Enhancement of mechanical properties of low carbon steel joints via graphene addition

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Enhancement of mechanical properties of low carbon steel joints via graphene addition

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ABSTRACT
Steel base metal laps or welding electrode surfaces were coated using graphene suspensions with various concentrations, and then the steel plates were welded using the shielded metal arc welding process. Microstructural observations showed that the addition of graphene to the weldment significantly refines the microstructure and promotes the formation of fine acicular ferrite. The results of mechanical testing indicated that with lower concentrations of graphene in the weldment, both the strength and ductility improve, but the hardness remains unchanged in comparison to the unreinforced weld metal. However, reinforcing with a higher concentration of graphene gives rise to the significant enhancement of the hardness and strength without deterioration of the ductility.

Introduction

Recently, carbonaceous nanostructures such as carbon nanotube (CNT) and graphene have been used as the reinforcement during the welding of different metals. In addition to the high elastic modulus and high strength, the carbonaceous nanostructures possess high thermal conductivity, low coefficient of thermal expansion (CTE), and self-lubricating characteristic [1]. Fattahi et al. [2] have shown that the tensile strength and microhardness of Al weldments processed by tungsten inert gas welding method conspicuously increased using 1.5 wt-% multi-walled carbon nanotube dispersed in Al as the filler metal. Sabetghadam-Isfahani et al. [3] have reported 65% enhancement in the tensile strength of AZ31 Mg alloy joints manufactured by the gas tungsten arc (GTA) welding using AZ31-1 wt-% CNT as the filler metal. Zhao et al. [4] have welded Al2009-3 vol.-% CNT nanocomposite plates produced via a powder metallurgy route by friction stir welding (FSW) processing and the joint efficiency (the tensile strength of the joint to the tensile strength of the base metal (BM)) of 87% was obtained. Izadi and Gerlich [5] have imbedded a high volume fraction (> 50%) of CNT in Al5059 plates via multi-pass FSW processing and have reported that the microhardness of Al5059/CNT composites was two times higher than that of the unreinforced Al alloy. Maurya et al. [6] have studied the effects of different types of carbonaceous reinforcements (graphite, CNT, and graphene) on the mechanical properties of Al6061 alloy processed by the FSW method. They stated that all the joints containing carbonaceous reinforcements demonstrated higher mechanical properties than the monolithic Al6061 weldment. In addition, among these reinforcements, graphene had the best performance since the highest elastic modulus and hardness together with the lowest coefficient of friction and wear rate were achieved for Al6061/graphene joints.

Graphene is a promising material as reinforcement not only in metals but also in polymers and ceramics [7–9]. An enormous specific surface area (2620 m² g⁻¹), excellent mechanical properties (Young’s modulus of 1 TPa and intrinsic strength of 130 GPa), an exceptionally high thermal conductivity (> 3000 WmK⁻¹), and a very high electronic conductivity (room temperature electron mobility of 25×10⁵ cm²v⁻¹s⁻¹) are some unique characteristics of graphene [10]. Based on the effectiveness of graphene in the solid state welding (e.g. FSW) [6], it is expected that graphene may be efficiently used in fusion-welded joints with improved mechanical properties as well. The addition of graphene into the weldments during fusion welding has been scarcely noticed. Recently, Fattahi et al. [11] have prepared Al4043-graphene nanosheet (GNS) filler wires through ball milling of the powder mixtures followed by hot extrusion to weld Al6061 plates by the GTA welding method. The results showed that as the amount of GNSs increased from 0 to 0.75 wt-%, the tensile strength and microhardness of welded metals were gradually improved due to the grain refinement and strain hardening. In the present study, we report fabricating graphene-reinforced low carbon steel joints using shielded metal arc welding (SMAW).
processing for the first time. In order to investigate the role of graphene on the mechanical properties, the tensile behaviour and microhardness of weldments are examined.

**Experimental procedure**

A low carbon steel plate was used as the BM. The chemical composition of the BM is given in Table 1. The BM was cut into rectangular coupons (100 mm × 37.5 mm × 5.5 mm) with a single V-shaped groove with an angle of 60° (Figure 1(a)). The surface of each plate was ground using abrasive SiC papers in order to clean up the contaminations and impurities. To prevent from misalignment and distortion, the beginning and the end of the plates were tack-welded.

