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DISSIMILAR FERROUS METAL WELDING USING ADVANCED GAS METAL ARC WELDING PROCESSES

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Abstract. The construction industry has for many years shown interest in opportunities offered by the welding of dissimilar metals. The need for appropriate and effective techniques has increased in recent decades with efforts to meet wide disparities constraints in services. In power plants, metals with different characteristics can be welded to fit heterogeneous working conditions. Early GMAW processes had limited control over the heat input, but the advanced GMAW processes of the last decades offer new perspectives for welding dissimilar metals.

The objective of this paper is to review the basic principles of fusion welding of dissimilar metals. The study briefly investigates advanced GMAW processes with an emphasis on differences in their general operating principles and arc control. Experiments performed with dissimilar metals, such as stainless steels, carbon steels, and low-alloyed steels are reviewed and the welding process achievements highlighted.

The study collects data from scientific literature on fusion dissimilar metals welding (DMW), advanced GMAW processes, and experiments conducted with conventional GMAW. The study shows that the welding procedure specification is an important factor in DMW. Advanced GMAW processes have significant potential in fusion welding of dissimilar ferrous metals. Accurate control of the heat input allows a more effective prediction of intermetallics and a better control of post-heat treatments.

Increased understanding of advanced processes will permit the development of more suitable specifications of GMAW welding procedures for DMW. Process flexibility and adaptability to robotic mass production will allow a wider application of this process and the avoidance of costly alternative methods.

1. INTRODUCTION

Dissimilar metal welding has become a critical technology in many areas [1,2], austenitic stainless steel/low-carbon steel or high-alloy material/low-alloy steel for parts requiring strength and corrosion resistance. The integration of efficient quality welding technologies for dissimilar metals will be a key component in the successful weld quality for transportation and power plant systems [3,4]. The welding of dissimilar metals with melting one of the metals is efficient if the welding conditions that determine the duration of the interaction between the solid and liquid metal are strictly controlled [4].

The properties of the welded joints and the feasibility of the welding processes are influenced by many factors: for example, carbon migration from the low-alloy side, the microstructure gradient and residual stress situations across different regions of the weld metal [1,5]. The process of welding dissimilar metals is a very complicated one because the alloy's gradient can result in brittle intermetallic compounds. Friction stir welding [6], laser welding

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Table 1. Welding procedure requirement for ferrous metal [10,11].

Considerations	Observations
Fundamentals	- Dissimilar Metal Welding (DMW) requires consideration of all the basic factors found in conventional welding. - In contrast to similar material welding, the difference of the base metal and weld must usually be carefully analyzed. - The most important consideration is the weld metal composition and its properties.
Service consideration	- The service life of dissimilar metal joints depends upon the mechanical and physical properties, microstructural stability, and resistance to oxidation and corrosion. - The mechanical and physical properties of the weld metal as well as those of the two heat-affected zones must be suited for the intended service.
Filler metal selection	- Requirements are met by welds that are produced within a range of acceptable dilution rates, metallurgy compatibility, as well as mechanical, physical, and corrosion properties. - Filler metal selection can best be accomplished by using a combination of scientific principles, and manufacturing and service experience of the industrial disciplines involved.
Welding process	- Welding process selection constitutes an important factor in dissimilar welding

[7], and laser–TIG [8] hybrid welding processes have been used to join dissimilar metals. Unfortunately, these methods involve expensive equipment and complex welding procedures [9].

The paper aims to investigate and identify key improvements in weld mechanical properties and the microstructural compounds of dissimilar ferrous metals. This information helps lay a baseline for advanced welding process specifications and also demonstrates the significant contribution that advanced GMAW processes can bring to this category of welding.

The study gathers key data from scientific publications related to dissimilar metals welding with both traditional GMAW processes and the latest innovations in advanced GMAW. The analysis is carried out in terms of assessing the significant progress in joint quality made over the last decades by advanced process GMAW. The paper discusses the results obtained, provides guidance on applications, and evaluates the benefits that may accrue from yet unexplored combinations. This study contributes to improvements in welding procedure specifications for dissimilar metals by advanced GMAW processes.

2. DISSIMILAR METALS WELDING

This section briefly presents the different considerations of welding procedure specifications for fusion welding of dissimilar metals, focusing on the GMAW process. Table 1 illustrates the key issues involved in welding dissimilar ferrous metal. There are four main features: the fundamentals of DMW, service considerations, filler metal selection and the welding process.

3. DISSIMILAR WELDING OF FERROUS METALS

Dissimilar welding of two typical ferrous metals involves a different base metal and a filler metal. In this section, the difficulties involving dissimilar ferrous metals are presented and their weldability discussed. It is possible to achieve successful dissimilar ferrous metal joints if proper procedures are followed.

3.1. Problems with dissimilar ferrous metal welding

Welding dissimilar ferrous metals presents some difficulties. Table 2 presents the difficulties encountered and observations made in previous investigations. It can be observed that when welding stainless steel to carbon and low-alloy steels, hot cracking may occur because of low melting point impurities, such as phosphor (P) and sulfur (S). Moreover, there is a risk of low-temperature cracking, because of the increase in dilution of the base metal on the carbon/low-alloy steel side; the weld metal contains a hard martensite phase. This hard martensite phase

Table 2. Possible combinations of ferrous metal grades [12-14].

Combination	Observations	Difficulties
Low-alloyed steel to mild steel	- Welding parameters shall be chosen according to the low-alloyed steel and the consumables according to the mild steel.	- Limited risk of hardenability of the weld metal because of the alloy element from low-alloyed steel. - The low-alloyed consumable suitable for the combination will not have a positive influence on the strength of the joint.
Dissimilar low-alloy steel	- Consumables of a similar type to the steel should be used. If possible, the C_E of the consumable should be similar to the C_E of the less hardenable steel. - In the case of very hardenable high-strength steel, compromise and use an austenitic stainless steel electrode and lower preheating level.	- If only C_E is different, welding is most often done without problems. - A risk of wide HAZ due to the heat input. Leading to crack risk. - Very hardenable high-strength CrNi (Mo)-steel may cause welding problems due to difficulties with the heat treatment.
Stainless steel/carbon or low-alloy steels/steel	- Butter the carbon or low-alloy steel. Stainless steel filler can be used if the in-service temperature does not exceed 370 °C. - Use a stainless steel filler metal with a total alloy content high enough to prevent the formation of martensite. - Chrome (Cr) and nickel (Ni) equivalent	- A risk of martensite formation in the weld after dilution by the base metal and residual amounts of ferrite resulting in possible hot cracking. - The deposition of carbon steel or low-alloy steel filler metal on austenitic stainless steel can result in hard, brittle weld deposits. - Hot cracking may occur because of low melting point impurities such as phosphor (P) and sulfur (S).
Stainless steel/ stainless steel	- Reasonable compromise for heat treatment - Control of the weld metal microstructure - Careful choice of filler metal and welding procedure - Chrome (Cr) and nickel (Ni) equivalent	- The ferritic base metal and transition zone have high hardenability and localized stresses after welding. - A risk of sensitizing austenite, formation of martensite, and microstructure susceptible to corrosion - Some filler metals may give too high ferrite content, particularly the high-chromium, low-nickel.

has extremely high hydrogen-induced delay cracking [12].

