Original Article

Influence of welding procedure and PWHT on HSLA steel weld metals

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\textbf{A B S T R A C T}

The development of consumables for welding of high strength steels represents a continuous challenge taking into account the great variety of alloy systems. In this regard, there are many applications, such as offshore structures, where the welding is still preferably done by the SMAW process. In order to evaluate the properties of weld metals obtained by other processes with higher productivity, the present work presents a comparative analysis between the mechanical properties of high strength steel weld metals obtained by shielded metal arc (SMAW) and gas metal arc (GMAW) welding processes. Multipass welding by SMAW and GMAW processes was performed with preheating of 200°C, in 750 × 150 × 19 mm plates. After welding, a post weld heat treatment (PWHT) at 600°C for 1h was performed and this condition was compared to the as welded one. Mechanical tests and metallographic examination by optical microscopy (OM), scanning electron microscopy (SEM) and electron backscattered diffraction (EBSD) were performed for mechanical and microstructural characterization. Thermodynamic calculations were also performed by using Thermo-Calc software, in order to evaluate the occurrence of carbides as a consequence of the PWHT.

Although presenting impact toughness behavior slightly different due to the chemical composition and carbide precipitates, as predicted by computational simulation, both processes showed a good relationship between mechanical strength and impact toughness for all analyzed conditions, even after PWHT.

Based on this scenario, it can be inferred that GMAW process can be applied as an interesting alternative for welding of high strength steels, once this process promotes a significant improvement in productivity with good quality.

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1. Introduction

With an industrial trend towards application of modern higher strength steels for different structures [1–4], it is necessary to develop new steel grades [5] with high strength combined with a low ductile-brittle transition temperature, which is associated with the appropriate microstructural design, once impact toughness in steels is driven by different microstructural constituents.

These steels with high strength and high toughness have been widely applied in pipelines, ship building and various manufacturing industries [2]. In the same way, Zhang et al. [6] state that these changes in the steelmaking technology and steel rolling process are a challenge for the production of welding consumables and joining technology. It is important to mention that, in contrast to production of wrought steel, the strength and toughness of weld metals must generally be achieved by means of alloying [7]. As a consequence, due to the complexity of welding processes and limitations of heat inputs and, consequently, cooling rates, the toughness of the weld metal at low temperature is lower than the base metal one [2].

Considering that the microstructure of weld metals with yield strength of 600 MPa or higher consists basically of bainite and martensite, instead of a microstructure with the predominance of acicular ferrite, the basic composition design of the weld metal should be different for each case [8]. In fact, for those applications, where the strength of weld metal consisting of acicular ferrite is not sufficient, the addition of specific solid solution strengtheners and other alloying elements is necessary in order to retard the austenite/ferrite transformation so as to produce martensitic welds with the required high strength [9].

For applications with stringent requirements of very high strength, in particular, such as naval vessels and offshore structures [10,11], there is an additional challenge, once qualification standards are limited to 120ksi (830 MPa) and do not take into consideration the influence of post welding heat treatment (PWHT) [12,13], which can be crucial in order to restore the properties of the base metals and relieve the residual stresses [14,15]. Consequently, works involving the effect of the PWHT on the mechanical properties of high strength steel weld metals are limited, once this condition is not required for qualification of welding consumables, except for specific cases [10].

Although PWHT usually presents a tendency to promote a reduction of mechanical properties [16–18], mainly the ultimate tensile strength, which is the critical property [19], it may cause unpredictable changes in the microstructure of hardened or high strength steel weldment, which is extremely complicated and normally very sensitive to heat [20]. However, even with all limitations, some previous works evaluating the behavior of high strength steel weld metals obtained by shielded metal arc welding (SMAW) process [17,21–23] revealed that a good relationship between mechanical strength and impact toughness can be obtained.

Based on this scenario, this work studies the influence of welding thermal cycle and PWHT on the mechanical and microstructural properties of high strength steel weld metals obtained by gas metal arc welding process (GMAW), in comparison with a weld metal produced by SMAW process, in order to evaluate if the use of GMAW process can promote an improvement in productivity of high strength steel welds while maintaining good quality even with a lower level of reheating [24–27].

2. Experimental procedure

2.1. Materials

Plates with dimensions of $19 \times 300 \times 700$ mm of an ASTM A 36 steel were used as base material.

Covered electrodes with 4.0 mm diameter according to the AWS E12018-M [12] and wire rods with diameter of 1.2 mm, according to the AWS S2 class ER 120S-G specification [13] for GMAW process, were used as welding consumables for SMAW and GMAW processes, respectively. Table 1 shows the chemical composition of the welding consumables as informed by the manufacturers.

