I, TMAZ II and TMAZ III

3.2 Weld interface notched tension test results
The tension test of MIAB weldments was carried out with a notch at the weld interface to determine Notch Tensile Strength (NTS) of TMAZ I. Table 2 shows notched tension test results. All notched tensile test specimens failed at the weld interface (Figure 3); hence the determined Ultimate Tensile Strength (UTS) represents the NTS of the TMAZ I. In correlation with hardness analysis, samples made with the higher upset current displayed higher NTS. With a higher upset current, the weld zone contains acicular ferrite and pearlite, leading to its strengthening [10]. With a lower upset current, the weld interface displayed lower NTS owing to LB zone formation.
For comparing the notch tensile properties, two parameters such as Notch Strength Ratio (NSR) and Normalized Notch Strength (NTS$^N$) ratio were determined from the NTS data. The NSR of TMAZ I is the ratio between its NTS to UTS value. Upon strengthening, samples made with the higher upset current failed in the base metal zone during the un-notched tension test. Hence the UTS of weld interface was not known for such samples. UTS of the base alloy was used for NSR calculation as it represents the lower limit value of UTS for TMAZ I [11]. For all samples, the calculated NSR value was greater than unity. This indicates TMAZ I of all MIAB weldments are "Notch-ductile" in nature. However, the formation of the LB zone reduced the weld NTS than that of base metal. Percentage increase or decrease in NTS at par with base metal was determined using the NTS$^N$ ratio, a ratio between weld NTS to base metal NTS. Base metal NTS is 610 MPa. About 10% loss in NTS was recorded in samples made with the lower upset current. Conversely, the samples made with a higher upset current displayed about 20% higher NTS value than that of base metal NTS.

Table 2. Notched tension test results for MIAB welded carbon steel tubes

| Sample Identification | Ultimate Tensile Strength (MPa) (Fracture location) | Notch tensile strength NTS (MPa) | Notch Strength Ratio (NSR) | Normalized notch tensile strength ratio (NTS$^N$) |
|-----------------------|---------------------------------------------------|-------------------------------|---------------------------|---------------------------------|
| S/1                   | 455(BM)                                           | 729                           | 1.60                       | 1.20                             |
| S/2                   | 455(BM)                                           | 723                           | 1.59                       | 1.19                             |
| S/3                   | 455(BM)                                           | 717                           | 1.58                       | 1.18                             |
| S/4                   | 455(BM)                                           | 720                           | 1.58                       | 1.18                             |
| S/5                   | 409(WI)                                           | 568                           | 1.38                       | 0.93                             |
| S/6                   | 385(WI)                                           | 572                           | 1.49                       | 0.94                             |
| S/7                   | 455(BM)                                           | 619                           | 1.36                       | 1.01                             |
| S/8                   | 315(WI)                                           | 555                           | 1.76                       | 0.91                             |

3.3 Notch tensile properties of other TMAZs
To determine the notch tensile properties of other TMAZs presents in the weldment, the notched tension test was conducted with notch positioned at the specific TMAZs. The position of TMAZs from the weld interface was determined using a hardness curve. Figure 1 shows the hardness curve of sample S/1. TMAZ I, TMAZ II, TMAZ III and base metal were located at 0 mm, 2.5 mm, 4 mm and 6 mm from the weld centerline respectively. Double-end 'V' notch was made at respective locations to determine their notch
tensile properties. Notched tension test data are given in Table 3. Among all TMAZs, TMAZ I displayed the highest NTS. TMAZ III containing fine-grained ferrite and pearlite grains showed a higher NTS value than TMAZ II. All zones exhibited an NSR value greater than unity. Hence all zones of MIAB weldments displayed notch ductility. NTSN of all TMAZs also exhibited value greater than unity. From the NTSN value, it is evident that there was no loss in notch strength in any of the TMAZs compared to the base metal. The microstructure at the fractured surface confirmed the region of failure in each tension test sample. SEM micrographs of all TMAZs and base metal showed the ductile type of fracture with dimples due to micro void coalescence.

### Table 3. Notched tension test data for all zones in sample S/1

| Notch Location | NTS (MPa) | NSR | NTSN |
|----------------|-----------|-----|------|
| TMAZ I         | 729       | 1.60| 1.20 |
| TMAZ II        | 658       | 1.45| 1.08 |
| TMAZ III       | 715       | 1.57| 1.17 |
| Base metal     | 610       | 1.34| 1    |

### 4. Discussion

#### 4.1 Analysis of Hardness Test Results

The change in welding parameter had an appreciable variation in hardness at the weld interface (TMAZ I) than other TMAZs. TMAZ I hardness was used as a response parameter to analyse the effect of the welding parameter. Among the chosen welding parameters, upset current exhibited a substantial effect on weld hardness. Figure 4 shows the influence of the welding parameters on the hardness of TMAZ I. Upset current influenced the formation of microstructure at the weld zone. During the last stage of MIAB welding, the upset current was applied to aid the expulsion of the liquid metal from the faying surfaces. Samples made with the higher upset current contain acicular ferrite and pearlite at TMAZ I.