3.2. Process weldability with dissimilar ferrous metals

The Schaeffler [15] constitution diagram in Fig. 1 shows the relationship between the weld metal constitution and structure, as well as possible problems. The thermal cycle is also a major factor because it governs the microstructure composition which relates to the chemical composition. To estimate the microstructure of a deposit, the nickel and the chromium equivalent are calculated from the composition, using a formula in abscissa and ordinate, respectively. Although the Schaeffer diagram is still widely used to predict the content of dissimilar weld deposits, the more recently developed diagrams have increased the scope and accuracy of ferrite number (FN) prediction, such as DeLong diagram [16], Espy [17], and Welding Research Council (WRC-1992) [18].

4. CASE STUDIES

The combination of ferrous metals widely differs in industries essential for power plants, such as the bioenergy, fossil or nuclear plant, as well as the food industries or manufactured products. This is due to the complexity and changes in the working conditions of all structures. For instance, the implementation of alloys in water wall membranes, which

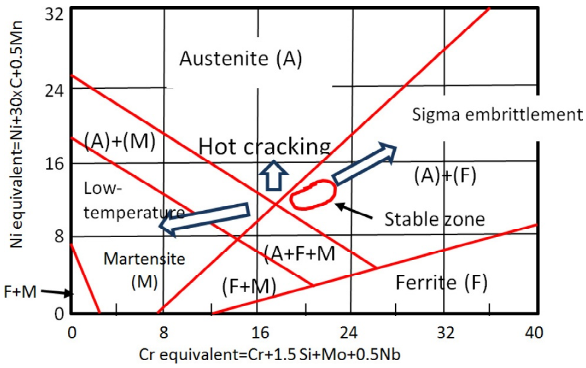

Fig. 1. Schaeffler constitution diagram and problems with welding dissimilar metals, stainless steel, and carbon steel, replotted from [19].

do not require post-weld heat treatment and the necessity for high creep strength and good oxidation resistance in superheater and reheater components, requires dissimilar metal weld (DMW) transition joints [20]. This section discusses and analyzes the different experiences of the fusion weld with different categories of ferrous metals. This analysis stresses the benefit that could be gained with advanced welding processes, the electrodes and the precautions to achieve better physical, mechanical, chemical, and metallurgical properties of the joint. This section is divided into three sub-sections: The first one considers the welding of dissimilar metals other than stainless steel, such as carbon steels and the high-strength low-alloy (HSLA) steels. Then the investigation focuses on the case of dissimilar welding steels previously analyzed with stainless steels. The analysis ends with dissimilar welding of stainless steels.

4.1. Other than stainless steel combinations

In industry it is often necessary to use non-stainless steel in places where oxidation is not the primary selection criterion. Other criteria such as the cost, high toughness, high strength, and high creep resistance at elevated temperatures are reasons to choose carbon steel, the HSLA steels, or structural steel. This choice can be made in the field of energy generation plants, bridges, housing, transportation, shipbuilding and aerospace. For example, given the complexity of power plants, it is very difficult to design them without welding different creep-resistance steels.

The mechanical properties of DMW joints regard the critical factors of load ability and safety warranty. In this regard, E. Lertora et al. [21] highlighted the use of a welding robot in a mass production setting. The enhanced process applied was a super-imposition metal active gas welding process (SP-MAG), which provided stable filler material transfer, based on adaptive waveform control. The study investigated dissimilar metals welds with S355 (EN 10025) steel and DP600 HSS (EN 10338). It was found that the process demonstrated the ability to produce a dissimilar weld with adequate structural characteristics. Fig. 2 shows the hardness profile with the absence of a softening area. Pouranvari [22] found in fusion resistance spot welding of similar and dissimilar high-strength low-alloy steel (HSLA) and low-carbon steel (LCS) that the microstructure and hardness of the fusion zone (FZ) were governed by the carbon content and alloy level of the FZ. In the particular case of dissimilar HSLA/LCS combinations, FZ chemical composition is affected by the mixing of both steels. Increasingly harder microstructures were observed as the carbon equivalent of the FZ increased. The mechanical performance of the joints combination revealed that the peak load of HSLA/LCS was similar to LCS/LCS. Both investigations show that proper welding heat input control and matching the electrode to minimize carbon migration can improve weld chemical and mechanical properties.

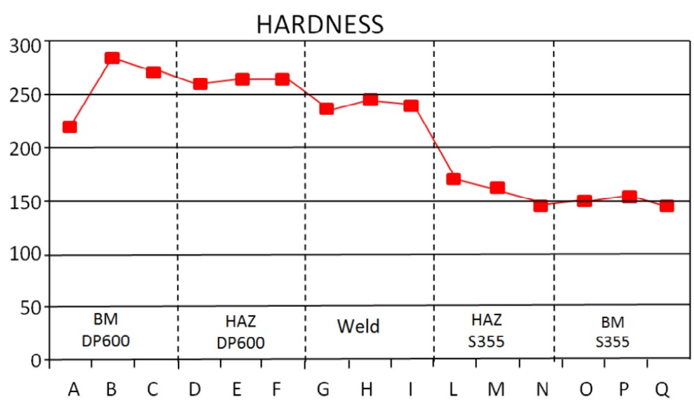

Fig. 2. Hardness profile measured in a S355 steel/DP600 steel heterogeneous joint, replotted from [21].

