Rev. Adv. Mater. Sci. 44 (2016) 146-159

# DISSIMILAR HIGH-STRENGTH STEELS: FUSION WELDED JOINTS, MISMATCHES, AND CHALLENGES

**B. Mvola, P. Kah, J. Martikainen and R. Suoranta**

Lappeenranta University of Technology, School of Energy Systems, P.O. Box 20, 53851 Lappeenranta, Finland

*Received: June 16, 2015*

**Abstract.** One of the major obstacles to the use of conventional steels in higher height infrastructure has been their weight. The demand for materials with a good ratio of high strength and light weight has arisen from new challenges inherent in changed working conditions and environments. In recent years, conventional steels have been successfully welded to high-strength steels (HSS). It is expected that demand for dissimilar welding of HSS will grow because of the characteristics of HSS and its diversity.

The objectives of this study are to develop a framework for dissimilar high-strength metal welding compatibilities and to provide suitable welding procedure specifications necessary to achieve acceptable weld quality and flawless joints. In addition, the study takes into consideration the effect of high-strength steel manufacturing techniques on welding properties.

The methods comprise an experimental review of scientific papers based on dissimilar metal welding experiments of high-strength steels and an analysis of the properties of different HSS grades, and the paper suggests different combinations of steels, electrode selection, welding processes and suitable heat treatments.

The results show that dissimilar high-strength steels provide better mechanical joint properties with higher impact toughness resistance and better ductile-to-brittle transition. The corrosion resistance of the heat-affected zone and the weld depend on the alloy elements and the manufacturing of the base metal.

Due to their diversity, dissimilar high-strength steels offer advantages in demanding applications such as industrial applications for nuclear plants, equipment operating in challenging environments, higher amplitude lifting devices and sustainable energy production.

## 1. INTRODUCTION

Welding joints with different metals is common, particularly when responding to the stress associated with the welded joint. It is often recommended that a welded joint with the same base metal should have a mismatch weld. This mismatch characteristic of the weld is to ensure that the welded joint withstands in-service constraints and provides good weld quality. Besides the desire to achieve acceptable weld quality, dissimilar welded joints may be aimed to meet a functional need. Particular functional needs can concern a specific quality of the weld, such as different thermal conditions near the joint, strength, type of wear, corrosion, or reduced total weight while maintaining essential physical properties. The need for dissimilar weld metals is significant because their application is becoming increasingly essential in design.

The definition of high-strength steel varies depending on the source. Steels with ultimate tensile strength (UTS) below 450 MPa are called conventional high strength steels. Steels with a UTS rating between 450 and 800 MPa are defined as advanced high-strength steels (AHSS). Ultra high-strength steels (UHSS) are those with a UTS beyond 980 MPa. Other sources designate all steels with a UTS

Corresponding author: B. Mvola, e-mail: Eric.Mvola.Belinga@lut.fi

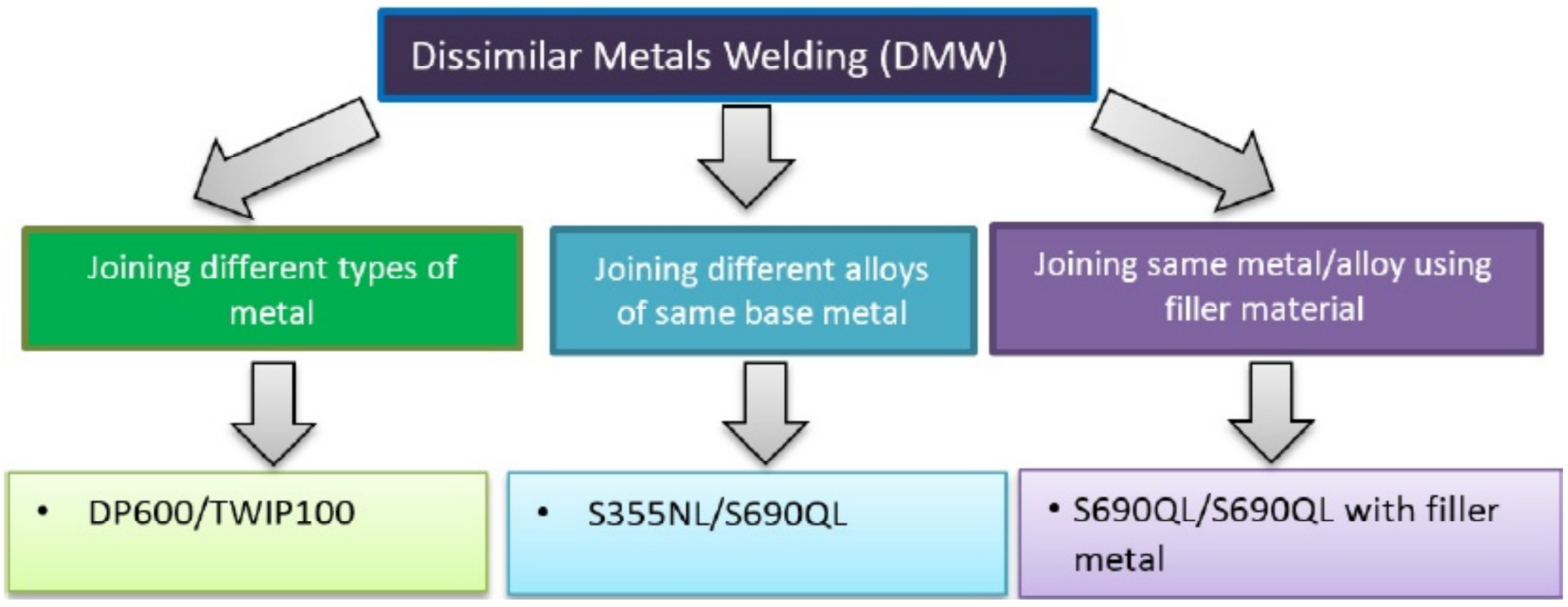


**Fig. 1.** Dissimilar welding categories.

above 550 MPa as UHSS. Several studies have been carried out on the welding of dissimilar HSSs. Most of these focus on resistance spot welding (RSW) [1,2], others on laser welding (LW) [3] and a rather small number on gas metal arc welding (GMAW) [4]. However, there are only few studies that address the DMW of HSS comprehensively considering the major challenge of the continuous reduction of the weldability lobe as the strength increases.

This study aims to investigate the fusion welding of HSSs to identify the difficulties involved, raise awareness of possible problems that may be encountered during welding, and provide guidance on various combinations of HSS. The study investigates combinations from 300 MPa up to the maximum available.

The study briefly reviews the welding of HSSs, then analyses the different categories of DMW and finally develops a cross-examination of different combinations, their associated incompatibility in different manufacturing processes and the effect of thermal treatments. Fig. 1 shows the different categories of DMW in fusion welding investigated in this study.

Better knowledge can mean significant progress in dissimilar welding in HSS welding procedures, and the advantages thus obtained are as vast as the wide range of applications of these metals, for example, in the energy industry (power plants, wind power), transportation (cars, vehicles, rail vehicles), lifting devices (mobile cranes, truck mounted cranes), infrastructure (housing, bridges), features that highlight precision and demand consistency, offshore platforms, and highly loaded applications such as roof supports in mines.

## 2. CHALLENGES IN WELDING DISSIMILAR HIGH-STRENGTH STEELS

High strength steels are designed to improve weldability of steels in general, however, it has been observed that some challenges still surround these steels. For example, it has been noted that difficulties and sensitivities in welding effects increase with increasing carbon content and alloying elements (e.g. Al, Si, Mn) [6]. The method of manufacturing of HSS steels, which combines thermal and mechanical control, poses additional challenges to the welding process [5]. To maintain HSS weldment qualities, it is necessary to perform very strict control of welding parameters. Transformations of these metals at the end of the welding operation, which significantly affect the microstructure and mechanical properties and fatigue life, are difficult or practically impossible to reverse despite post heat treatments after welding [7,8]. Because of the different methods that are used to manufacture the various high strength steels available, welding conditions that are applicable to one steel may not be applicable to another [7,9,10]. This is an important factor to consider in the case of welding dissimilar metals. Fig. 2 shows how two different high-strength steels from different weldability zones may exhibit different challenges in welding and require the designing of specific welding procedures.

The carbon content is a factor to be considered along with other austenite stabilizers, as has already been noted above. Risks are particularly associated with a significant increase in the diffusion quantity of brittle component elements during very rapid cooling, especially around the fusion zone (FZ) and heat affected zones (HAZ) [1]. These risks are the fundamental reason for the establishment of appropriate welding procedures for these metals in general and particularly for the dissimilar welding of high strength steels.