The graphene powder used in this study was purchased from API Technology Pioneers Company. The specifications of graphene nanosheets are as follows:

Table 1. The chemical composition of the BM.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Cu</th>
<th>Mo</th>
<th>Cr</th>
<th>Ni</th>
<th>P</th>
<th>S</th>
<th>Mn</th>
<th>Si</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>99.02</td>
<td>0.028</td>
<td>0.007</td>
<td>0.078</td>
<td>0.063</td>
<td>0.004</td>
<td>0.03</td>
<td>0.295</td>
<td>0.125</td>
<td>0.112</td>
</tr>
</tbody>
</table>

impurities: < 70 ppm, the carbon-to-oxygen ratio: ∼ 8, the thickness of nanosheets: < 3 nm, and the lateral dimension of nanosheets: < 44 μm. A scanning electron microscopy (SEM) micrograph from GNSs is shown in Figure 2. It is clear that the graphene sheets are very thin. The GNS powder was poured in ethanol to attain the concentrations of 2.75 and 5.5 g L⁻¹. In order to break down the agglomerates and achieve uniform dispersions, the suspensions were ultrasonicated for 30 min. The graphene suspensions were coated on either electrode surfaces or BM laps. Three cellulose-coated electrodes (AWS E6010) were dip-coated in graphene suspensions for three times. Graphene suspensions were also drop-casted on the surfaces of two tack-welded BM laps. In order to dry the ethanol, the coated electrodes and plates were heated at 150°C for 24 h in an oven.

The welding was performed by means of SMAW process. The welding parameters are summarised in Table 2. The graphene-coated V-shaped groove laps were welded by uncoated electrodes since the unreinforced laps were welded by graphene-coated electrodes. In addition, the BM laps without coating were welded by an AWS E6010 electrode. The nomenclatures

Figure 1. The dimensions of (a) the welded metal and (b) the tensile specimen.
Figure 2. The SEM micrograph form graphene nanoplatelets.

Table 2. The welding parameters used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding process</td>
<td>SMAW</td>
</tr>
<tr>
<td>Process type</td>
<td>Manual</td>
</tr>
<tr>
<td>Electrode</td>
<td>AWS E6010</td>
</tr>
<tr>
<td>Electrode size</td>
<td>3.22 mm</td>
</tr>
<tr>
<td>Electrode coat type</td>
<td>High cellulose sodium</td>
</tr>
<tr>
<td>Electrode current type</td>
<td>DCEP</td>
</tr>
<tr>
<td>Arc current</td>
<td>80 A</td>
</tr>
<tr>
<td>Arc voltage</td>
<td>20.32 V</td>
</tr>
<tr>
<td>Average welding speed</td>
<td>150 mm min⁻¹</td>
</tr>
<tr>
<td>Average heat input</td>
<td>651.84 J mm⁻¹</td>
</tr>
</tbody>
</table>

Table 3. The nomenclature of weldments.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Concentration of graphene suspension (g L⁻¹)</th>
<th>Place of coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>S2</td>
<td>2.75</td>
<td>V-shaped groove laps</td>
</tr>
<tr>
<td>S3</td>
<td>5.5</td>
<td>V-shaped groove laps</td>
</tr>
<tr>
<td>S4</td>
<td>2.75</td>
<td>Electrode</td>
</tr>
<tr>
<td>S5</td>
<td>5.5</td>
<td>Electrode</td>
</tr>
</tbody>
</table>

Results

A typical macrostructure of the cross-section of SMAW joints is illustrated in Figure 4. Figure 5 shows variations in Vickers microhardness across the weldments with and without graphene. The average Vickers
The hardness of welded metals measured at BM, HAZ, and FZ regions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>BM</th>
<th>HAZ</th>
<th>FZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low carbon steel plate</td>
<td>150 ± 0</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>S1</td>
<td>147 ± 1</td>
<td>166 ± 1</td>
<td>205 ± 10</td>
</tr>
<tr>
<td>S2</td>
<td>142 ± 5</td>
<td>143 ± 1</td>
<td>209 ± 16</td>
</tr>
<tr>
<td>S3</td>
<td>138 ± 1</td>
<td>204 ± 9</td>
<td>225 ± 4</td>
</tr>
<tr>
<td>S4</td>
<td>129 ± 1</td>
<td>143 ± 4</td>
<td>204 ± 14</td>
</tr>
<tr>
<td>S5</td>
<td>127 ± 1</td>
<td>155 ± 0</td>
<td>234 ± 25</td>
</tr>
</tbody>
</table>