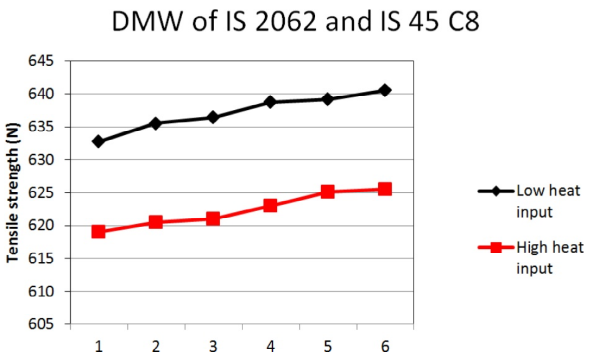

Fig. 3. Tensile strength for IS 2062 and IS 45 C8 joint at different heat inputs, replotted from [24].

Although the combination of mild steel and carbon steel can provide high rupture energy and bearing quality, their weldability poses a challenge because of the chemical composition difference. Mir Sadat et al. [23] evaluated the mechanical properties of the welded joint between dissimilar metals, mild steel IS 2062 (S275 JR according to EN 10025), carbon steel IS 45 C8 (C45E according to EN 8), bearing quality steel IS 103 Cr1 (EN-31), and carbon steel IS C 55 in the pairs IS 2602 and IS 45 C8, IS 2602 and IS 103 Cr1, as well as IS C 55 and IS 103 Cr1, and the effect of process parameters. When comparing the hardness of the parent metal, it was shown that the slight variation of alloying elements did not result in considerable physical changes for IS602, even though a significant change occurred in the mechanical properties. In addition, Monika et al. [24] investigated the effect of the heat input on the mechanical properties of GMAW welded two dissimilar joints, IS2062-IS 45 C8 and IS2062-IS103 Cr 1. It was observed that as the heat input decreases, there is an increase in the tensile strength in both dissimilar welded joints, and as the heat input increases, there is an increase in the hardness. Fig. 3 from Monika's studies shows a higher tensile strength corresponding to low heat input and a lower tensile strength corresponding to higher heat input. For both investigations it can be concluded that when materials with considerable differences in their mechanical properties are welded by an arc welding method, the mechanical properties of the weld bead depend to a great extent on the type of filler material used, the heat input applied, and the preheating and post-heating conditions of the weld bead. The findings indicate that the mechanical properties are considerably improved by the process control rather than being dependent mainly on the alloy element.

In order to combine low weight and higher toughness, high-strength steels are widely used in industry such as pressure vessel construction because of their good weldability and formability. They are, however, very sensitive to welding heat input and weld diffusion. Mohandas et al. [25] studied the heat affected zone softening in high-strength low-alloy steels. The effect of the chemistry of the steel and the welding processes SMAW, GTAW, and GMAW were investigated. The extent and degree of softening have been observed to be maximum in GTAW and GMAW, which are high heat input processes. Post-weld heat treatment in the austenite region eliminated the softened zone. It is possible to achieve successful DMW with HSLA steels if proper welding procedures are followed. Ranjbarnodeh et al. [26] carried out an investigation on the influence of welding parameters on residual stresses in dissimilar HSLA steels welds. A series of dissimilar steels joints based on the S600MC

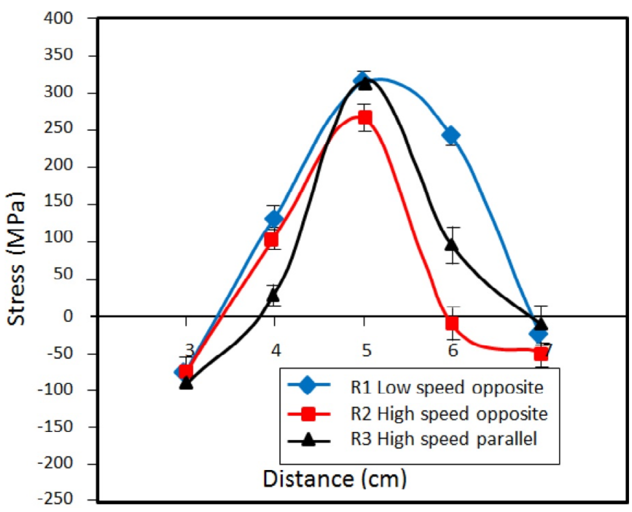

Fig. 4. The effect of welding speed and direction on residual stresses for a rectangular patch, replotted from [26].

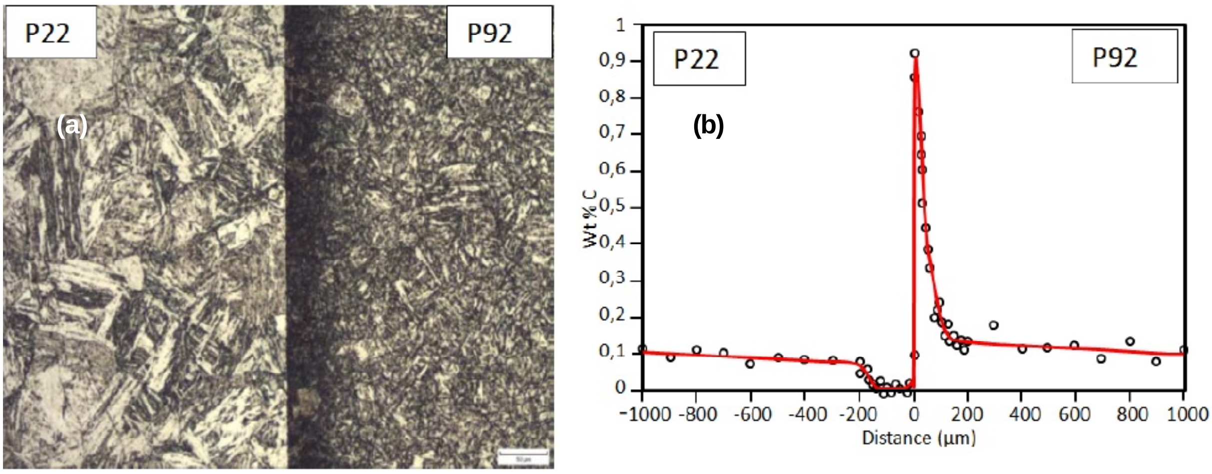

Fig. 5. P22/P91 weld after annealing 575°C/320h (a) Weld interface joint, (b) Carbon distribution, replotted from [31].