2.2. Welding

As the objective of the work is to study the weld metal, a joint geometry illustrated in Fig. 1, with the root opening of 13 mm was adopted, in order to minimize the influence of the dilution with base material.

Weld metals were obtained in the flat position, 200 °C preheat, direct current, electrode positive by SMAW and GMAW processes using covered electrodes with 4.0 mm diameter according to the AWS E12018-M [12] and wire rods according to the AWS S2 class ER 120S-G specification [13], respectively. For GMAW process, a mix of 20% CO₂–80% Ar was used as shielding gas.

The welding parameters are shown in Table 2 and Fig. 2 shows the deposition sequence. Cooling times were calculated for the position where test pieces for mechanical properties were removed according to EN 1011-2 Annex D [28].

In order to evaluate the possible effect of cooling rates on the mechanical properties of GMAW welds obtained in the present work, an additional analysis with different preheats was performed. Table 3 shows the welding parameters for the experiment.

After welding, magnetic particle and ultra sound inspections were performed and no welding defects were observed.
2.3. Post-welding heat treatment (PWHT)

The weld metals were tested in both conditions: as-welded and after PWHT performed at 600 °C for 1 h followed by air cooling.

2.4. Metallographic examination

Metallographic analysis of the weld metals was carried out by optical microscopy (OM) and scanning electron microscopy (SEM) in secondary electron mode and electron backscattered diffraction (EBSD), in samples removed from regions related to the positioning of the Charpy-V notch.

Quantitative analysis of the columnar and reheated regions at the position relative to the Charpy-V notch was performed on the OM screen, in order to evaluate the influence of different number of passes on reheating of the weld metals.

Additionally, quantitative analysis of microstructural constituents was performed by point to point counting technique using a 10 × 10 grid on the SEM screen. At least 1000 points were counted for each weld metal.

The samples were prepared with emery paper up to 1200 mesh and diamond paste with 6, 3 and 1 μm for final polishing, followed by nital 2% etching. The EBSD maps were collected with SEM operating at 20 kV and with a step size of 1–4 μm on samples polished with colloidal silica.

2.5. Thermodynamic calculations

In order to evaluate the evolution of the phases resulting from the welding procedure, thermodynamic calculations were performed using Thermo-Calc software with TCFEB database [29]. Due to the influence of the multiple passes on the evolution of the microstructure of the weld, for SMAW and GMAW processes, isopleth diagrams were elaborated to present the effect of chromium segregation on phases formation. Additionally, diagrams presenting the evolution of phases with temperature, a step diagram with mass fraction of all phases versus temperature and an isopleth diagram with temperature versus mass fraction of Cr were constructed for each process.

2.6. Mechanical tests

Specimens were removed at 2 mm down the surface for tension, impact Charpy-V and microhardness tests.

Tension tests at room temperature, were performed on test specimens removed longitudinally to the weld metals (all weld metals) according to ASTM A 370 [30] and ASTM E8 [31]; with gauge length and diameter of 50 and 8.75 mm, respectively.

Charpy-V impact tests at −60, −40, −20, 0 and 20 °C temperatures were also performed on standard test pieces (10 × 10 × 55 mm) removed transversally to the weld bead, according to ASTM A 370 [30] and ASTM E23 [32]. The notch was

![Image](image_url)

**Fig. 2 – Deposition sequence.**

<table>
<thead>
<tr>
<th>Table 1 – Chemical composition of the welding consumables.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld metal</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td>SMAW</td>
</tr>
<tr>
<td>GMAW</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2 – Welding parameters and calculated cooling times.</th>
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</thead>
<tbody>
<tr>
<td>Process</td>
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<tr>
<td>---------------</td>
</tr>
<tr>
<td>SMAW</td>
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<tr>
<td>GMAW</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3 – Welding parameters and calculated cooling times for GMAW process with different preheats.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheat (°C)</td>
</tr>
<tr>
<td>--------------</td>
</tr>
<tr>
<td>150</td>
</tr>
<tr>
<td>250</td>
</tr>
</tbody>
</table>

located in the thickness section at a position corresponding to the weld metal center line (Fig. 3).

Vickers microhardness tests were also performed, with a load of 500gf, at points located within the weld metal in region related to the positioning of the Charpy-V notch.

2.7. Chemical analysis

Chemical composition of the weld metals was performed by spectroscopy of optical emission in order to evaluate the main chemical elements at the position where the Charpy-V notch were positioned.