Microhardness values of the weldments at the fusion zone (FZ), the heat-affected zone (HAZ) and the BM zone are given in Table 4. The hardness variations in all of the samples are similar; the hardness values of the BM zone were lower than the hardness value of the low carbon steel plate. Meanwhile, the hardness values were found to be increased at the HAZ and FZ and the highest hardness values were attained at the FZ. In order to investigate the origin of hardness changes, the microstructure of welded metals at the BM, HAZ, and FZ are examined, as shown in Figure 6. According to Table 4, the hardness of the BM zone slightly decreased in the unreinforced weldment (S1) and in the samples welded by the graphene-coated electrodes (S2, S3). Nevertheless, the hardness decline in the welded metals in which graphene had been coated on the groove laps (S4, S5) was more significant. As seen in Figure 6, the microstructure of the BM zone consists of equiaxed ferrite–pearlite. No significant changes were observed in the microstructure of S1, S2, and S3 samples in this zone except that the ferrite grain size slightly increased in the graphene-contained weldments (Figure 6(a,d,g)). On the other hand, a bimodal grain structure consisting of fine and coarse ferrite grains was observed in the microstructure of S4 and S5 samples (Figure 6(j,m)). However, the ferrite grains in the S5 weldment were coarser than those in the S4 sample, which resulted in a lower hardness value in the former.

A considerable grain refinement of the ferrite was taken place in the HAZ of the S1 sample (Figure 6(b)), and thus the hardness value increased to 166 Hv. Nevertheless, the microstructure of graphene-reinforced weldments in the HAZ was significantly changed, which in turn influenced the hardness of weldments in this zone. As seen in Figure 6, the microstructure consisted of ferrite and pearlite, but the morphology of ferrite was altered so that equiaxed ferrite grains were completely diminished. The microstructural changes in the graphene-reinforced weldments could be attributed to the high thermal conductivity of graphene, which led to the high cooling rates in these samples [13]. Three types of ferrites were distinguished in the microstructure of weldments: (i) allotriomorphic ferrite, (ii) Widmanstätten ferrite, and (iii) acicular ferrite. These ferrites are distinguished in Figure 7. It is known that the transformation of austenite to ferrite during continuous cooling started with the formation of allotriomorphic ferrite at austenite grain boundaries. As the temperature decreased, Widmanstätten ferrite nucleated at austenite grain boundaries and extended into austenite grains. By further reduction of the temperature, acicular ferrite would nucleate on inclusions present in the steel [14]. It is clear from Figure 6 that...
Figure 6. The optical micrographs from the microstructure of weldments at three different zones (BM, HAZ, and FZ).
as the graphene content in the weldment increased, the size of allotriomorphic ferrite colonies and Widmanstätten ferrite sawtooths decreased. Meanwhile, the amount of acicular ferrite raised, especially in the weldments in which graphene had been coated on the groove laps (see Figure 6(h)). Thus, the hardness of weldments became greater by increasing the amount of graphene in the welding nugget.

The microstructure of weldments at the FZ consisted of fine ferrites (allotriomorphic, Widmanstätten, and acicular) and carbides both in the unreinforced and graphene-reinforced samples, as seen in Figure 6. In addition, graphene nanosheets are observed in the FZ, revealing their stability and effective incorporation into the steel matrix during the welding process (Figure 8). Second phase particles (distinguished by circles in Figure 8) were also detected in the microstructure of all the weldments. In the weld metals containing graphene, ferrite grains in the FZ were notably refined in comparison to those in the HAZ. Furthermore, the amount of acicular ferrites significantly raised in the FZ (Figure 6). Thus, the hardness values of the welding nugget in all the weld metals were superior to those of the HAZ. As the graphene content in the weldment increased, the microstructure was more refined and the amount of acicular ferrites increased, giving rise to higher hardness values in the weldments. The S5 weld metal had the highest hardness (234 Hv) among all the weldments owing to its finest microstructure and highest quantity of the acicular ferrite, as clearly seen in Figure 6(o).

The improved mechanical properties of the graphene-reinforced joints are also confirmed by the engineering stress–strain curves, which are plotted in Figure 9. The corresponding tensile properties of the weldments are summarised in Table 5. The tensile stress–strain curves illustrate a yield point followed by the strain hardening. Both the yield strength (YS) and
Table 5. The tensile properties of the weldments.