(EN 10149-2) (as base plate), S355 (EN 10025) (as the patch plate) and ER70S-6 (EN440 G3Si1) (as filler metal) were produced using robotic GMAW. It was found that the final state of residual stresses depends on the welding speed, the shape of the patch, and the balance by opposite direction. Figure 4 illustrates the effect of the welding speed and the direction of residual stresses for a rectangular patch. It can be seen that the minimum magnitude of residual stresses in the weld zone correspond to high-speed welding in the opposite direction. The sensitivity of residual stresses in the HAZ shows a direct relationship to the yield strength of the base metal. With regard to Mohandas and Ranjbamodeh's studies, the processes have a significant effect on the welding outcome; therefore, dissimilar HSLA steels can be done with careful control of the heat input and a suitable welding procedure specification (WPS).

In new installations or upgrades of steam turbines, dissimilar joints between modern 10% chromium steel and low-alloy steels are unavoidable. However, fusion welds made, for instance, between P22 (10CrMo9-10 according to EN 10028-2) and P91 (X10CrMoVNb9-1 according to EN 10302) steels which differ in their chromium contents have been shown to suffer microstructural instabilities at the DMW interface [27,28]. Figs. 5a and 5b show a sample of resistance welding with dissimilar metals P22 and P91, namely, their microstructure and carbon distribution respectively. When the gradient of carbon activity across the weld interface is at a temperature of 575°C, a distinctive change can be observed at 320 hours and the maximum concentration of carbon measure in the carbon enriched zone (CEZ) was 0.91 mass %. Seliger et al. [29] studied the high temperature behavior of dissimilar welded components of steel grades P22 and P91. The forged pipes with 45 mm thickness were welded using GTAW for the root pass and SMAW for the filler material. The dissimilar welds were welded with a P22-like electrode (2.25% Cr). A post-weld heat treatment was conducted at 760 °C for two hours and was cooled with air. Observation revealed a carbon/carbide depleted zone due to carbon diffusion from the P22 weld to the higher Cr containing P91 base metal. This migration had led to the formation of a dark seam of carbides adjacent to the weld interface. In addition, a softened area noticeable at the P22 side was the consequence of the decarburized zone in the P22 weld metal.

Tammasophon et al. [30] investigated the effect of PWHT on the microstructures and hardness of GTAW weldment of dissimilar P22 and P91 steel with Inconel 625 filler metal (Ni based filler metal, ERNiCrMo-3 according to EN 18274). The post-weld heat treatment at 750 °C for 2, 4, and 6 hours was applied in order to reach the proper microstructure and hardness for high performance in mechanical properties at elevated temperatures. It was observed that 750 °C for PWHT was suitable to reduce the hardness of the heat affected zone (HAZ) of P91 steel. The above finding reveals that an adequate weld between high temperature creep-resistance steel is a combination of suitable welding conditions, filler materials, and heat treatment.

4.2. Stainless steel to carbon or low-alloy steels

Dissimilar stainless steel and other steels are most often used where a transition in mechanical properties and/ or performance in service is required. For example, austenitic stainless steel piping is often

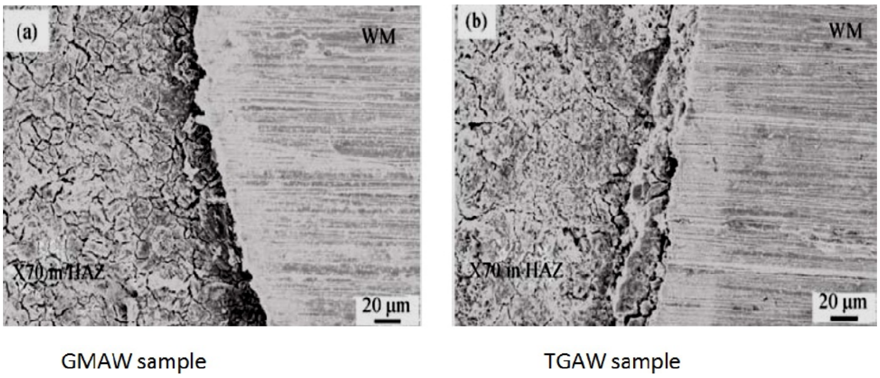

Fig. 6. Micrography of the weld after immersion for 30 days in artificial deep water, replotted from [35].

used to contain high temperature steam in power generation plants. Below a certain temperature and pressure, however, carbon steels or low-alloy steels perform adequately, and a transition from stainless to other steels is often used for economic purposes, because carbon steel or low-alloy steel is much less expensive than stainless steel [32].

Because of a difference in the chemical composition, it is difficult to melt both high corrosion resistance and low-carbon steels without a risk of affecting the mechanical properties. In this regard, Kaewkuekool et al. [33] studied parameters affecting the mechanical properties of dissimilar stainless (AISI 304) and low-carbon steel using the gas metal arc welding (GMAW) technique, and the application of three different filler metals were tested (GFW 304L, 308L [EN 12073] and 316L [EN 12072]). The result showed that welding parameters such as the welding speed, current, as well as filler metal type significantly affected the ultimate tensile strength and elongation. These parameters are among those affecting the microstructure of the weld. It is well known that there is a relation between the welding parameters and weld microstructure. Furthermore, the microstructure constitution is related to mechanical properties; Kim et al. [34] investigated dissimilar joints between STS441 (X2CrTiNb18 according to EN 1.4509), a ferritic stainless steel, and SS400, a carbon steel, and evaluated the microsture and high temperature properties of DMW. The experiments were performed using the GMAW process technique with a consumable electrode STS430LNb. Martensite was formed at the region between SS400 (S235JR according to EN 1.0037) and the weld metal because the chromium (Cr) and niobium (Nb) content in this region decreased due to the dilution of SS400 carbon steel during welding. From the welding process aspect, different processes may produce different weld results. Wang et al. [35] evaluated the quality of dissimilar weld joints in GMAW and GTAW welding of UNS S31803 duplex stainless steel (X2CrNiMoN22-5-3 according to EN 10088-3) and API X70 low-alloy steel (L485MB according to EN 10208-2) with ER2209 (EN 12072-99) welding wires with GTAW and GMAW, respectively. Figs. 6a and 6b from Wang's study show a severe corrosion of the GTAW sample at the fusion line compared to the GMAW sample.