3. Results

Table 4 shows the chemical composition of the deposited weld metals where it can be noted the main differences relative to the elements Cr and Ni, as consequence of composition of welding consumables (Table 1). In addition, it is important to observe the low influence of dilution on the chemical composition in the weld metal center line, where the analyses were performed.

Fig. 4 shows the macrographs of the welded joints, where it can be noted the effect of different number of passes for each process. As consequence, the percentage of columnar region was 54% and 73% for SMAW and GMAW processes, respectively.

Table 5 – Results of tensile tests.

<table>
<thead>
<tr>
<th>Weld metal</th>
<th>Condition</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>El (%)</th>
<th>RA (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMAW</td>
<td>As-welded</td>
<td>839</td>
<td>909</td>
<td>17</td>
<td>59</td>
</tr>
<tr>
<td></td>
<td>PWHT</td>
<td>786</td>
<td>892</td>
<td>17</td>
<td>56</td>
</tr>
<tr>
<td>GMAW</td>
<td>As-welded</td>
<td>774</td>
<td>875</td>
<td>18</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>PWHT</td>
<td>774</td>
<td>841</td>
<td>16</td>
<td>52</td>
</tr>
</tbody>
</table>

YS, yield strength; UTS, ultimate tensile strength; El, elongation; RA, reduction of area.

Fig. 5 shows the refined microstructure of the weld metals, when observed by OM. In order to clarify the occurrence of tempered martensite (M) and tempered bainite (B), SEM analysis was necessary (Fig. 6), which revealed a similar microstructure for both weld metals.

PWHT promoted a more intense precipitation of carbides (Fig. 6), with different results for each weld metal, as consequence of the chemical composition (Table 3), mainly Cr and Mo, as evidenced by Thermo-calc analysis (Figs. 7 and 8).

Table 5 shows that both welding processes promoted high strength, being the results obtained by SMAW process higher than those obtained by GMAW process.

PWHT promoted only a slight reduction on the mechanical strength (Table 5) and microhardness (Fig. 6).

Fig. 9 presents the results of impact of toughness for both weld metals. It is noted that the best results were observed for GMAW process.

4. Discussion

4.1. Influence of the welding process on the mechanical properties

Table 2 shows that the deposition rate of GMAW process was higher than the one for SMAW process, being 3.32 kg/h and 1.99 kg/h, respectively. These results are in accordance with other researchers [23,33–35]. Consequently, GMAW process is able to provide a significant gain in productivity, once it allows
Fig. 5 – Microstructures of the region corresponding to Charpy-V notch position of the weld metals (OM). Etching: nital 2%.

Fig. 6 – Microstructures of the region corresponding to Charpy-V notch position of the weld metals consisting of tempered martensite and tempered bainite (SEM). M – martensite; B – bainite. Etching: nital 2%.

Fig. 7 – Step diagram of mass fraction of all phases versus temperature for weld metals.
the deposition of the required material in 61% of the time spent by the SMAW process.

It is important to mention that, although a lower number of passes had promoted a higher percentage of columnar region for GMAW process (54% for SMAW and 73% for GMAW process), which can have a significant effect on the mechanical properties of the welded joint [22,24,25,27], some works [22,23,34,36,37] show that, for weld metals with higher strength, it is possible to achieve good mechanical properties even with higher productivity processes, once the high hardenability of the weld metals promotes the occurrence of similar microstructural constituents in both columnar and reheated regions [22,23,34,36,38–40].

According to Pirinen et al. [41], the microstructure and mechanical properties of high strength steel welded joints are determined by the chemical composition of the weld and of the parent metal, as well as by the cooling rate. Depending on the chemical composition and cooling rate, the obtained mechanical properties may be different, being these results reported also by other works [19,40,42,43]. In this regard, Keehan et al. [40] and Ismar et al. [42], working with SMAW, suggest that high strength and good toughness are obtained for cooling times of about 3–13 s and 5–15 s between 800 and 500 °C, indicating that the results obtained in the present work agree with these works (Table 2).

In general, a good relationship between mechanical properties depend on the Ni and Mn contents [38–40,43–50], particularly, when nickel is added to C–Mn deposits, it is necessary to reduce the manganese content to maintain optimal impact toughness in balance [51]. Based on Keehan et al. [45], Lalam et al. [47], Murugananth et al. [49] and Zhang et al. [50] findings, the chemical composition observed in the present work (Table 4) indicates that good mechanical properties are expected, mainly due to the contents of Ni, Mn and C. In the particular case of the weld metals studied in the present work, the association of similar cooling times (Table 2) and same value of the parameter Pcm (Table 4) allows a comparison between the weld metals obtained by SMAW and GMAW processes.

