Impact of mechanical properties of structural steel by three transfer modes in gas metal arc welding

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Abstract. In manufacturing, great advantages such as high resistance and reliability have been acquired through permanent bonding processes such as welding. Electric arc welding under the name of gas metal arc welding is one of the most widely used welding processes due to its high productivity index and the quality of its weld seams. The application parameterization allows three modes of metal transfer to be developed which depend on voltage and amperage. The microstructure and mechanical properties of the base material are modified with the modes of metal transfer, due to the heat input that must be made to be able to join them, without having numerically quantified the level of affectation. In this work, the application of transfer modes on structural steel was developed following the normative models that govern technology and industry. Experimental procedures of microscopy and mechanical tests were applied to determine correlations between the mechanical properties and the parameters established during the application, the microstructures were reviewed in contrast to the results obtained.

1. Introduction
Welding technology can be classified into two groups, which are fusion welding and solid-state welding. The first group covers the welding processes in which the coalescence of the molten base metal (BM) is carried out and, in some cases, a molten filler material is added. In the second case, the BM does not reach its melting temperature and the coalescence is carried out using pressure or heat, without adding filler material [1,2]. Fusion welding is the most used category at an industrial level [3], in this category is electric arc welding, in turn, the welding process gas metal arc welding (GMAW) belongs to the category of electric arc welding. This welding process produces an electric arc between a wire that is continuously fed and a pool of molten material, in addition, a protective gas is used which is added externally [4,5]. The parameterization of the GMAW welding process allows the development of three transfer modes that depend on the size of the droplets transferred to the pool of molten material [6].

Variables such as the welding current, the composition of the shielding gas, the polarity and the welding material produce the different transfer modes in GMAW [7]. The short circuit transfer mode is characterized by low heat input in the fusion zone of the welded joint and the transfer occurs when the electrode is electrically short-circuited. Globular metal transfer presents large droplets from a consumable electrode through an arc. The axial spray mode is the transfer of higher energy because deposition rate of molten metal occurs at high energy levels and uses high current values with which small drops of molten material are achieved [8,9].
These transfer modes add heat to the BM. Mechanical properties and microstructure of this materials are affected [10]. However, it is important to quantify which of the three transfer modes makes influence in BM than the others, generating a larger heat-affected zone (HAZ). This work presents the level of damage in a material type structural steel ASTM A36 [11] due to three transfer models, in which tensile tests and hardness scans were carried out, in addition, micrographs were taken to observe the size of the HAZ.

2. Method
For the development of the experimental phase an ASTM A36 structural steel plate with 4.5 mm of thickness was used, whose chemical composition and tensile strength are shown in Table 1 with data from the manufacturer [11]. The specimen preparation process considered cross-sectioning to maintain the homogeneity of the properties of the material to be joined. This plate was cut into six sections 15 cm wide by 40 cm long to join them utilizing three transfer modes of the GMAW welding process. It was guaranteed that the cut would be made without thermally affecting the microstructure of the material, therefore the cut was made with hydraulic shears.

| Table 1. Physical and chemical properties of the test material. |
|---------------------------------------------------------------|
| Chemical composition | Mechanical properties |
| %C | %Si | %Mn | %P | %S | %Cr | Yield stress (MPa) | Tensile stress (MPa) | Elongation (%) |
| 0.150 | 0.100 | 0.280 | 0.012 | 0.007 | 0.032 | 264.3 | 448.7 | 10.5 |

Table 2. Parameters of each transfer mode.

| Metal inert gas (MIG) welding carriage | Welding equipment parameters |
|----------------------------------------|-----------------------------|
| HUAWEI set parameters | SWEISS Sky MIG 5040 |
| Transfer mode | Wide (in) | Cycle (min⁻¹) | LMR (s) | Voltage (V) | Current (A) | Gas composition (%) | Gas flow (LPM) |
| Short circuit | 0.4 | 100 | 0.5 − 0.3 − 0.5 | 21.0 | 198 | 80%Ar−20%CO₂ | 20 |
| Globular | 0.6 | 50 | 0.0 | 21.0 | 239 | 80%Ar−20%CO₂ | 30 |
| Spray | 0.6 | 90 | 0.0 | 25.1 | 184 | 80%Ar−20%CO₂ | 30 |

For the tension test, the dimensions and criteria mentioned in ASTM E8-16a for rectangular specimens were established [13,14]. The equipment used to perform the test was an MTS BIONIX universal testing machine shown in Figure 3, with a static load capacity of 25,000 N. The sampling rate was 50 data per second and the controlled variable was strain rate, with a range of 4 mm/min. Equation (1) and Equation (2) were also used to determine the stresses and unit deformation supported by each specimen [15].
\[ \sigma = \frac{P}{A} \]  

Figure 1. Equipment used for welding

\[ \varepsilon = \frac{l_f - l_o}{l_o} \]  

where \( l_f \) is final length in meters, and \( l_o \) is initial length in meters. The microindentation test for Vickers hardness was performed according to ASTM E384-17 standard [16] and the metallographic preparations of the hardness specimens were performed according to ASTM E3-11 standard [17], polishing the specimen on the transversal face to the forward direction of the weld bead, from abrasive paper No. 120 to abrasive paper No. 5000, in addition, the specimen was polished with an abrasive cloth polisher to create a mirror-like surface as shown in Figure 4.