Kaewkuekool, Kim, and Wang's studies point out that necessary compromises of different parameters are important to optimize a dissimilar stainless steel and carbon steel joint. A matching filler material and the use of buttering are necessary to reduce the alloy element gradient and carbon migration; furthermore the heat input control can contribute to a decreased risk of corrosion.

T. Maruyama [19] reported that during welding of stainless steel to carbon and low-alloy steels, it is of utmost importance to predict the nature of the mixed-composition weld metal, and the key aspects to be considered include the appropriate selection of welding additives and welding conditions. The observation gives clear evidence that different factors are to be controlled carefully and need to be adjusted during welding. Consequently, only feedback control is suited for the task. Teker et al. [36] pointed out that when welding ferritic steel (X6Cr17 according to EN 10088-2) and quenched and tempered steel (C30E according to EN 10083-1) with GMAW-P, welded joints exhibited superior tensile strength (Fig. 7), less grain growth, and a narrower heat affected zone compared to the GMAW welded joint, mainly due to better heat control, a finer fusion zone, and higher fusion hardness. That is to say, GMAW should provide optimal heat input and adequate performance to prevent the need for post-weld heat treatment.

Semi-automatic gas metal arc welding (GMAW) was used to weld a dissimilar butt joint in research by Sedek et al. [37]. A fine-grained low-alloy 18G2A

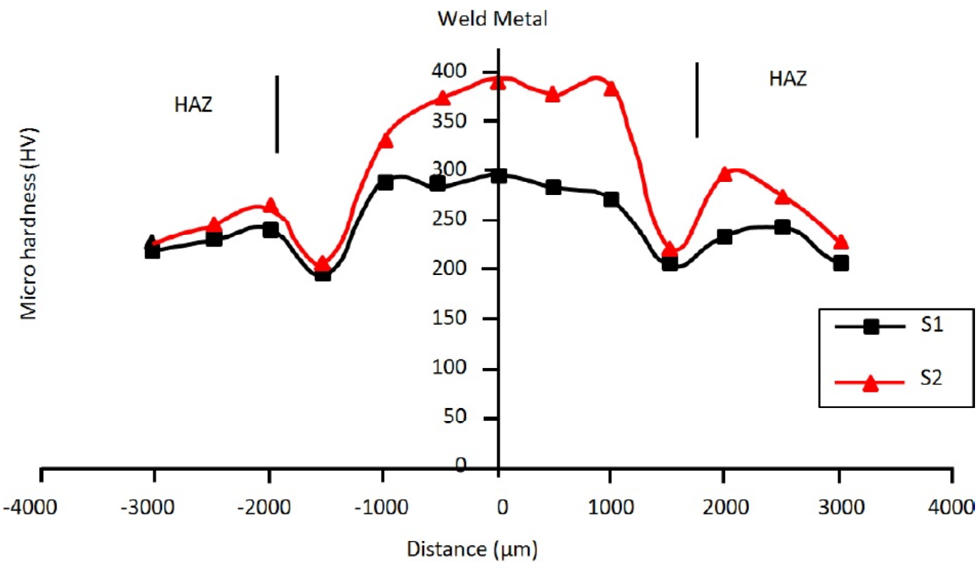

Fig. 7. Microhardness graphics of S1 (GMAW) – S2 (GMAW-P) sample, replotted from [36].

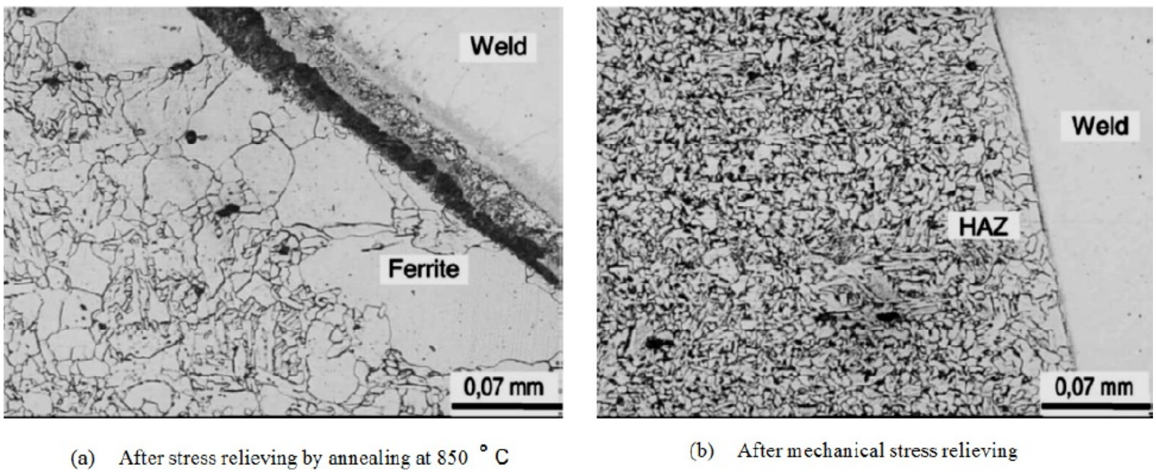

Fig. 8. Microstructure of the 18G2A/1H18N10T steel joints after stress relieving, replotted from [37].

steel (P355N according to EN 10028-2) and an austenitic 1H18N10T steel (X6CrNiTi18- 10 according to EN 10088-2) were used. A weld was formed which was free of unacceptable defects. The study evaluated the residual stress relief in the GMAW of dissimilar metals. The microstructures of the area close to the fusion boundary of the ferritic 18G2A steel and austenitic weld metal are shown in Figs. 8a and 8b, respectively, for the test joint stress relieved by annealing and by mechanical pre-stressing. The analysis of the results showed that the thermal relieving of the welded joint between dissimilar steels is not effective and may even increase residual stresses, due to the considerable difference in thermal expansion. Faber et al. [38] noted that thermal releasing faces difficulties because of different thermal coefficients and potential for the reactive carbon to migrate to areas with a higher concentration of carbide forming elements. Joseph et al. [39] conducted an experiment where the weld joint between the stainless steel pipe AISI 316 (X5CrNiMo17-12-2 according to EN 1.4401) and the ferritic 2.25Cr-1Mo (10CrMo 9-10 according to EN 1.7380) steel pipe is made using a conventional manual GTAW process with Inconel-82 filler metal (ERNiCr-3 according to EN 18274). The experiment was conducted with and without a few buttered layers of Inconel-82 filer metal on the ferritic side of the base metal. The study revealed that the Inconel-82 buttering layer employed in the dissimilar weld joint is useful in reducing the residual stresses in the HAZ of the ferritic steel and thus the buttering will be beneficial to avoid and minimize residual stress related failures in dissimilar metals welding.