Welding procedures in the case of high strength steels include several key factors. Among them, there are the use of equivalent carbon (CE) equations to evaluate weldability. Grafille's diagram in Fig. 2 is an illustration for determining the degree of difficulty of welding a high strength steel. In addition to carbon equivalent must be added analysis of the

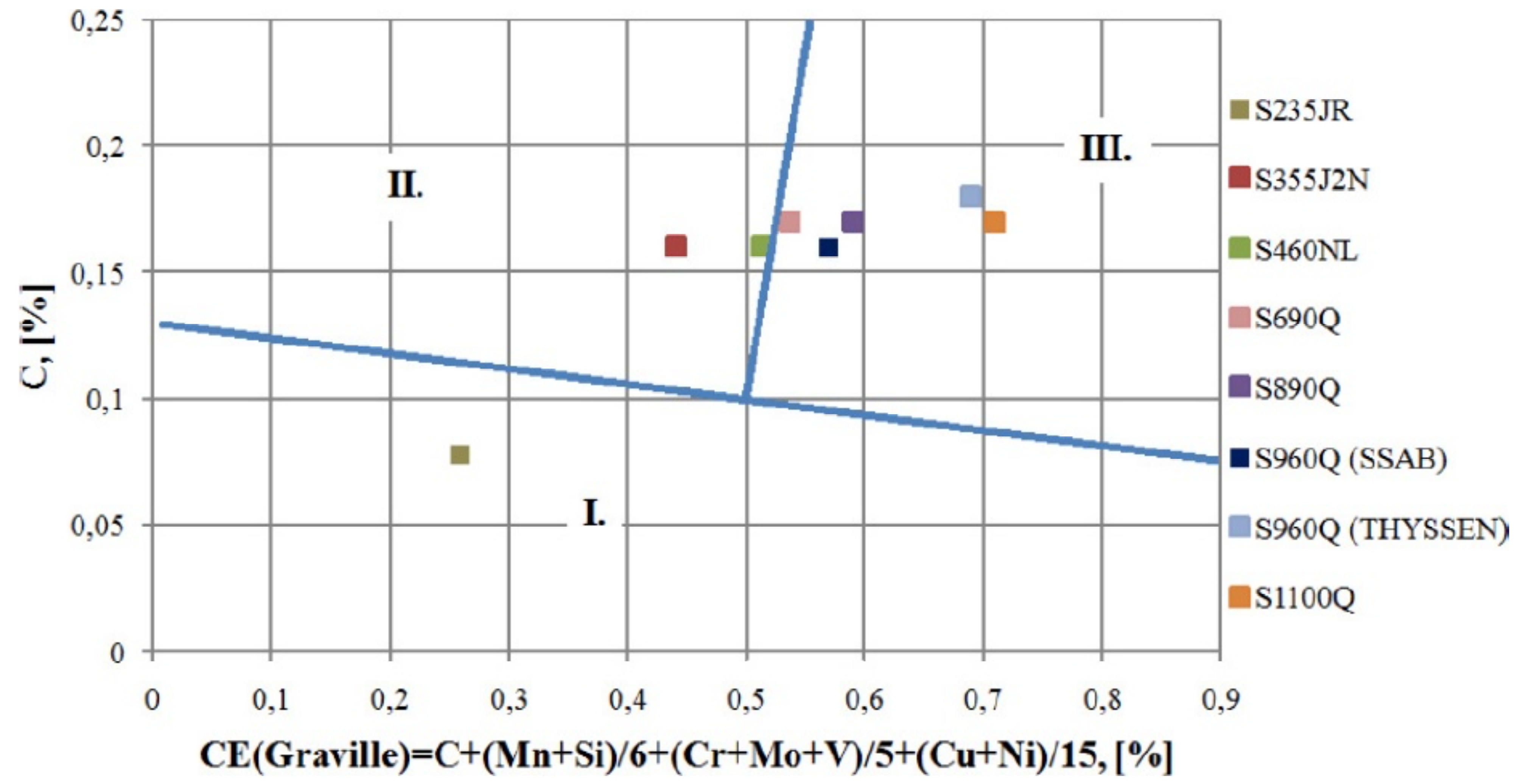


**Fig. 2.** Weldability of structural steels by the Graville diagram. Reprinted with permission from Gáspár et al. // *Production Processes and Systems*, **6** (2014) 1. © 2014 OSZK.

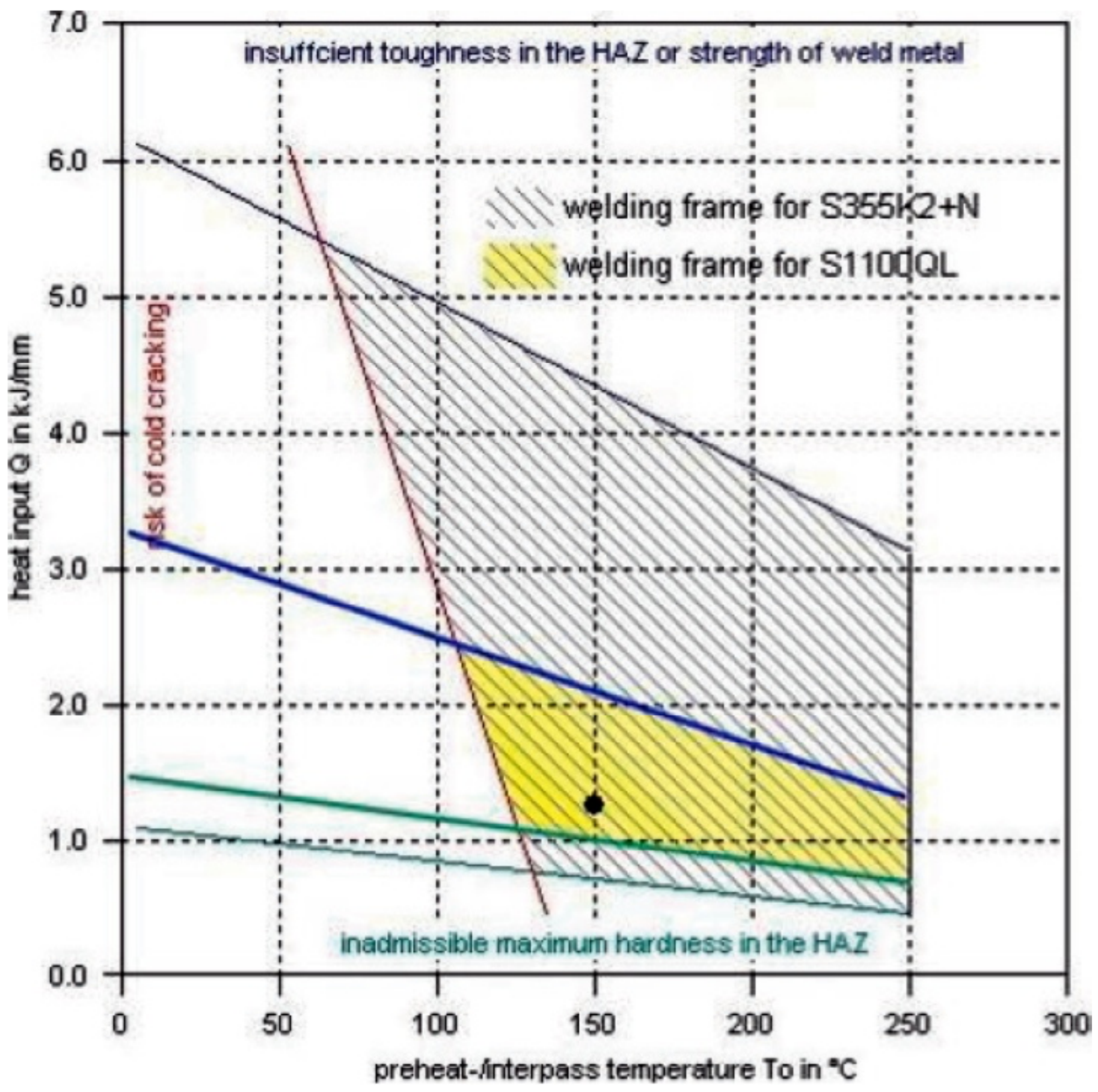


**Fig. 3.** Welding frames of S335K2+N and S1100QL grades. Reprinted with permission from *Thyssenkrupp*, (2015) 28. © 2015 Thyssenkrupp.

thermal conditions of the welding process, as they define the welding cooling time and conditions. The admissible temperature limit takes into account the preheating and possible inter-pass temperatures. It is possible to define an acceptable welding lobe for each HSSs on the basis of the temperature of the pre-heat or inter-passes and heat input required. Software thus makes it possible to plot the allowable welding limit frame of the HSS. Fig. 3 presents the two welding frames of S355K2+N and high S1100QL grades given by welding software based on the CE method [12]. In the case of a dissimilar weld between the two metals, it is necessary to take care to keep the temperature within S1100QL limits, since its welding temperature condition is smaller and inside the allowable heat frame of S355K2+N. This example is evidence that high-strength steels have more restrictions on welding conditions than mild steel and require a method to ensure these conditions are respected.