This is confirmed when analyzing the evidences shown in Fig. 10, which presents the results obtained in the present work in comparison with various experimental works that studied high strength steel weld metals [1,17,21,22,34,36,45,46,52–56]. It can be noticed that the
The present results are slightly superior to those obtained in other works, which can be a consequence of the refined microstructure with high volume fraction of tempered martensite observed in both weld metals (Figs. 5 and 6), in consistence with the chemical composition studied (Table 4). In fact, Park et al. [57] state that the reason for the additional strengthening in Ni-Cr-Mo low alloy steel with higher Ni content could be an increase in the martensite fraction, as well as a decrease in the effective grain size by Ni addition.

The higher values observed for SMAW process (Table 5) are consistent with Surian et al. [19], Ramirez [58] and Talas [59], who state that the weld metal strength increases with carbon equivalent number (Table 4).

According to Narayanan et al. [60], the classification of welding microstructures using optical microscopy proposed by the International Institute of Welding [61] is sufficient and very useful for traditional C-Mn and low alloy weld metals. However, for higher strength steel weld metals, this classification system is not adequate to show detailed differences of the refined weld microstructures, as observed in the present work (Fig. 5). In fact, although a microstructure composed by tempered martensite and tempered bainite is expected, the resolution of this technique is unable to clarify the main microstructural constituents, even with a magnification of 1000X. In agreement with this statement, Rabiei et al. [18] comment that detection of martensite in steels with low carbon content is difficult, because the volume fraction of octahedral spaces that are occupied with carbon atoms is very small and martensite tetragonality descends to nearly one. Therefore, in such steels with low carbon content, the pick angles of martensite and ferrite are similar in XRD pattern [62]. In this respect, although some methods are used to evaluate the microstructure of high strength steels, such as color metallography [62], ferrite scope [57] and X-ray diffraction [57,62], SEM analysis is still an effective technique to measure the volume fractions of martensite and bainite. According to Park et al. [57], ferrite scope is not adequate to differentiate martensite and bainite, because both phases have ferromagnetic properties, while EBSD technique is more appropriate to measure grain size, mainly in Ni-Cr-Mo systems due to its complex boundary morphologies, such as prior austenite boundaries and packet boundaries. It is important to remember that analysis in high strength steel weld metals are more complex, due to the reheating caused by the multiple welding passes besides the low carbon content. Consequently, the used of SEM for evaluation of the microstructure (Fig. 6), showed the occurrence of tempered martensite and tempered bainite as the main microstructural constituents.

The results obtained in the present work agree with other authors [2,17,38,40,41,63] who studied high strength steel weld metals and also observed a similar microstructure.

Although in higher strength steel weld metals martensite is traditionally avoided due to its association with poor toughness in welds, it should be recognized that not all martensite is brittle even in the not tempered form [64]. Consequently, low-martensite needs not to be avoided in an effort to make stronger weld metals. These statements are in accordance with the results obtained in the present work, once the results of Charpy-V impact tests (Fig. 9) present adequate values even for temperatures lower than −40 °C. In addition, it can be observed that the weld metal obtained by GMAW process, even with a high percentage of columnar region, presented similar results of impact toughness in comparison to the weld metal obtained by SMAW, which can be associated with a better balance of the chemical composition (Table 4). The lower chromium content, in particular, is important due to its known deleterious effect on impact toughness [17,51,54,65].

### 4.2. Effect of PWHT

According to Surian et al. [19], when designing an electrode formulation starting with C-Mn consumables, the main concern is to maintain the toughness requirements and to reach the adequate tensile properties. Consequently, it can be a problem in the present day to achieve the requirements for this property when working with high and extra high strength steel weld metals, mainly when PWHT is applied. Generally, it has been shown that the application of a PWHT adversely affect the UTS of weld metals [16–18,21,22,66–68] due to the over tempering of the microstructure [69]. However, some works [17,21,22,66] show that the higher is the UTS of the weld metal the lower is the difference on this property, as observed in the present work, where the difference for both weld metals were lower than 5% (Table 5). These results are expected, once tempered martensite was the main constituent for both weld metals (Fig. 6) and the effect of martensite tempering on ultimate tensile strength is well known.

The same behavior was observed for impact results (Fig. 9), which did not present significant differences due to the PWHT. Indeed, high values of absorbed energy were also obtained even for low temperatures for both weld metals.