4.3. Stainless steel to stainless steels

One stainless steel may be joined to another stainless steel, and varying degrees of dissimilarity are possible. For example, steels with different alloy

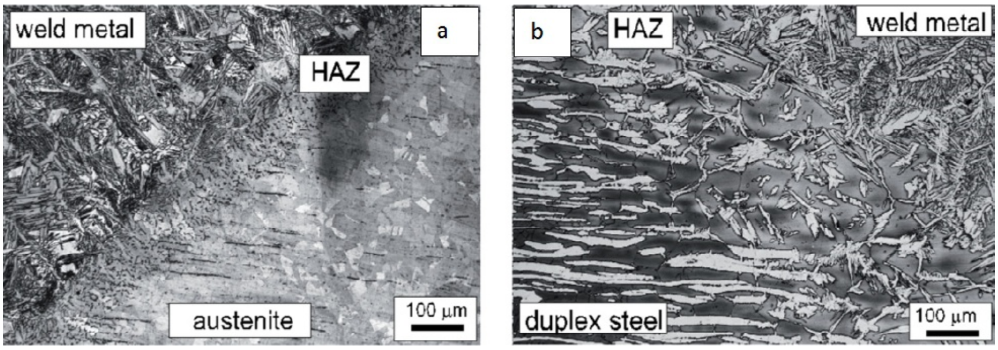

Fig. 9. Micrograph of dissimilar weld, (a) HAZ microstructure, austenitic side (b) HAZ microstructure, duplex steel side, replotted from [14].

contents but similar microstructures may be joined, or steels with different alloy contents and microstructures may be joined. Since stainless steels can have martensitic, ferritic, austenitic, or duplex microstructures, there are numerous microstructural combinations. The reasons for these combinations may be economic and/or properties considerations, or sometimes just convenience. A common convenience issue is to identify a single matching filler metal suitable for more than one base metal [32]. Fig. 9 shows micrographs of weld zone area between dissimilar austenitic and duplex stainless steel.

Local stresses resulting from the large creep-strength mismatch between the different regions of dissimilar weld joints can occur at the operating temperature [40]. Complex metallurgical structures can develop at the weld interface of dissimilar weld joints either during welding, during subsequent post-weld heat treatment (PWHT), or during service at elevated temperatures [41,42]. Furthermore, carbon migration from the ferritic steel into austenitic steel weld metal can produce a decarburized zone in the ferritic steel adjacent to the fusion boundary [43]. The use of a nickel base weld metal can cause a semi-continuous band of carbides to develop close to the weld interface during PWHT and during service [43]. Heat input and filler metal are among the key factors that govern microstructure formation. Mukherjee et al. [44] investigated the effect of heat input on martensite formation and impact properties of GMAW with welded modified stainless steel 409M (X2CrTi12 according to EN 1.4512) using two different austenitic filler wires (308L [EN 12073] and 316L [EN 12072]). Weld metals submitted to elevated heat inputs exhibited higher martensite laths and toughness compared to those submitted to medium and low heat input, which was also true for both the filler wires. Moreover, 308L weld metals provided a higher amount of martensite laths and toughness than 316L weld metals at the same heat input. The investigation revealed that the microstructure as well as the impact property of the weld metal was significantly affected by the heat input and filler wire. Concerning the filler metal, Shanmugam et al. [45] and Kotecki [46] suggested austenitic filler metals to be the most suitable ones from the point of view of mechanical properties. It is often used to prolong the life of ferrite–austenite dissimilar weld metals due to improvements in toughness, strength (due to the formation of stress induced martensite), and corrosion resistance.

In stainless steel welds, the microstructures were related to solidification types [16] i.e. solidification and subsequent transformation behavior. The heat input is handled differently for each welding process and can result in different effects on the dissimilar stainless steel welded joins [47]. Hsieh et al. [48] studied the microstructure, recrystallization, and mechanical properties in the heat affected and fusion zones of dissimilar stainless steels. Two types of stainless steels, namely 304 (X5CrNi18-10 according to EN 1.4301) (fully austenite containing a few ferrite phases) and 430 (X6Cr17 according to EN 1.4016) (fully ferritic microstructure) were welded using GTAW without a filler material. The recrystallization phenomenon was evident with the second pass heat-affected zone (HAZ-2) and indicated equiaxed grains after second pass welding. The contents of δ-ferrite exhibited the highest value of all situations in the first pass fusion zone (FZ-1) during first pass welding (Fig. 10). These findings confirm the effect of heat input even when filler is not used. However, it should be pointed out that the filler metal and buttering are unavoidable when the dissimilarity between the base metals cannot result in joints that are free of flaws.

5. COMPARISON AND BENEFIT

This section compares advanced GMAW concepts with the conventional GMAW process in dissimilar

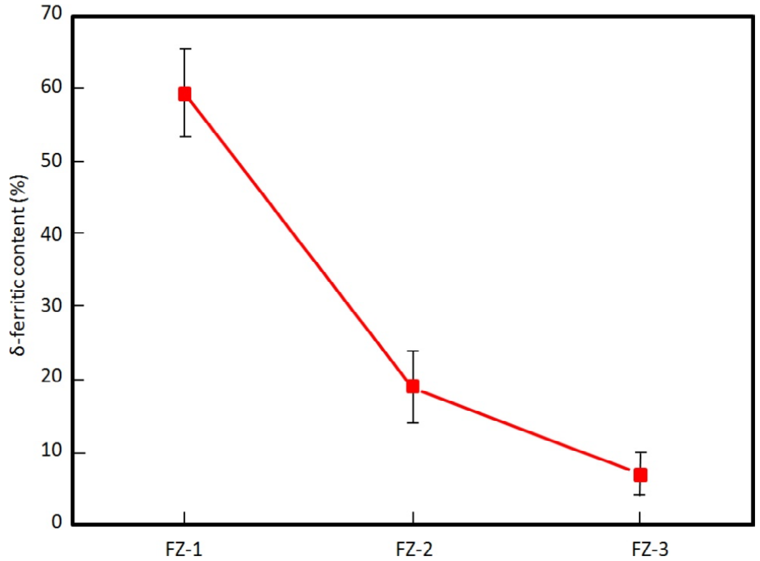

Fig. 10. The δ-ferrite content of the fusion zones at various welding passes during multi-pass welding, replotted from [48].

metals welding. Table 3 presents the relationship between welding control technologies, combinations of base metals, and expected weld quality. It can be clearly seen that the control mode has a very significant effect on the chemical, physical, and mechanical properties of the weld. The control mode regulates the size of the heat affected zone, the composition of intermetallic compounds, and the

Table 3. Comparison of advanced GMAW concepts when used in DMW.