<table>
<thead>
<tr>
<th>Sample</th>
<th>YS (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>190 ± 2</td>
<td>472 ± 11</td>
<td>4.5 ± 0.2</td>
</tr>
<tr>
<td>S2</td>
<td>184 ± 18</td>
<td>496 ± 37</td>
<td>8.2 ± 1.8</td>
</tr>
<tr>
<td>S3</td>
<td>196 ± 12</td>
<td>515 ± 35</td>
<td>4.1 ± 1.0</td>
</tr>
<tr>
<td>S4</td>
<td>229 ± 18</td>
<td>565 ± 40</td>
<td>9.5 ± 0.4</td>
</tr>
<tr>
<td>S5</td>
<td>275 ± 23</td>
<td>576 ± 35</td>
<td>5.4 ± 0.5</td>
</tr>
</tbody>
</table>

Table 5. The tensile properties of the weldments.

The ultimate tensile strength (UTS) of the unreinforced weldment have been determined to increase by the addition of graphene. The only exception is a slight reduction in the YS of the S2 welding metal in comparison to the S1 weldment. Approximately 3–45% improvement in the YS and 5–22% enhancement in the UTS have been detected in the graphene-reinforced weldments in comparison to the unreinforced sample. Interestingly, not only the YS and UTS, but also the ductility of weldments was significantly enhanced by the graphene addition to the welding nugget. For example, the elongation to failure of the S4 weldment is more than twice that of the S1 welding metal. According to Table 5, as the graphene content in the weldment increased, both the YS and UTS improved, while the ductility exhibited a decreasing tendency. It should be noted that the YS and ductility were affected much more than the UTS by increasing the graphene content in the welding metal. For instance, in the case of the samples welded by graphene-coated electrodes, as the concentration of graphene doubled, the YS and elongation to failure were altered +20 and −43%, respectively, since the UTS increased only 2%. Finally, the samples welded by graphene-coated electrodes possess superior tensile properties than the weldments in which graphene had been coated on the groove laps.

Figure 10 shows SEM micrographs obtained from fracture surfaces of tensile samples. The fracture surfaces are characterised by ductile dimples and second phase particles. As seen in Figure 10(a,b), the fracture surface of the unreinforced weldment is covered by many second phase particles with irregular morphology and size range from ~0.4 to 2μm. A completely different fracture surface morphology is observed in the case of graphene-reinforced weldments, as shown in Figure 10(c–k). The fracture surfaces mainly consisted of ductile dimples resulting from the microvoid coalescence. Some graphene nanosheets which are exposed on the fracture surface are specified with circles in Figure 10. In fact, when a crack extended along the interface between steel and graphene, the interface debonding occurred and the GNS was appeared on the fracture surface. Similar observations have been reported by Chen et al. [15]. From the fracture surface of the S2 weldment, which is seen in Figure 10(c,d), it is deduced that the second phase particles are present as well. However, the size and amount of the particles are significantly lower than those in the S1 weldment. The size of the second phase particles was determined to be in the range of ~0.2–1 μm. The fracture surface of the S3 weldment is almost similar to the S2 weld metal except that the dimples in the former are larger and shallower than those in the latter. In addition, the amount of second phase particles significantly declined in the S3 weldment so that their detection on the fracture surface is difficult (see Figure 10(e,f)). It should be noted that the spherical particles seen within dimples in Figure 10(f) are
manganese sulphide (MnS) inclusions. It is clear that MnS inclusions are loosely bonded and the microvoids are nucleated from these particles during the tensile deformation. The fracture surfaces that appeared in the samples welded by graphene-coated electrodes are almost similar to the S3 weldment, as shown in Figure 10(g,j). Here, the second phase particles were almost disappeared while MnS inclusions were detected on the fracture surfaces. As the graphene content in the weldment increased, the size of dimples increased since their depth decreased.

The EDS spectra acquired from the tensile fracture surfaces are illustrated in Figure 11. The main elements characterised on the fracture surfaces were Fe and Mn. Meanwhile, a large amount of O and S was detected on the fracture surfaces of the S1 and S2 weldments. The composition of the second phase particles in the S1 sample was analysed by EDS mapping, as shown in Figure 12. Fe, S, and O were detected, suggesting the nature of second phase particles as iron oxide and iron sulphide. The complementary information on the phases present in the weldments was obtained by means of XRD analysis (Figure 13). The XRD patterns of all the weldments show the ferrite phase. Moreover, iron oxide was detected in the XRD pattern of S1, S2, and S3 samples; Fe₃O₄ was present in the S1 and S3
Figure 12. EDS X-ray mapping from the second phase particles in the S1 weldment.