**Table 1.** High-strength steel (HSS) characteristics and examples.

| (UTS<600 MPa)<br>Characteristic features | Example |
|---|---|
| BH (bake hardening): increase strength during paint treatment by controlled carbon (C) aging | BH 280/400 (YS: 300-360 MPa, UTS: 420-480 MPa) |
| IF-HS (high-strength interstitial free):increase strength by manganese (Mn) and phosphorus (P) addition | IF 300/420 (YS: 320 MPa, UTS[mini]: 420 MPa) |
| P (rephosphorised): phosphorus-alloyed strength steels | H220PD (YS[mini]: 220 MPa, UTS [mini]: 420) |
| IS (Isotropic): increase in strength with sisotropic flow behaviour, micro-alloyed with Ti or Nb | HC260I (YS: 220/260, UTS[mini]: 300/380) |
| CMn (Carbon-manganese): strengthened with an increase of C, Mn and Si addition for solid solution strengthening | CMn 440 (YS[mini]: 295 MPa, UTS [mini]: 510) |
| HSLA (high-strength low-alloy): strengthened by micro-alloying with Nb or Ti | HSLA 550/650 (YS: 585 MPa, UTS[mini]: 650 MPa) |

**Table 2.** Advanced high-strength steel (AHSS) characteristics and examples.

| (600 MPa<UTS<1060 MPa) Characteristic features | Example |
|---|---|
| DP (Dual phase): content ofmicrostructure of ferrite and 5–30 volume % martensite islands. | DP 980 (YS: 644 MPa, UTS: 1009 MPa) |
| TRIP (transformation induced plasticity): | TRIP 800 (YS: 478 MPa, UTS: 825 MPa) |
| PM (partially martensitic): partially or fully martensitic steels | M220 YS[mini]: 295 MPa, UTS [mini]: 510) |
| CP (complex phase): Mixture of strengthened ferrite, bainite and martensite | CP 1050//1470 (YS: 1060 MPa, UTS: 1470 MPa) |

**Table 3.** Ultra high-strength steel (UHSS) characteristics and examples.

| (UTS>1060 MPa) Characteristic features | Example |
|---|---|
| HMS-TRIP (high manganese-TRIP): contents an alloying concept with strain-induced | MS1250/1500 (YS: 1265 MPa, UTS: 1500MPa) |
| HMS-TWIP (high Mn-twining induced plasticity): Content alloying that mechanical twining occurs when straining. | TWIP 1000 (YS: 496 MPa, UTS: 1102 MPa) |

Tables 1, 2, and 3 give an idea of the variety of high strength steels. Each table shows the ultimate tensile strength (UTS) limits, the method used to increase the strength and examples of existing grades. It can be observed that the methods utilized in manufacturing become increasingly complex as the strength increases. In addition it can be seen that strengths are becoming higher up to 1300 MPa.

## 3. WELDING CONSUMABLE

Apart from the welding category that does not use an electrode for welding, it should be noted that the filler metal plays a leading role in fusion welding. Filler metal is used for the case of different base metals, metals of the same group but differing in strength characteristics or alloying elements, and finally the same class of base metal but a different metal filler.

For the most common case in welding, the dissimilar welds with the same base metals but different filler metal, there is a relationship between the mismatch of the electrode and weld joint strength. In the specific case of consumable electrode welding, the performance of the weld depends on the size and the level of mismatch [13]. The following categories usually emerge from this mismatch; overmatched, matched or undermatched welds, respectively a weld metal (WM) whose ultimate strength is greater, equal or below the base metal (BM). The choice of the mismatch depends on the application of the weld strength in service. Thus, overmatched welding is generally applied to components subjected to tension, to ensure an efficient transfer of strength [14]. Generally, failure takes place either in the weld metal or heat affected zone. Undermatching is generally used for joints with high strength steels to minimize the risk of defects related to hydrogen such as the cold cracking. This application of undermatching can help to reduce or prevent the need for costly pre-heating operations. The reduction gain in temperature depends on the deposited metal and, in particular, the strength and impact toughness required for the welded joint [15]. Fig. 4 shows the effect of different filler metals on the tensile strength and yield strength of a welded X96 grade metal. The difference becomes increasingly significant from the fusion line (FL), heat-affected zone (HAZ) and weld metal (WM).

Because of the significance for welding quality of the choice of electrode, it is important to re-asses the prescriptions of European standards and gaps must be filled to meet the requirements of higher high strength steels and most importantly for the welding of dissimilar high strength steels. The benchmark for the design code is EC 3-1-8 [17], which defines the characteristics for matching electrodes of all welds. It is recommended that matching elec-

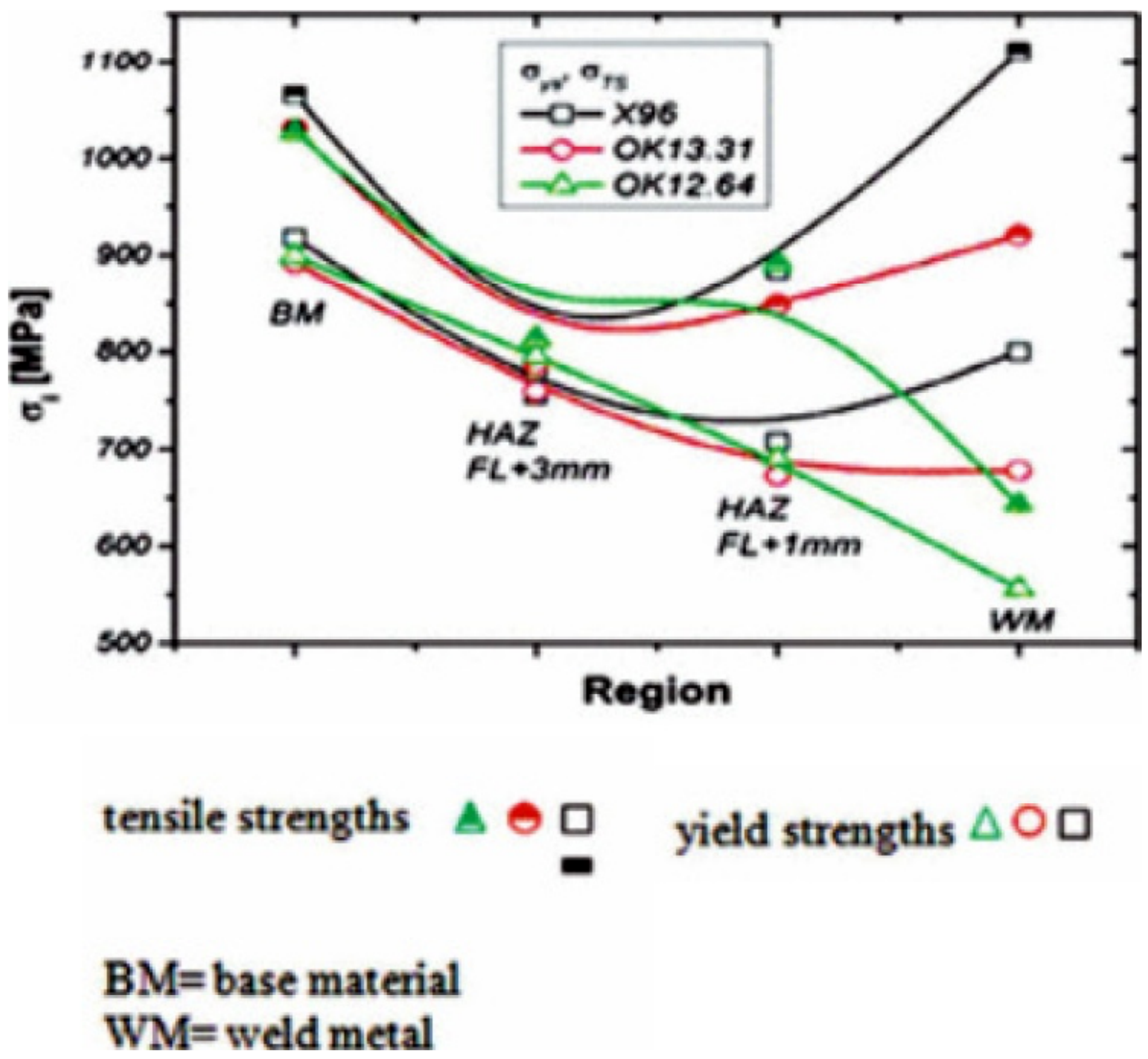


**Fig. 4.** Strength of filler metals in terms of the joint region. Reprinted with permission from *Hitsaustekniikka*, (2010) 3. © 2010 SHY.

trodes be applied, if the steel grades are less than 460 MPa yield strength, which is a requirement that poses no significant difficulty. However, reassessment of the requirement for matching electrodes is needed for higher strength steels because there are no electrodes to date with sufficiently high strength and use filler metal will likely cause some problems from the viewpoint of manufacturing, which is not the case with available electrodes with lower strength.

Research in the area of mismatch is currently a topic of considerable interest. For example, while it was established years ago that overmatching is a necessary condition to obtain acceptable weld toughness of structural steels, it is very difficult to combine both acceptable toughness and overmatching strength for AHSS. Consequently, it is essential to assess the need to apply overmatching for this type of steel and to determine the possible level of undermatching that could best be applied [18].

There are some consideration for the design of the weld that provide guidance and form a basis for this reflection. For the case of a T-joint, because of demands related to this type of welding, there is no specific need for matching electrodes. However, there is a requirement for mismatching in some codes; an example of such a rule can be found in the Swedish code [19]. Björk et al. [20] studied the behaviour of T-joints of high strength steels, including in their analysis the effect of the geometry of the joints and their ability to resist deformation. It appeared from this study that the distortion of these joints is crucial to their quality. To this end, the use of undermatching filler metals can improve the performance of this type of joint. Furthermore, given the essential contribution of heat input for welding UHSS, one should take this factor into account as an additional failure criterion in the design code. This additional precaution is necessary because of the softening of the zone affected by heat.

Regarding butt joints, lack of strength is generally associated with undermatching electrodes. For example, if the joint is completely subjected to transverse load, a matching electrode is the best fit. For other butt joints, undermatching electrodes are suitable. Note that the European Code 1-12 design rules, in part I, encompass yield strength grades up to 700 MPa and recommend use of an undermatching consumable electrode [21]. Fig. 5 depicts the tensile strength of the weldment as a function of the tensile strength of the base metal depending on the strength of the filler material. It can be seen that as the tensile strength of the base metal increases the weldment strength increases as well but there is a difference depending on the type of filler used. Higher-strength filler metals provide a stronger weldment compared to filler metals with lower strength. Therefore, attention should be paid to the base metals and consumable electrode strength and a compromise should be made choose compatibility with both resistances. This should take into account forces related to the in-service use and their directions and orientations.