![Figure 4. Interaction effect of welding variables on weld interface hardness](image)

On the other hand, there was an incomplete expulsion at the weld zone in samples made with the lower upset current. Such samples displayed lower weld hardness as they contain decarburized microstructure known as Light Band zone [6,7,12]. The LB zone had a coarse polygonal ferritic structure due to loss in carbon at the interface. With lower upset current, a marginal increase in hardness was observed with lower arc rotation current and higher arc rotation time. This is due to the development of more plasticized metal which aids in metal expulsion at the interface resulting in the formation of a narrow LB zone [7].
4.2 Analysis of weld interface notch tensile strength

In correlation to hardness analysis, the samples made with higher upset current exhibited higher NTS. The presence of acicular ferrite contributed to higher NTS than the base metal (Figure 5). Acicular ferrite morphology is the most preferred weld microstructure in carbon steel weldments since its lathlike ferrite structure improves both the material strength and toughness [13,14]. Low heat input and higher cooling rate during MIAB welding favour the acicular ferrite formation. Unlike arc welding and other solid-state welding like flash butt welding, MIAB welding uses very low welding current during the arcing period and high upset current is used for a very short span for the expulsion of molten metal [15]. Proper expulsion of molten metal and impurities plays a vital role in the formation of microstructure at the weld zone. In samples made with lower upset current, LB zone containing decarburized structure with polygonal ferrite was present at TMAZ I (Figure 5).

Figure 5. Optical micrograph of notched tension test specimen fracture surface (LB- Light Band Zone, AF-Acicular ferrite, P –Pearlite, PF-Polygonal Ferrite and GBF-Grain Boundary Ferrite)
Among the samples welded with lower upset current, sample S/7 exhibited NTS at par with the base metal NTS. Lower arc rotation current and higher arc rotation time showed a positive effect on the NTS because of the narrow LB zone (Figure 6b). Sufficient melting and larger plasticized zone aid expulsion resulting a narrow decarburized zone at the interface [6]. Longer arc rotation time was beneficial only with lower arc rotation current since higher arc rotation current causes excess melting leading to wider LB zone formation. The samples welded using lower upset current and higher arc rotation current displayed 10% lower NTS than the base metal due to higher decarburization and improper expulsion. All samples welded using a higher upset current irrespective of arc rotation current displayed a higher NTSN value due to strengthening at the weld interface (Figure 6a). NTS of such samples is about 20% higher than the base metal NTS. All samples displayed notch ductility with NSR greater than unity. This indicated that the weld interface does not contain brittle microstructure. Instead, the samples with LB zone at the weld interface displayed a lower Normalized tensile strength ratio (NTSN).

4.2.1 Fracture surface analysis of weld interface
The fracture surface of the weld interface is shown in Figure 7. The fracture surface of the sample welded with higher upset current exhibited ductile fracture with the fracture surface showing gross plastic deformation and microvoid coalescence at the higher magnification (sample S/1). The sample S/5 showed quasi cleavage fracture with larger cleavage fracture and SEM micrograph at higher magnification showed oxide particles at the specimen surface due to improper expulsion of impurities. These oxide particles induce brittleness although the microstructure exhibited ductile nature. In correlation to NTS data, sample S/7 welded with lower arc rotation current and higher arc rotation time showed higher ductile features than other samples welded with the lower upset current. Further minimal oxide particles were seen in the micrograph contributing to higher notch tensile properties matching the base metal NTS.
4.3 Notch tensile properties of other TMAZs

The notch tensile properties of TMAZ I, TMAZ II, TMAZ III and unaffected base metal of sample S/1 are given in Table 3. Microstructures of TMAZ II and TMAZ III showed ferrite and pearlite with different grain sizes in each zone (Figure 8). TMAZ II showed slightly coarser grains than TMAZ III due to varying weld thermal cycles. TMAZ II was exposed to a higher peak temperature than TMAZ III, hence the grains are held at a higher temperature for a longer duration leading to grain coarsening. Due to lower welding current and shorter welding cycle, minimal grain coarsening had resulted in this zone without degrading the mechanical properties. NTS of TMAZ II was equivalent to that of the base metal NTS. The normalized notch tensile strength is 1.08. In TMAZ III, recrystallized grains of ferrite and pearlite were formed due to lower peak temperature and high cooling rate. Grain refinement in TMAZ III resulted in higher NTS than TMAZ II and base metal. TMAZ III has NSR of 1.57 and NTSN of 1.17. Fracture surface analysis of TMAZ II and TMAZ III showed ductile fracture with dimpled structure due to the presence of tougher microstructure in these zones (Figure 8). Lower heat input utilized during MIAB welding showed a positive effect on TMAZs properties with higher NTS and NTSN.
Figure 8. Optical micrograph and SEM micrograph of TMAZs and base metal fracture surface

5. Conclusion

- In correlation to hardness analysis, the upset current had a significant effect on the notch tensile properties of the weld interface.
- Formation of stronger acicular ferrite at the weld interface accounts for higher NSR and NTS in samples with a higher upset current.
- LB zone with impurities at the weld interface resulted in lower NTS.
- Lower heat input used in MIAB welding exhibited a positive effect on notch tensile properties of TMAZ II and TMAZ III with NSR and NTS greater than unity.

6. References

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