Control Technique		Limitation	Application	Observations of applicability
Advanced and adaptive GMAW	Waveform control	If restricted to the wave form, the technique may only affect the control of heat input and stability of the arc.	- Low-alloy to mild steels - Dissimilar low-alloy steels - Stainless to low-alloy steels - Dissimilar stainless steel	Very good ability
	Waveform and filler control	If restricted to the wave form and alternative wire motion, the technique may only affect the control of heat input and stability of the arc.	-Low-alloy to mild steels - Dissimilar low-alloy steels - Stainless to low-alloy steels - Dissimilar stainless steel	Higher, excellent ability
Conventional control		Limitations in control dramatically affect the control of heat input, stability of the arc, and regulation of the flow gas.	- Low-alloy to mild steels - Dissimilar low-alloy steels - Stainless to low-alloy steels - Dissimilar stainless steel	Fair ability

microstructure of the weld and the heat affected zone, and thus overall weld quality. Acceptable weld properties require a thin layer of an intermetallic compound, sufficient dilution to minimize alloy elements migration, and an excessive heat affected zone which results in softening the area.

6. CONCLUSIONS

This study investigated advanced and adaptive GMAW processes as applied to dissimilar welding and presented data to improve welding procedure specifications. Based on the review of previous studies, the below presented conclusions can be drawn.

Several combinations are possible with metals other than stainless steel. A number of them consist of carbon steel and alloy steels. To this list we can add high-strength steels and high temperature creep resistance steels. Advanced control welding techniques are a major asset for the fusion welding of these dissimilar welding metals. For high-strength low-alloy (HSLA) steels and low-carbon steels (LCS) the risk is of carbon migration from the LCS side to the HSLA side when welding is done without a filler material. It therefore becomes necessary to involve a suitable filler metal and acceptable temperature control to minimize the dilution zone and the heat affected zone (HAZ) by temperature.

The welds between carbon steels, structural steels, or bearing quality steel are very sensitive to welding heat input. Although the choice of filler metal has crucial influence, the heat source intensity factor significantly affects mechanical properties as well. The hardness increases with high heat, and, contrary to the tensile strength, it reduces as the heat input increases. It appears that once a selection of the welding wire is made, the control of welding parameters such as current, voltage, and speed must be carefully controlled for in order to have the desired mechanical property results.

A major problem when high-strength steels are welded is the softening of the heat affected zone (HAZ) by the heat input. It has been shown that post-heat treatment in areas with austenite significantly reduced the softened area. An exception must be made to some high tensile strength methods, such as the thermo–mechanical process control for which a post-heat treatment may not be able to correct the softening due to excessive heat. In addition, the welding processes generating a high amount of heat input, i.e. GTAW and GMAW are likely to generate the largest heat affected zone. The HAZ has a direct effect on the yield strength. Welding parameters such as the welding speed and welding direction directly impact on the residual stresses.

Provided that the growing importance of the use of high temperature creep-resistance steels, DMW is inevitable in power plants during their repair or upgrading. These welds suffer from flaws of microstructure due to their different elements such as chromium, but also carbon. When welded without a filler metal, there is a strong migration of carbon toward the lower concentration of the chromium side. Choosing a suitable filler metal is strongly recommended, e.g. a nickel-based filler metal would lead to a good weld quality. A wire metal and a proper supply of post-weld heat treatment (PWHT) are necessary to significantly reduce the hardness of the heat affected zone.

Fusion welding of stainless steels and carbon steels is possible. However, a harmful effect on the mechanical properties of the base metals is likely to occur because of their chemical constitution differences, but numerous studies indicate that a compromise between the filler metal, welding speed, and current produces acceptable welds. The use of different processes such as GMAW and GTAW showed significant differences after immersion in artificial water depth at 4 °C. In addition, a manual GMAW and GMAW-P have shown clear differences in weld hardness tests. In order to reduce stress concentrations it is highly recommended to perform mechanical stress relieving rather than stress relieving by annealing at 850 °C method. This may aggravate residual stresses due to the thermal coefficient difference of both metals.

The welding of dissimilar stainless steels can lead to undesirable phases such as martensite, which is likely to develop when the heat input is important. This is true regardless of the filler metal; however, it should be indicated that 308L, for instance, showed a propensity to develop martensite more than 316L, when used for welding stainless steels 409M. Austenitic filler metal is recommended for welding dissimilar stainless steels like austenitic and ferrite. During multi-pass welding where recrystallization was observed between 304 and 430 stainless steels, the content of d-ferrite is the highest at the fusion zone of the first pass. The welding conditions and process affects the mechanical properties, chemical resistance, and corrosion cracking.

The weldability of dissimilar ferrous metals requires observing different criteria: the base metal properties, the electrode, in-service, as well as the selection of the welding process. The utilization of robots with advanced process GMAW for welding dissimilar metals, such as S3455 and AHSS, gives satisfactory results as regards both the composition of the microstructure and the physical properties. When STS441, a ferritic stainless steel, and SS400, a carbon steel, were welded with GMAW, the dissimilar weld had a high temperature tensile strength equal to STS441, and martensite at the interface had nearly no influence on the high temperature tensile strength of the dissimilar weld.

Adaptive control GMAW permits the optimization of the welding parameters such as current, voltage, electrode feeding rate, and contact tips to work distance (CTWD), which improves its feasibility for fusion welding of dissimilar metals. Consequently the dilution control minimizes the migration of alloy elements, such as phosphor, sulfur, and carbon. The ability to control dilution is beneficial for dissimilar welds of high-alloy to stainless steel, and quenched steel to ferritic steel.

Selecting the welding process is a key factor when welding dissimilar ferrous metals, as well as choosing the proper electrode. Since the heat input affects dilution and alloy element migration, the greater flexibility and sensitivity of adaptive GMAW allows a reduction in the dilution and residual stress caused by differences in the thermal coefficient.