## 4. PRE OR POST-HEAT TREATMENT AND INTERPASSES

The number of publications related to the welding of steels of very high strength is abundant, but a large part is only concentrated on the chemical composition of these steels, the microstructure and mechanical properties. A very limited number is dedicated to the thermal treatment related to the actual welding. Among the studies available, the vast majority just address the effect of some alloying elements and focus only on high strength low-alloyed steels.

Heat treatments, despise their cost, are crucial operations for welding high strength steels. The heat treatment operations depend primarily on the composition of the base metals of the steel and the filler metal and consist of pre-heat treatment, and post-heat treatment (PWHT). Pre-heat treatment is used to limit heating metal too long at critical temperatures or to reduce cracking risk. For example, pre-heating is used to prevent cracks due to hydrogen. It increases the cooling period, and a longer cooling period allows the diffusion of hydrogen from the weld, which avoids the creation of hydrogen cracks. In addition, using higher inter-passes temperature in-

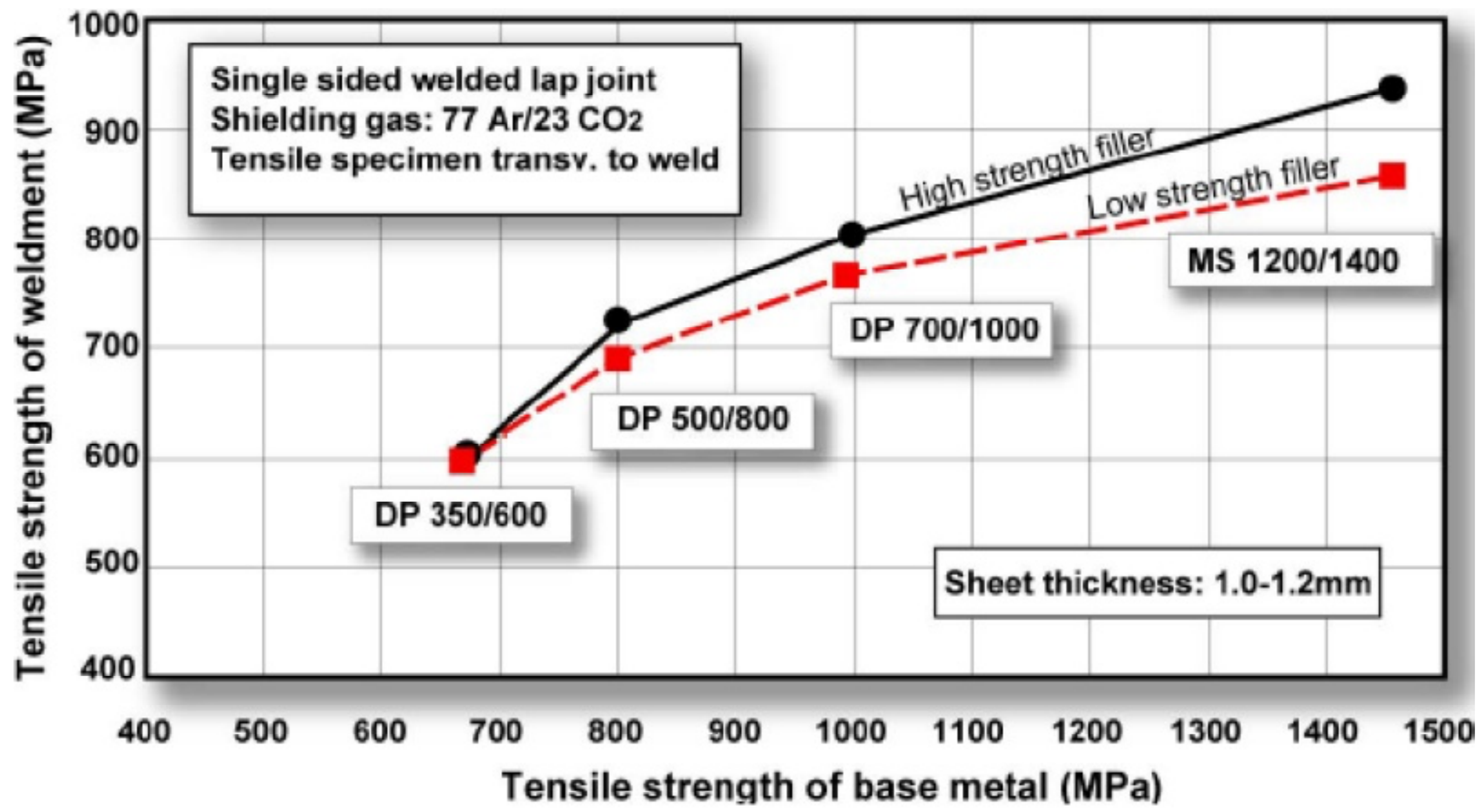


**Fig. 5.** Influence of filler metal strength in arc welding of DP and MS. Reprinted with permission from Cuddy et al. // *EU Report*, R585 (2004). © 2010 *EU*.

creases, time spent in the critical temperature range. Post-heat treatment allows relaxation of the internal tensions and leads to desired microstructures. These operations are guided by the EN-1011-2 standard [25]. Fig. 6 shows the effect of PWHT on the energy absorbed by the weld.

Certain studies have emphasized the importance of post weld heat treatment as this treatment improves quality of welding. Jorge et al. [27] studied the effects of post weld heat treatment by analyzing the effects on mechanical properties. The tested steel had a tensile strength greater than 860 MPa. The operation was applied with filler metal e of 4 mm diameter, joint design was a butt-welded joint with several passes. The base metal was 19 mm thick and preheating at 200 and 250 °C and post-weld heat treatment performed at 600 °C for 2 h. The results showed a higher mechanical quality required.

The close relationship between the microstructure obtained after post weld heat treatment and mechanical properties noted in Jorge et al. [27] confirms earlier studies. For instance, Svensson [28] reports, following analysis of a weld of yield strength higher than 690 Mpa, that the weld metal was composed of acicular ferrite, martensite and bainite. This is corroborated by Karlsson et al. [29] who presented that a high strength steel containing between 2% and 3% Ni in the weld consists of acicular ferrite, martensite and bainite. In addition, the variation of the percentage of each of these elements had a direct influence on the mechanical properties of the weld.

Dissimilar welding of HSSs can produce brittle welds if they are not post-weld heat-treated (Fig. 7). For that reason there is growing interest in reduction of the carbon content in DP steel to below 0.1 weight percent and reduction in carbon content has become an important issue in steels manufacturing [30]. Despite the possibility of improving the quality of welds through post-weld heat treatment, it must nevertheless be noted that because of the sensitivity of these steels, post weld heat control operations are very strict. For dissimilar welds, there should be room for compatible heat treatment.

## 5. CASE STUDY AND APPLICATIONS

As mentioned earlier, case studies on welding high-strength dissimilar metals are not numerous. This is due to the fast increase in the metals available,