Figure 13. XRD patterns from the fracture surfaces of the weldments.

weldments since Fe$_2$O$_3$ was found in the S2 welding metal.

**Discussion**

It is known that CNTs possess good chemical and environmental stability owing to their near-perfect structure. Nevertheless, graphene with 2D structure reacts more easily with many metals such as Al, Fe, and Ti and forms metal carbides at high temperatures [16]. For instance, the formation of Al$_4$C$_3$ in Al/graphene composite prepared by hot isostatic pressing and hot extrusion at 550°C has been reported by Bartolucci et al. [17]. They have stated that the harmful and brittle Al$_4$C$_3$ degraded the hardness and strength of Al/graphene composite. Thus, the fabrication of high-performance graphene-reinforced MMCs is challenging, especially
using melting and solidification or liquid phase sintering techniques due to the less knowledge about the interaction between the graphene and the metal matrix. It should be noted that the formation of carbide would decrease the contact angle of liquid metal and graphene, which will increase the wetting and improve the interfacial bonding [18]. To the best of authors’ knowledge, only one effort has been made for the fabrication of Fe/graphene composite. Lin et al. [18] have prepared Fe matrix composites reinforced with 2 wt-% graphene oxide (GO) by the laser sintering technique. XRD and HRTEM examinations of Fe/GO composites revealed the generation of cementite (Fe3C) at the edge of GO and the surface microhardness showed ∼94% increase compared with that of the BM. The strengthening of Fe was related to the survived GO during the melting and solidification process through laser sintering. Our tensile test and hardness measurement results indicated that the steel joints reinforced with graphene possessed superior mechanical properties in comparison to the unreinforced weldment (Tables 4 and 5). The enhanced mechanical properties of the graphene/steel weldments can be attributed to the survived graphene within the steel matrix, as clearly observed in Figures 8 and 10. The melting temperature of graphene (∼3200°C [19]) is much higher than that of the steel (∼1530°C). Thus, during the welding process, the steel was melted since GNSs were stable. On the other hand, the rapid heating and cooling during the welding process helped the GNS survive during the melting and solidification process. In spite of the addition of a relatively high amount of GNSs to the composite weldments, the XRD results (Figure 13) indicate that there is no carbide formation in our graphene/steel weldments, which may be attributed to the short contact time between the steel melt and GNSs before the solidification of the welding pool. However, the future further metal/graphene interface characterisation would be desirable for the validation of this result. The lack of iron carbide indicates that the high hardness and strength of graphene/steel joints are mainly attributed to the reinforcing effect of graphene through the following mechanisms: (i) grain size refinement, (ii) promoting the formation of acicular ferrite, (iii) dislocation strengthening, (iv) load transfer, and (v) impeding the formation of iron oxide. A significant grain refinement of the welding nugget zone occurred by the graphene addition, as confirmed by microstructural observations (Figure 6). The formation of finer grain structure has been reported in several graphene-reinforced metal-matrix composites [20,21] and ceramic-matrix composites [22,23]. It is believed that graphene hinders the grain coarsening during thermal processing owing to the effective pinning of grain boundaries [20]. The microstructure of weldment was changed from allotriomorphic ferrite and Widmanstätten ferrite to the fine acicular ferrite via the introduction of graphene in the welding nugget, as confirmed by Figure 6. The promotion of the formation of acicular ferrite in the steel weldments by the introduction of precipitates [24], inclusions [25–28], and reinforcement particles [29,30] has been frequently reported. For instance, Dabiri et al. [30] have shown that the amount of acicular ferrite in the welding metal increased through the intragranular nucleation on the ZrO2 nanoparticles. In fact, when the welding pool begins to solidify, the graphene nanosheets act as heterogeneous nucleation sites for the formation of acicular ferrite grains. The improvement of mechanical properties through the formation of acicular ferrite has been previously stated [29,31–33]. Dislocations can be piled-up against graphene nanosheets and forming dislocation forests due to the CTE mismatch between the metal matrix and graphene [34,35]. Since graphene and steel have CTE of approximately ∼8 × 10⁻⁶ K⁻¹ [36] and 15 × 10⁻⁶ K⁻¹ [37], respectively; thus graphene-reinforced composite joints possess significant CTE mismatch, which would result in the forest strengthening. The dislocation density generated by thermal mismatch in the iron matrix nanocomposite reinforced by GO was estimated as ∼1.45 × 10¹⁴ m⁻³ [18]. Furthermore, graphene nanosheets act as obstacles against the motion of dislocations, leading to the pile up of dislocations [38]. Orowan strengthening bowing mechanism can also be contributed to the strength improvement of graphene-reinforced composites. The impediment of dislocation movement increased the critical stress for dislocation glide, causing in the strengthening of metal-matrix composites [39]. The applied stress can be transmitted from the matrix to the reinforcement by means of shear stresses developed along the metal/graphene interface (Shear lag model) [40]. It should be noted that the stress could effectively transfer from the matrix to the reinforcement when a good interfacial bonding between them had been formed. A good interfacial bonding between the steel matrix and graphene nanosheets was proved by the SEM images from the fracture surface of the joints which displayed pulling out of some graphene nanosheets, as seen in Figure 10(f). Thus, the efficient stress transfer from the steel to the GNS could result in an increased strength of the composite. Similar observations have been previously reported in Al/graphene nanoplatelet [21] and Cu/graphene nanoplatelet and reduced GO [39] composites. Finally, one of the main factors affecting the mechanical properties of the joints is the formation of iron oxide particles during welding. It is known that E6010 electrodes used on low carbon steel generate a large quantity of iron oxide particles [41]. The formation of a significant amount of large iron oxide particles in the welding nugget of the unreinforced weldment was verified in Figures 10–13. Hence, both strength and ductility of the unreinforced weldment were degraded by iron oxide particles (Table 5). The addition of graphene through the coating on the groove
forced with graphene, including Al/graphene [42–44]. A further enhancement in the mechanical properties of weldments was achieved via welding by means of graphene-coated electrodes due to the almost complete elimination of detrimental iron oxide particles from the joints (Figures 10 and 13). The comparison of mechanical properties of graphene-reinforced weldments revealed that the addition of graphene into the welding nugget through the coating of electrodes was more efficient than the graphene addition by means of the coating on the groove laps. This was attributed to the higher weldability and arc stability during the welding by graphene-coated electrodes. In fact, oxygen penetrates and readily combines with the iron to form iron oxides due to the lack of arc stability during the welding of the samples in which graphene coated on the groove laps.