The different behavior on the impact toughness presented by the SMAW and GMAW welds can be due to the occurrence of different carbides, as suggested by Thermo-Calc analysis (Figs. 7 and 8). Actually, for the GMAW weld the Cr-rich MoC is estimated (~0.7%), as well as the Mo-rich MC (~0.25%), while for the SMAW weld, the Cr-rich M23C6 (~0.9%) and the Mo-rich MC (~0.25%) are estimated (Fig. 8). The difference in type of precipitated carbides (both Cr-rich and Mo-rich) can be related to the difference in Cr/C and Mo/C ratios for the alloys used for each process (Table 2). The higher Cr/C ratio for the SMAW (SMAW = 14.0 and GMAW = 3.1) favors the precipitation
of $M_{23}C_6$ instead of $M_2C_3$, as well as the higher Mo/C ratio for the SMAW (SMAW = 10.0 and GMAW = 4.8) favors the precipitation of the Mo-rich $M_6C$ instead of the MC. In Fig. 8, the isopleth $T$-Cr for the GMAW weld shows the $M_2C_3$ field for lower Cr content. As this alloy has a higher C-content than the one used for the SMAW process, with increased Cr-content, a transition to $M_{23}C_6$ occurs. The isopleth $T$-Cr for the SMAW weld (Fig. 8) reveals an extensive $M_{23}C_6$ field. Due to the lower C content in this weld, this precipitate is stable even for lower Cr contents.

Of utmost importance is the good correlation between mechanical strength and impact toughness obtained after PWHT, particularly for GMAW welds, indicating its use for welding of high strength steels with higher productivity, where the application of PWHT can be mandatory [21,23,70].

4.3. Influence of cooling time for GMAW process

As discussed earlier, different cooling rates can promote significant changes on the mechanical properties of high strength steel weld metals [1,36,40–43]. Considering the good behavior observed when using a preheat of 200°C, it was decided to evaluate the influence of different cooling rates on the mechanical properties of GMAW welds obtained in the present work.

The results showed a tendency for reduction of mechanical strength and an increase on impact toughness (Fig. 11), as consequence of some important aspects such as: lower percentage of martensite (Fig. 12), coarsening of the microstructure (Figs. 12 and 13) and a higher proportion of high-angle boundaries (>15%) (Fig. 14) [71–74].

4.4. Final comments

The changes in steelmaking and steel rolling technologies are a challenge for welding consumables and joining technology. This is more critical for strength levels superior to 830 MPa, where no specific rules for approval of welding consumables are available. In addition, for welding of high strength steels, the main problem is the usual reduction of UTS due to the need of PWHT [16–18,21,22,66–68].

![Fig. 11 – Influence of cooling times on the mechanical properties of GMAW weld metals after PWHT.](image)

![Fig. 12 – Influence of cooling time on the microstructure of GMAW weld metals with different cooling times (SEM) Etching: Nital 2%.](image)

![Fig. 13 – Influence of cooling time on microstructure of GMAW weld metals as evidenced by EBSD analysis.](image)
Fig. 14 – Influence of cooling time on distribution of grain boundary misorientation of GMAW weld metals.

According to Keehan et al. [40], in order to minimize the PWHT effect, different approaches can be adopted. One approach is to define an operational window within which high strength and good toughness can be achieved, and a second approach is to obtain a greater tolerance to variations in the weld thermal cycle with higher alloy content weld metals. The last could be more appropriate to the present case, because of the lower cooling rates due to the higher thickness, different groove shape or higher preheat and inter-pass temperatures, which are usually necessary when welding base metals with different carbon equivalent values, being all these procedures very familiar to manufacturing processes on the shop floor.

Of the most importance is the good correlation between mechanical strength and impact toughness obtained after PWHT for GMAW welds even with different cooling times, indicating the possibility of its use for replacement of SMAW process in welding of high strength steels with higher productivity in applications where the use of PWHT can be mandatory.

5. Conclusions

Based on the aspects discussed and considering the experimental conditions applied in the present work, the main conclusions are:

(a) High strength steel weld metals obtained by GMAW can reach mechanical properties equivalent to those provided by SMAW process;
(b) it is possible to perform PWHT without significant changes on mechanical properties;
(c) Thermodynamic estimation of phases showed that Cr-rich and Mo-rich carbides are expected for the microstructure. However, the stoichiometries of the carbides are dependent on the Cr/C and Mo/C ratios. On the one hand, lower Cr/C and Mo/C ratios favor the M_{23}C_6 and MC carbides, respectively, while, on the other hand, higher Cr/C and Mo/C ratios favor the formation of M_{23}C_6 and M_6C carbides;
(d) Longer cooling times show a tendency for improvement of impact toughness and reduction on mechanical strength of high strength steel weld metals obtained by GMAW process; and
(e) The use of GMAW process can promote an increase in productivity of high strength steel welds with good quality.

Conflicts of interest

The authors declare no conflicts of interest.

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