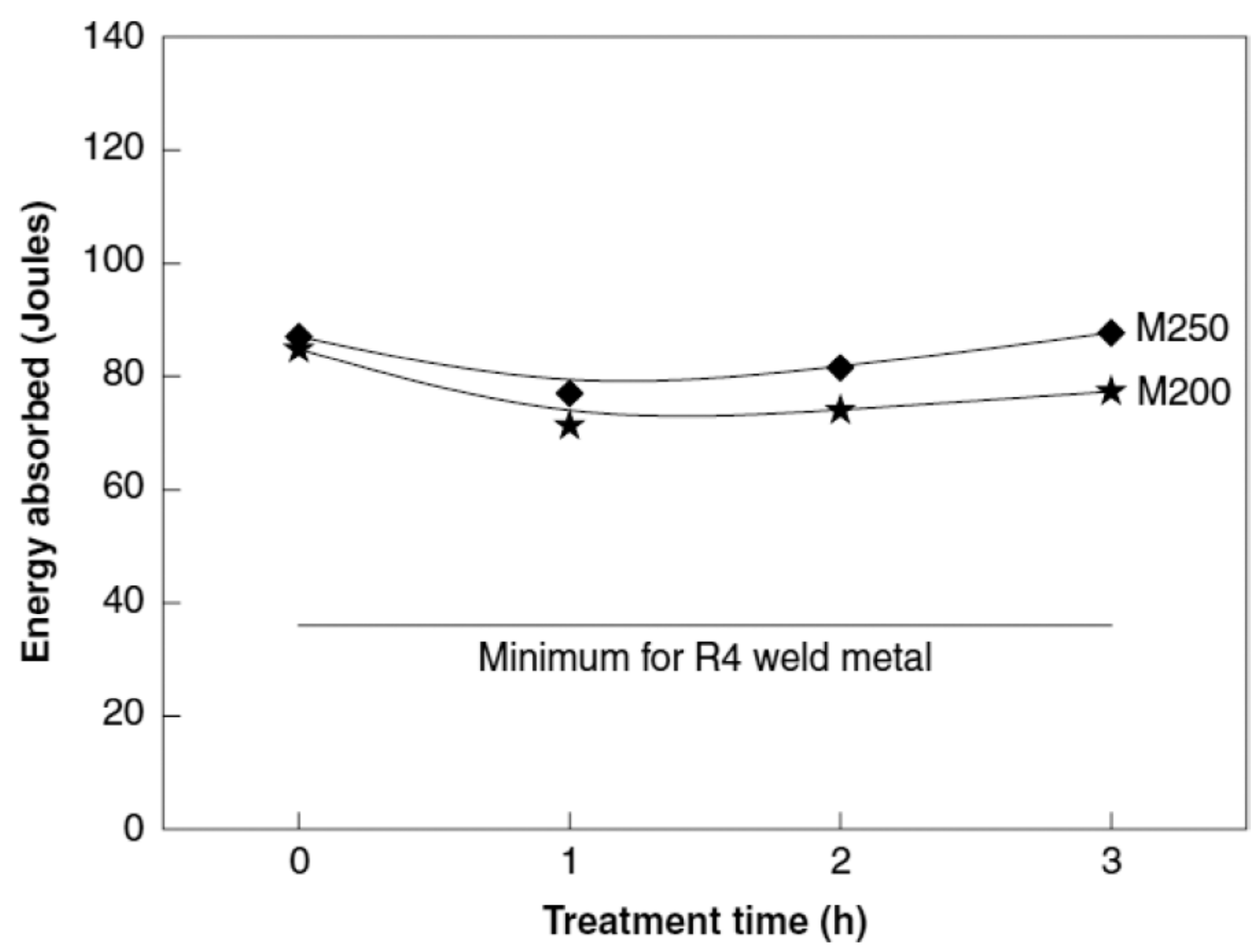


**Fig. 6.** Effect of PWHT (post-weld heat treatment) time on the mechanical strength/ structural robustness of the weld metal. Reprinted with permission from Faragasso et al. // *National Congress on Welding* (2011). © 2011 *ABS*.

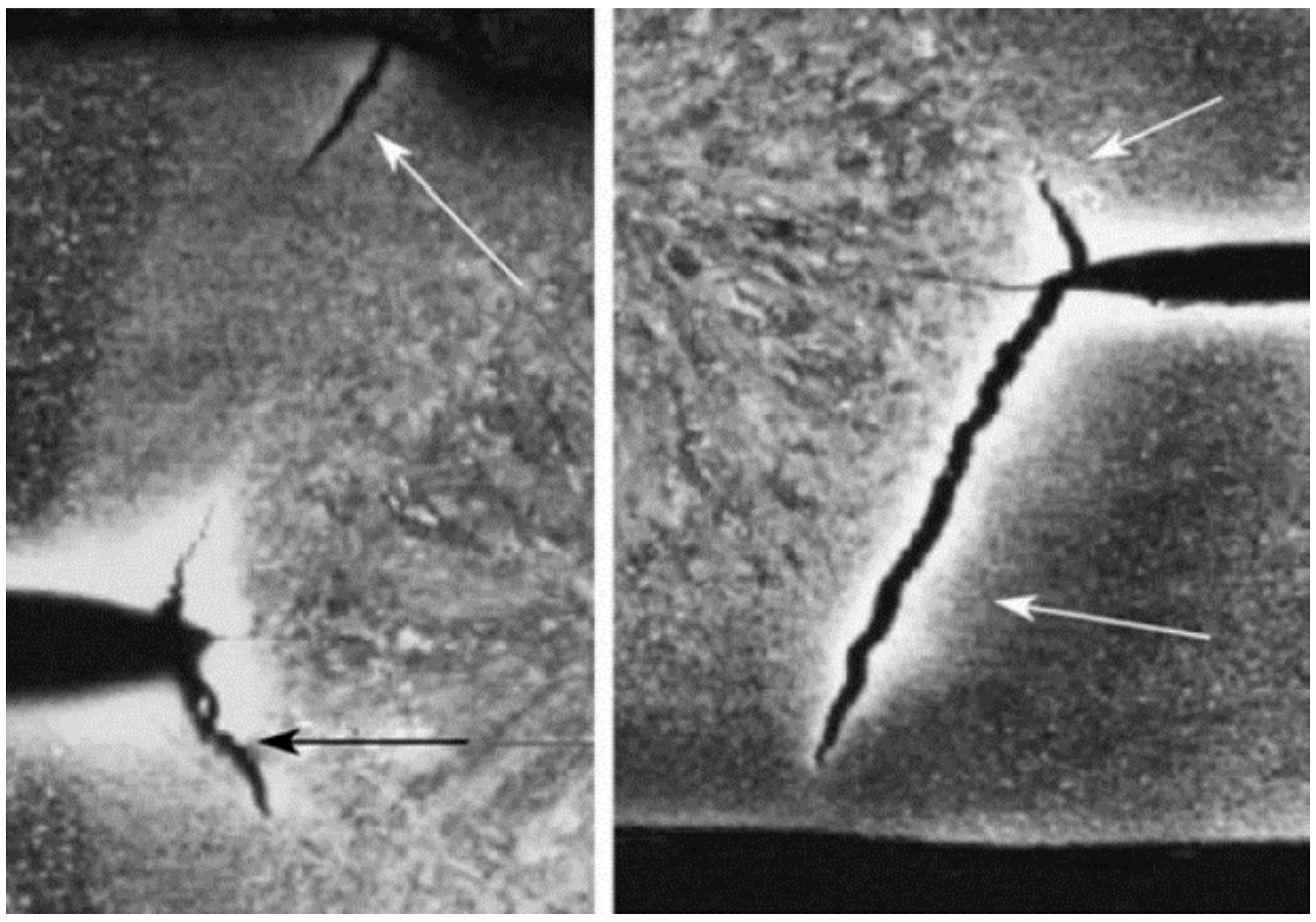

**Fig. 7.** Appearance of cold cracking in the heat affected zone of spot welded DP780 (0.15%C). Reprinted with permission from M. Hardy // *Adv. Manuf*. **1** (2014) 28. © 2014 Springer.

their diversity, the complexity of their manufacturing process, as well as the slow updating of welding procedures. There is however enough material to build a benchmark of this research. For each of the categories listed in this study, experimental example cases using different welding processes such as arc welding, laser welding and hybrid arc-laser welding are analysed.

## 5.1. Welding different base metals with and without filler metal

Dissimilar welding of high strength steels can take place in two categories; without use of a consumable electrode and with use of the consumable electrode. The cases that serve as examples for our study in this subsection include both types. In this case, evaluation of the carbon equivalent of the weld between the two base metals is used.

Santillan Esquivel et al. [3] studied different combinations of welding steels of very high strength (DP600, DP780, TRIP780: DP600 / TRIP780, DP780 / TRIP780) using the laser diode welding process. A comparative study of combinations of similar and dissimilar metals was performed. The analysis after welding was to examine the mechanical properties of the weld microstructure and the different component parts of the weld. A curve analysis of the fusion zone was plotted (Fig. 8), under the calculated carbon equivalent, and the outcome of hardness tests. Fig. 8 shows the three main regions. Region I with the highest carbon equivalent shows a complete martensite structure or close to the theoretical calculated martensite hardness. Region II is characterized by a mixture of martensite and bainite, which is the average level of hardness. Region III as the region II deviate from the hardness obtained from experiment. This area is a mixture of ferrite and martensite and has a considerably lower carbon equivalent. It is clear from this analysis that the carbon equivalent can actually be used to predict the microstructure of the fusion zone.

The influence of alloying elements of the above-mentioned metal combinations is confirmed by other experiments carried out with different welding processes. Hernandez et al. [1] during their study of the resistance spot welding (RSW) of metals of dif-