According to Table 5, not only strength and hardness, but also ductility was enhanced in the graphene-reinforced welding joints in comparison to the monolithic welding metal. This is an interesting result, since strengthening a metal with a reinforcement phase frequently gives rise to reducing its ductility. The elimination or reduction the quantity and size of brittle iron oxide particles obviously enhanced the elongation to failure of the graphene-reinforced weldments. Nonetheless, the improvement of strength without sacrificing ductility has been recently stated for some metal-matrix composites reinforced with graphene, including Al/graphene [42–44] and Mg/graphene [45,46]. This exceptional behaviour can be mainly attributed to the highly wrinkled structure of graphene and pulling out from the matrix through the graphene addition can be effective in the improvement of ductility [47]. However, the ductility of graphene-reinforced joints was degraded when the content of graphene in the weldment increased. This observation can be related to the agglomeration and coalescent of graphene sheets, which in turn led to the weak interfacial bonding between graphene and metal matrix [43,48].

Conclusions

The low carbon steel joints reinforced with graphene nanosheets were successfully fabricated using SMAW processing. The main findings can be summarised as follows:

(i) Microstructural examination showed that equiaxed and fine ferrite grains in the HAZ of the unreinforced weldment were replaced by allotriomorphic, Widmanstätten, and acicular ferrites in the graphene-reinforced welding metals.

(ii) The microstructure of both unreinforced and graphene-reinforced weldments at the FZ consisted of fine allotriomorphic, Widmanstätten, and acicular ferrites. As the graphene content in the weldment increased, the size of allotriomorphic ferrite colonies and Widmanstätten ferrite saw-teeths decreased while the amount of acicular ferrites increased.

(iii) With the addition of graphene to the welding metals, the hardness and strength of the weldments were significantly enhanced due to ferrite grain size refinement, promoting the formation of acicular ferrite, dislocation strengthening, load transfer, and impeding the formation of iron oxide.

(iv) The ductility of weldments was significantly enhanced by the graphene addition to the welding nugget, which can be attributed to the elimination/reduction of brittle iron oxide particles, grain refinement, and straightening the highly wrinkled structure of graphene and pulling out from the metal matrix during plastic deformation.

Disclosure statement

No potential conflict of interest was reported by the authors.

References