The equipment used to perform the hardness test was a BRUKER UMT TriboLab tribometer which is observed in Figure 5 and was configured with a load \( P = 4 \text{ N} \), a load application time of \( t = 15 \text{ s} \) and separation between indentations of 0.4 mm, an result of image is shown in Figure 6. The Vickers hardness was calculated with Equation (3) [16] since the load and diagonal length values are known, which was measured with a twenty-magnification lens.

\[ HV = 1854.4 \cdot \frac{P}{d^2} \]  

where \( P \) is the force in gram-force, and \( d \) is the length of the long diagonal in micrometers. To observe the three zones that make up the welded joint, macrographs were made by performing a macroetch attack on the surface transverse to the direction of the weld application, such attack was performed with Nital at a concentration of 2% per 10 seconds, that test indicated the shape and size of the BM, the HAZ, and the weld metal (WM), as evidenced in Figure 7.
Micrography was performed with a ViewMet BUEHLER inverted microscope together with two lenses of 10x and 20x magnification respectively.

Figure 4. Hardness tester with mirror-like surfaces.

Figure 5. BRUKER UMT TriboLab tribometer.

Figure 6. Indentation observed to 5x.

Figure 7. Macrograph showing BM, HAZ, and WM.

3. Results and discussion

¡Error! No se encuentra el origen de la referencia. shows the results for the tensile test of the unwelded base material, and the three transfer modes analyzed in this investigation.

Figure 8. Stress-strain graph for BM and three transfer modes.
It was observed that the unwelded material has higher elongation, before reaching its breaking point, and in the curves corresponding to the three transfer modes the apparent elastic limits disappear. The range of data found inside box A, in the elastic zones of the four curves, was analysed again in Figure 9.

Each transfer mode presents a different elastic zone and consequently a different module of Young, the yield stress being characteristically higher for the short-circuit transfer mode and lower for the spray transfer mode. The yield stresses were calculated according to section 7.7.1 Offset method of the ASTM E8 Standard [13] and the results were recorded in Table 3 together with the maximum stresses and strains.

| Specimen        | Strain (%) | Max. stress (Mpa) | Yield point (Mpa) |
|-----------------|------------|-------------------|-------------------|
| Base material   | 10.57      | 491.2             | 342.5             |
| Short circuit   | 8.23       | 446.5             | 283.3             |
| Globular        | 8.17       | 444.6             | 271               |
| Spray           | 9.73       | 444.4             | 269               |

The results of the Vickers hardness scans for the three transfer modes are shown in Figure 10, and in Figure 11 and Figure 12 are attached two micrographs made with 10x and 70x lenses, where the changes of microstructures of the three characteristic zones of the welded joint are observed.
The Figure 10 presents two almost constant hardness zones and one in which the hardness increases linearly; the first change in hardness occurs at 5 mm in which the transition between BM and HAZ occurs, the second change in hardness occurs at 8 mm, which indicates the start of the WM of the welded joint.

The HAZ shows a stronger mixing of the influence of dilute pearlite on the initial ferritic model which starts from the blue vertical line shown in Figure 11 and Figure 12.

![Figure 11. Micrograph of the BM and WM.](image1)

![Figure 12. Micrograph of the BM and HAZ.](image2)

4. Conclusions

It is necessary to review which is going to be the working scheme of the material to be used and which will be subjected to the welding process, if it is a scenario where the shape of the material is going to be modified within the plasticity zone, the spray transfer mode is preferable since this transfer mode allows greater elongation in the deformation and has greater resistance, in contrast to the short circuit transfer mode. But if a material with good strength is needed without the need to exceed the elastic zone, then welded material can be used under the short-circuit transfer mode.

The hardness of the material tends to increase according to the heat input that was delivered to the welded joint. It was identified that the spray transfer mode presents higher hardness values in the base metal, in the heat-affected zone, and the weld metal compared to the short circuit or globular transfer mode in which the hardness is lower.

The pearlite increases much more in the heat-affected zone due to the carbon content added by the filler material. It is suggested to do a grain size analysis to compare the grain densities along with the base metal, the heat-affected zone, and the weld metal.

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