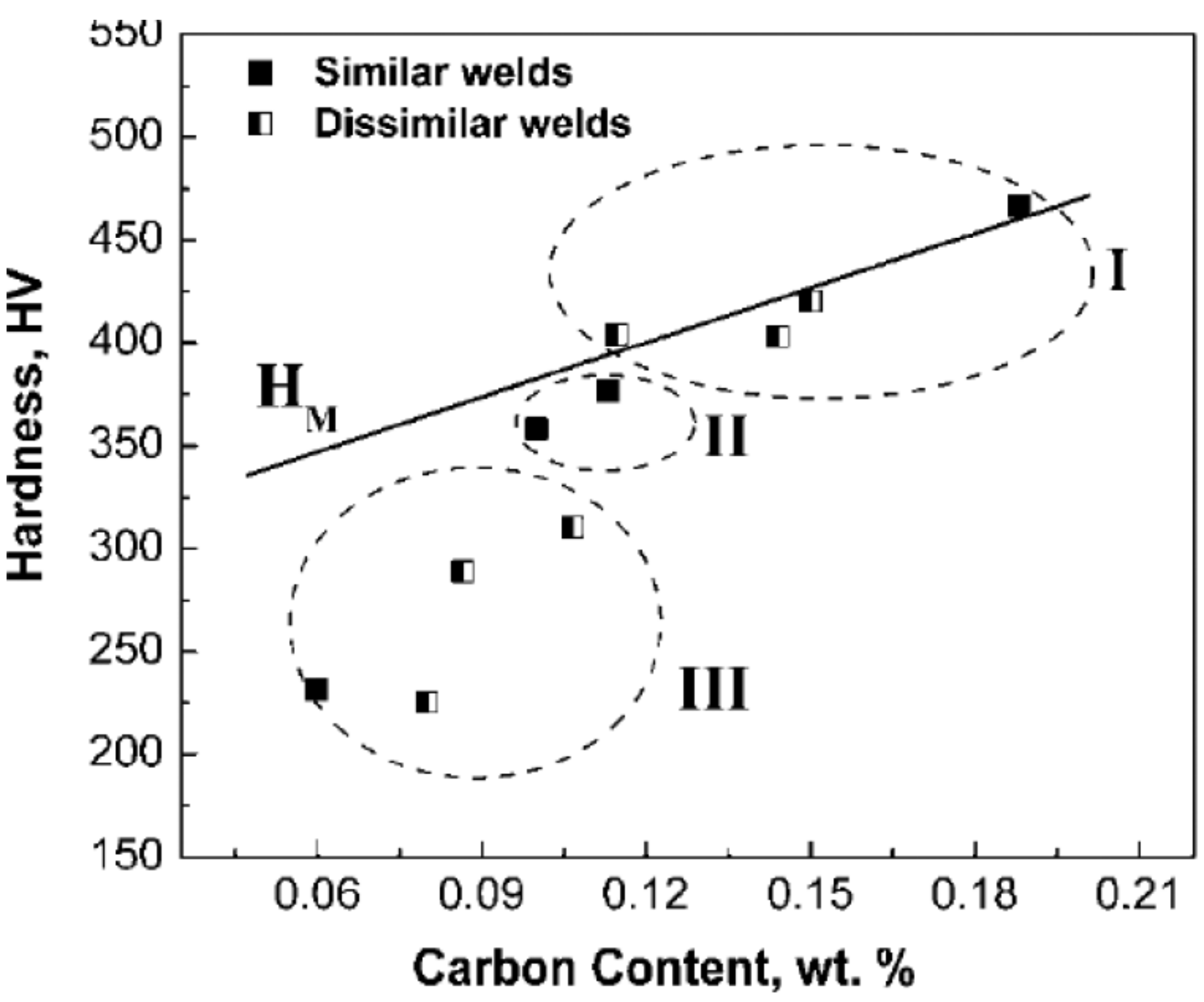


**Fig. 8.** Variation of FZ hardness as a function of the carbon content in AHSS laser welds: Calculated martensite hardness Hm using the Yrioka formula is also included as a straight line to assist in predicting FZ microstructure. Reprinted with permission from Santillan Esquivel et al. // *Canadian Metallurgical Quarterly* 51 (2012) 3. © 2012 Maney.

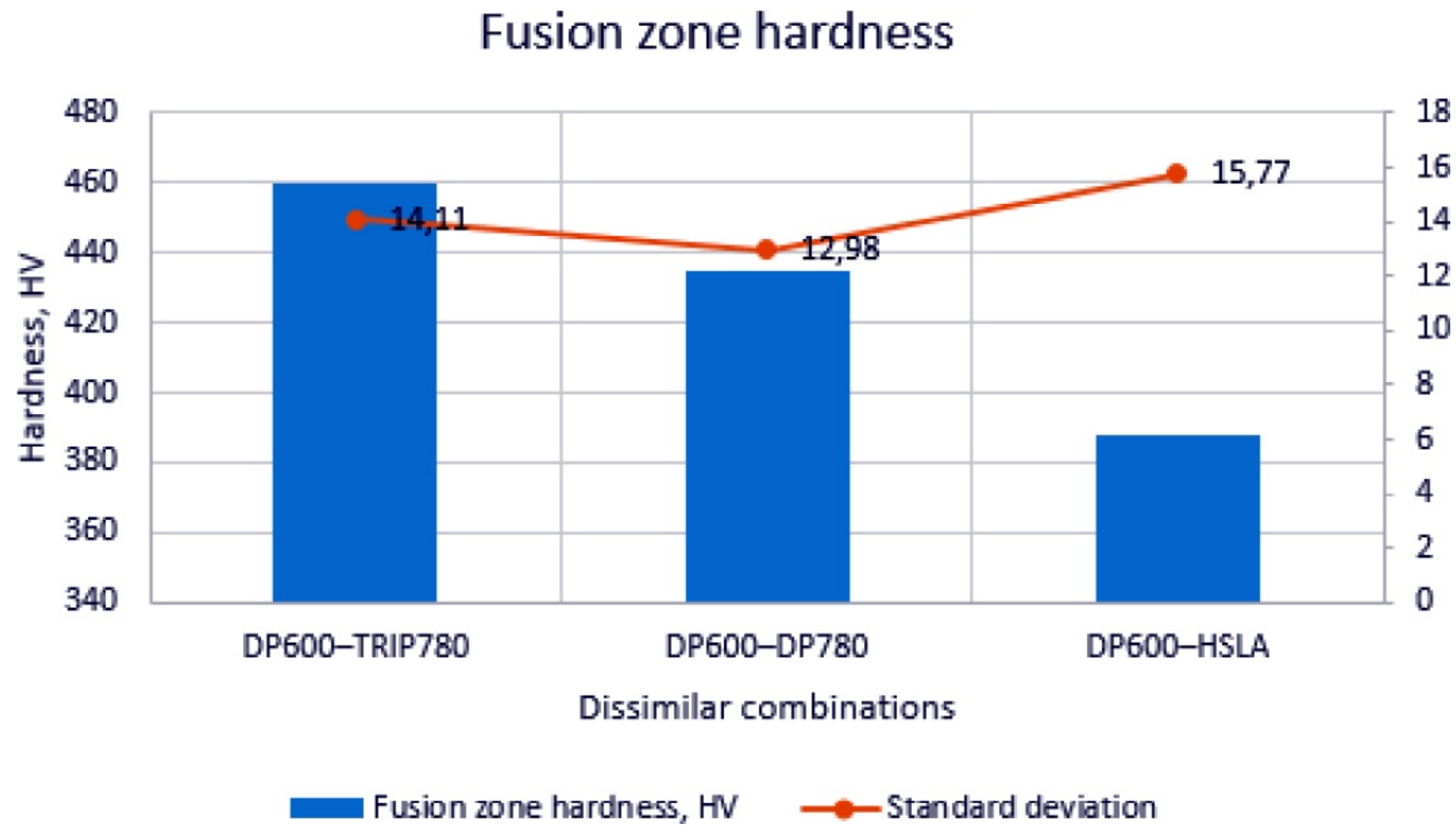


**Fig. 9.** Average fusion zone hardness and standard deviation.

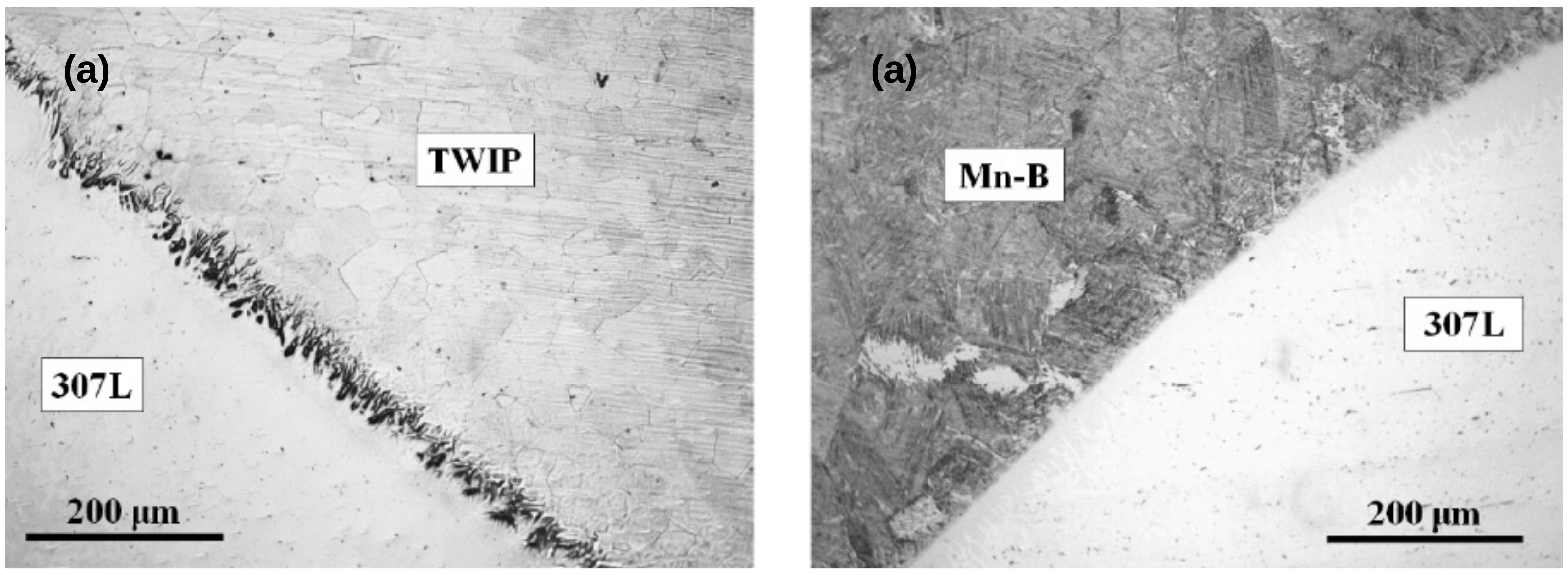


**Fig. 10.** Metallographic examination of (a) TWIP/DP and (b) TWIP/MnB weld seams. Fusion zone (not etched) and HAZ. Reprinted with permission from Spena et al. // *National Cofenrence, IGF XXII*, (2013). © 2014 IGF.

ferent high strength (DP600 / HSLA DP780 / TRIP780) observed an increase in hardness at the fusion zone of the dissimilar combinations. The increase in hardness at seemed to grow as the percentage of alloying elements increased. In the specific case of the combination DP600 / HSLA a predominant presence of martensite was noticed. Fig. 9 shows the carbon equivalent of each pair with DP600 and their standard deviation. It is observed that the hardness increases with increasing level of alloying elements in the carbon equivalent (CE). It appears in this analysis that in the case of welding of high strength steels without filler metal, hardness depends on the fusion level of both metals. The mechanical properties depend on the microstructure and fusion zone as well as the welding process used.