REFERENCES

[1] P. Praveen and P. Yarlagadda // *J. Mater. Process. Technol*. **164** (2005) 1106.

[2] T. Aizawa, M. Kashani and K. Okagawa // *Weld. J.* **86** (2007) 119.

[3] K. Hwan-Tae and K. Sang-Cheol // *Commun. Comput. Inf. Sci.* **341** (2012) 199.

[4] Y. V. Budkin // *Weld. Int*. **25** (2011) 523.

[5] Z. Sun and R. Karppi // *Mater. Process. Technol.* **59** (1996) 257.

[6] M. Aonuma and K. Nakata // *Mater. Sci. Eng. B* **173** (2010) 135.

[7] R. Borrisutthekul, Y. Miyashita and Y. Mutoh // *Sci. Technol. Adv. Mater.* **6** (2005) 199.

[8] L. Liu, X. Liu and S. Liu // *Scr. Mater*. **55** (2006) 383.

[9] H. Zhang and J. Song // *Mater. Lett*. **65** (2011) 3292.

[10] A. O'Brien, *Welding Handbook, Volume 4 - Material and Application, Part 1* (American Welding Society, Florida, 2011).

[11] J. W. Elmer, D. L. Olson and D. K. Matlock // *Weld. J*. **61** (1982) 293.

[12] D.L. Olson, T.A. Siewert, S. Liu and G.R. Edwards, *ASM Handbook, Volume 6, Welding, Brazing, and Soldering* (ASM International, Ohio, 2003).

[13] J. N. Dupont and C. S. Kusko // *Weld. J*. **86** (2007) 51.

[14] J. Łabanowski // *J. Achiev. Mater. Manuf. Eng.* **20** (2007) 255.

[15] A. L. Schaeffler // *Met. Prog*. **56** (1949) 680.

[16] C. J. Long and W. T. DeLong // *Weld. J.* **52** (1973) 281.

[17] R. H. Espy // *Weld. J*. **61** (1982) 149.

[18] D. J. Kotecki and T. A. Siewert // *Weld. J.* **71** (1992) 171.

[19] T. Maruyama // *Weld. Int*. **17** (2003) 276.

[20] K. Dawson and G. J. Tatlock, In: *The Eighth International Charles Parsons Turbine Conference* (IOM3: London, 2011).

[21] E. Lertora, C. Gambaro and P. Cypres // *Weld. Int.* **25** (2011) 767.

[22] M. Pouranvari // *Can. Metall. Q.* **51** (2012) 67.

[23] A. Mir Sadat and R. Srinivasa // *Int. J. Eng. Sci. Technol.* **3** (2011) 4411.

[24] K. Monika, M. Bala Chennaiah, P. Nanda Kuma and K. Prahalada Rao // *Int. J. Eng. Res. Technol*. **2** (2013) 1406.

[25] T. Mohandas, G. Madhusudan Reddy and B. Satish Kumar // *J. Mater. Process. Technol*. **88** (1999) 284.

[26] E. Ranjbarnodeh, M. Pouranvari and A. Fischer // *Metall. Mater. Eng.* **19** (2012) 33.

[27] C. Sudha, V. T. Paul, A. L. E. Terrance, S. Saroja and M. Vijayalakshmi // *Weld. J.* **85** (2006) 71.

[28] H. Heuser, C. Jochum, W. Bendick, B. Hahn and R. Fuchs // *Weld. World* **52** (2008) 217.

[29] P. Seliger and A. Thomas, In: *5th International Conference on Mechanics and Materials in Design* (Porto, Portugal, 2006), p. 1.

[30] C.-C. Hsieh, D.-Y. Lin, M.-C. Chen and W. Wu // J. *Met., Mater. Miner.* **21** (2011) 93.

[31] P. Šohaj, V. Jan and O. Dvořáček, In: 1*9th annual Conference METAL* (Rožnov pod Radhoštěm, Czech Republic, 2010), p. 1.

[32] J. C. Lippold and D. J. Kotecki, *Welding metallurgy and weldability of stainless steels* (John Wiley & Sons, New Jersey, 2005).

[33] S. Kaewkuekool and B. Amornsin, In: *Proceedings of the 1st WSEAS International Conference on MATERIALS SCIENCE* (Bucharest, Romania, 2008), p. 105.

[34] J.K. Kim, S.G. Hong, K.B. Kang and C.Y. Kang // *Met. Mater. Int.* **15** (2009) 843.

[35] J. Wang, M.-X. Lu, L. Zhang, W. Chang, L.-N. Xu and L.-H. Hu // *Int. J. Miner. Metall. Mater.* **19** (2012) 518.

[36] T. Teker and T. Kurşun // *Mater. Manuf. Process*. **26** (2011) 926.

[37] P. Sedek, J. Brózda, L. Wang and P.J. Withers // *Int. J. Press. Vessel. Pip*. **80** (2003) 705.

[38] G. Faber and T. Gooch // *Welding in The World* **20** (1982) 87.

[39] A. Joseph, S. K. Raib, T. Jayakumar and N. Murugan // *Int. J. Press. Vessel. Pip.* **82** (2005) 700.

[40] R. W. Evans and B. Wilshire, *Design of High Temperature Metallic Components* (Elsevier Applied Science Pub, New York, 1984).

[41] B. Nath, In: *Proc. 4th Int. Conf. Deutschen Verband fur Schweibtechnik* (Dusseldorf, Germany, 1982).

[42] N.A. McPherson, T. Baker and D. Miller // *Metall. Mater. Trans. A* **29** (1998) 823.

[43] R.L. Klueh and J.F. King // *Weld. J.* **61** (1982) 302.

[44] M. Mukherjee and T. Pal // *J. Mater. Sci. Technol.* **28** (2012) 343.

[45] K. Shanmugam, A. K. Lakshminarayanan and V. Balasubramanian // *J. Mater. Sci. Technol*. **25** (2009) 181.

[46] D. J. Kotecki // *Weld. J*. **84** (2005) 14.

[47] G. Madhusudhan Reddy, T. Mohandas and A. Sambasiva // *Mater. Manuf. Process*. **20** (2005) 147.

[48] C.C. Hsieh, D.Y. Lin, M.C. Chen and W. Wu // *Mater. Trans*. **48** (2007) 2898