Arc welding process such as gas tungsten arc welding, and gas metal arc welding are welding process which has been used for decades, have regained larger applications with significant improvements from the point of view of control of welding parameters. Gas metal arc welding (GMAW) has shown in recent years promising results in welding HSS. This weld quality improvement was achieved by use of advanced technology control or hybrid welding processes.

The next cases considered in this section are those of welding of different metals with a consumable electrode. Russo Spena et al. [4] conducted a study to examine dissimilar high-strength steels (TWIP1000 / DP600, TWIP1000 / MN-B) weld using GMAW and a consumable electrode 307L. It was observed in the HAZ of the TWIP steel that the microstructure was of a coarse austenitic grain size compared to DP and Mn-B. The full martensite microstructure was noted in the HAZ of DP and Mn-B steels near the fusion zone (Fig. 10). The HAZ observed in the Mn-B side was higher than noted in the side of the DP and TWIP steels. The difference between the maximum and minimum hardness in MN-B is greater than in DP. This hardness difference is due to the lower carbon percentage of DP compared with Mn-B. The tensile test showed that for the TWIP / DP combination, rupture occurred sometimes in the fusion zone or in the HAZ of the DP steel. In the case of the combination TWIP / MN-B, rupture occurred either in the HAZ of TWIP

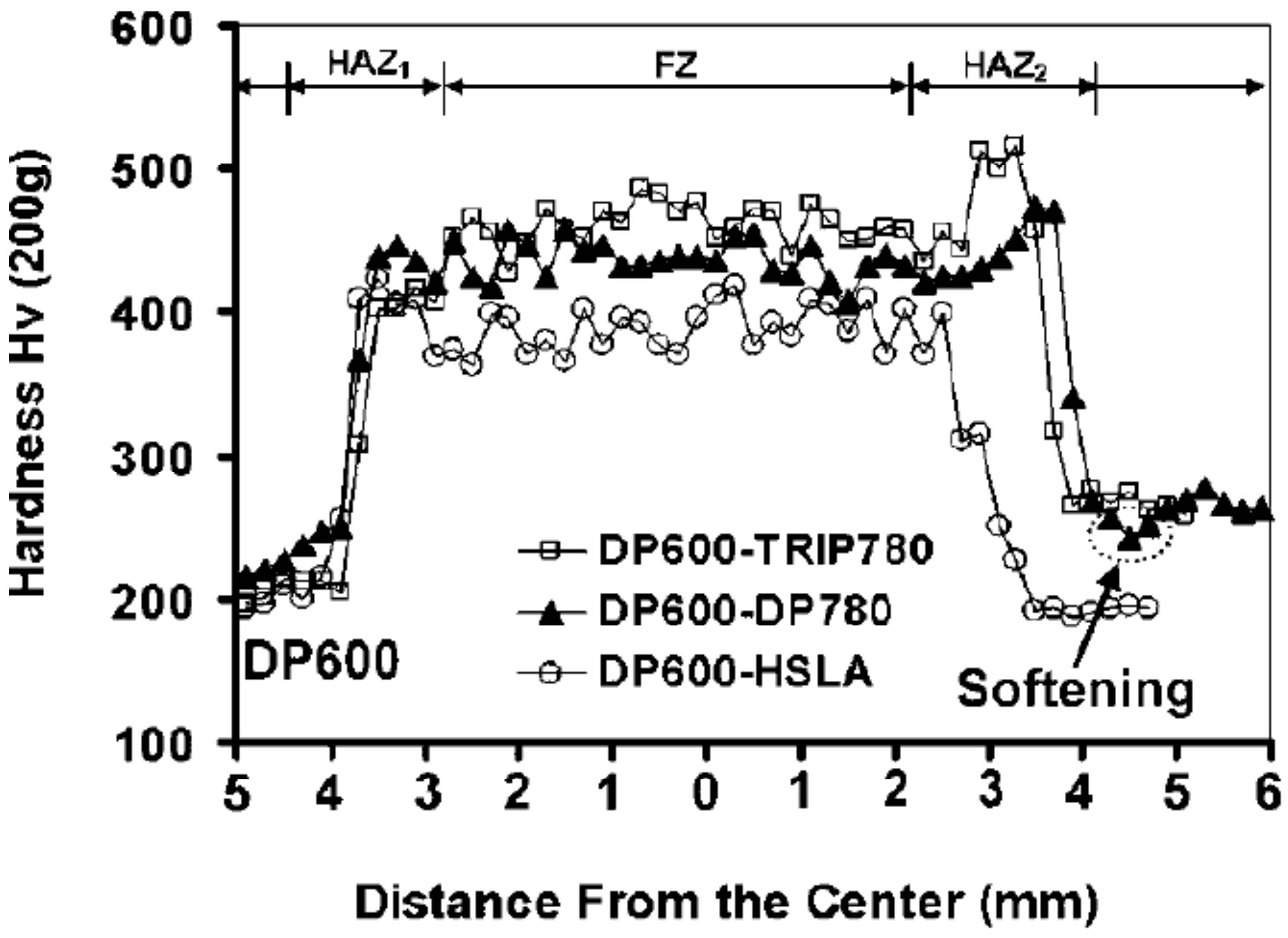


**Fig. 11.** Cross-weld hardness profiles for dissimilar spot welds. Reprinted with permission from Hernandez et al. // *Science and Technology of Welding and Joining* ,13 (2008) 8. © 2008 Maney.

or Mn-B. It is recommended to avoid incomplete penetration because it is the origin of fracture failure initiation and brittle fracture failure because of the notch in the fusion zone.

## 5.2. Welding different alloys of the same base metal with and without filler metal

Welding the same type of base metals but different strength or different alloying elements (e.g. DP600 / DP780 dissimilar welding) with or without filler metal is the second case of this study. This case is not far from the previous case in terms of the applicable welding processes, procedural rules to be observed and the risk of brittle element formation. It is also necessary here to consider the carbon equivalent (CE), analysis of critical temperatures $t_{8.5/5}$ and the Graville diagram to predict the quality of the weld. The risk hardness and brittle components is however less than in the case of the previous study, because the principle of manufacture of the base metal is the same. The difference between the base metals is basically in alloying elements. High-risk areas include; the fusion zone (FZ) and heat affected zone (HAZ). The former because it may result to alloying elements gradients and an increase in carbon or the formation of structural martensitic compounds, and the latter because difference of heat resistance capacity can lead to dramatic softening of the HAZ of the base metal with lower heat capacity resistance. The risk of diffusion of the alloying element is greater in welds without consumable electrode. In the case of use of an electrode, it is necessary to ensure a proper mismatch that does not cause fracture failure at the weld or HAZ. Some example to better illustrate the case are presented below.

Hernandez et al. [1] in their experiments studied dissimilar high strength steels welding using the welding process without filler metal resistance spot welding (RSW). Several combinations were analyzed. Considering in that investigation the case that correspond to this specific case of investigation (eg DP600 / DP780). Fig. 11 shows that in dissimilar welding of DP600/DP780 without use of filler metal, the HAZ of DP780 has undergone a noticeable softening. This softening is due to the tempering of the martensite. One can also see an increase in the hardness in the fusion zone, in comparison to both base metals. This increase in hardness is the result of a growth of each alloying element quantity. [31]

The second example analyzes the case of welding with use of a filler metal. Rak et al. [32] studied the welding of dissimilar high strength low alloyed steels (HSLA) using a submerged arc welding method (SAW). The weld joint design was a narrow gap, the base metals were S355NL (HT50) (YS: 380 MPa) and S690QL1 (HT80)(YS: 680 MPa) and thickness 50 mm. The cold cracking parameters (Pcm) for S355NL, S690QL1 and the weld metal, were respectively 0.101, 0.256, and 0.205. Given the dissimilar nature of the welded joint, mismatching was calculated for each side in all weld parts such the base metal, weld cap, weld middle and weld root. The results of calculation on the matching factor *M* indicated undermatching for S690QL1 and overmatching for S355NL1. Because of a very large difference in the mismatching, failure fracture occurred in the crack tip opening displacement (CTOD) test from the coarse grain heat affected zone (CGHAZ) to the weld or the base metal. Fig. 12 shows the mismatch of the two side welding of the different base metals. The difference in the weld metal and area close to both base metal is significant.

## 5.3. Welding the same base metal with a different filler metal

Welding dissimilar metal with the same base metal and a different filler metal is probably a more frequent case than the earlier two cases. This case is essentially based on mismatching between both the base metal and the filler metal. This mismatching in advanced ultra-higher strength steels constitutes one of the key research topic in welded joint design [33,34].

Unlike with mild steels, steels for high strength can well accommodate undermatching to reduce

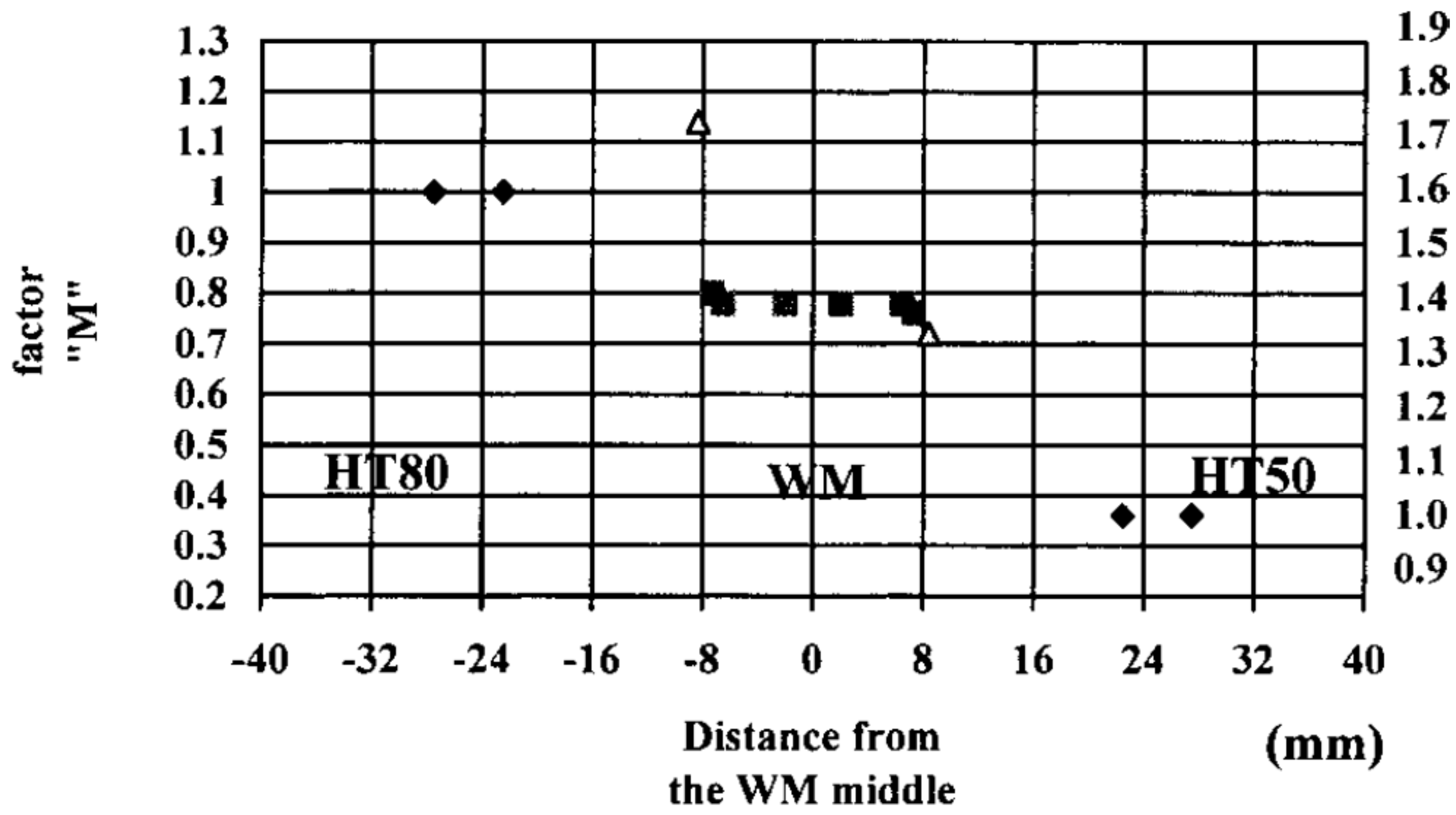


**Fig. 12.** Global/local mismatch factor *M* in the dissimilar weld joint cross-section. Reprinted with permission from Rak and Treiber // *Kovine, Zlitine, Technologije (Metals, Alloys, Technologies)* 32 (1998) 2. © 1998 KZLTET.

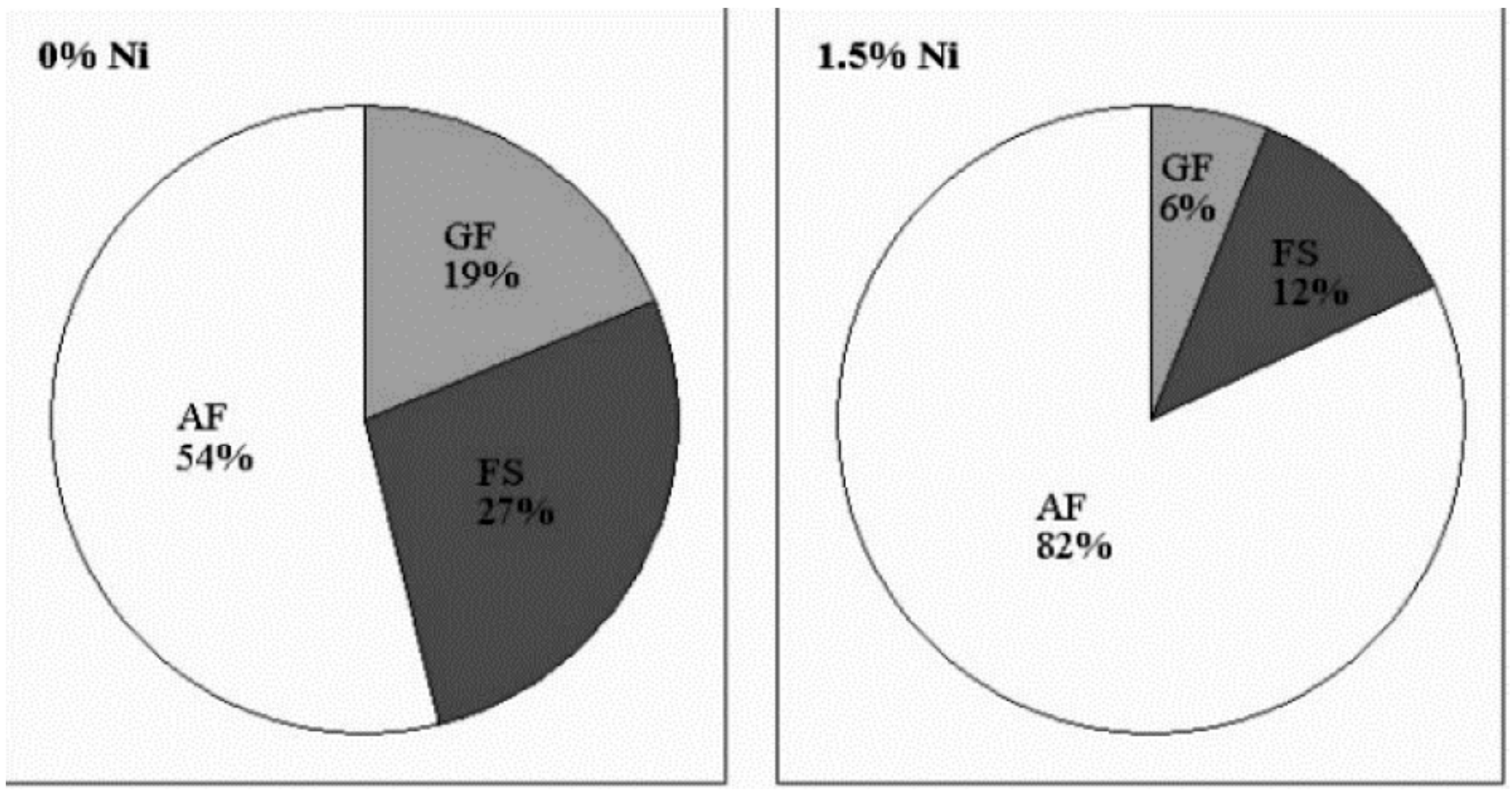


**Fig. 13.** Quatitative analysis result of weld metal microstructure of different types of electrodes. Seo et al. // *Journal of Achievement in Materials and Manufacturing Engineering* 27 (2008) 2. © 2008 ACMSSE.

the risk of cold cracking and lamellar tearing. Analysis for the matching level should reflect not only the strength but also ductility. As the strength increases, the choice of mismatching filler metal should be more precise and delicate. The strength requirement in the case of advanced high strength steels (AHSS) or ultra-high strength steels (UHSS) is that the filler metal should be one or two percent categories lower than the base metal. However, this suggests at the same time four to five percent higher categories for elongation. To combine both undermatching for strength and overmatching for elongation, the design of the filler metal can rely on appropriate alloying elements choice such as nickel (Ni) and molybdenum (Mo) in the constitution of a filler metal [35]. The alloying elements of the filler metal promote a microstructure beneficial for weld properties. An example experiment shows how the change in alloying element portion influences the formation of microstructures and its effect on the properties of the joint.

Seo et al. [36] made an investigation of the type of microstructures parameters that control cold cracking risk. The results shows that for the same level of exposure to hydrogen, filler metal having 1.5% Ni is more resistant to cold cracking compared to filler metal containing 0% of Ni, regardless of any high strength microstructure componund and carbon equivalent. Fig. 13 shows the difference in percentage of acicular ferrite (AF) in a weld made with a filler metal with Ni 1.5% in comparison with a weld made with a filler metal with 0% Ni.

The second case examines the mismatching of base metal with the filler metal. Gáspár et al. [11] examined the matching and mismatching between the base metal and the filler metal. Base metal S960QL according to EN 10025-6, of thickness of 15 mm was welded with a filler metal (4 T69 Mn2NiMo MM) or (G 5 89 M Mn4Ni2, 5CrMo) solid wire electrode using GMAW. The weld joint design was X with the use of multi-pass welding and optimal control parameters for $t_{8.5/5}$. Fig. 14 shows the

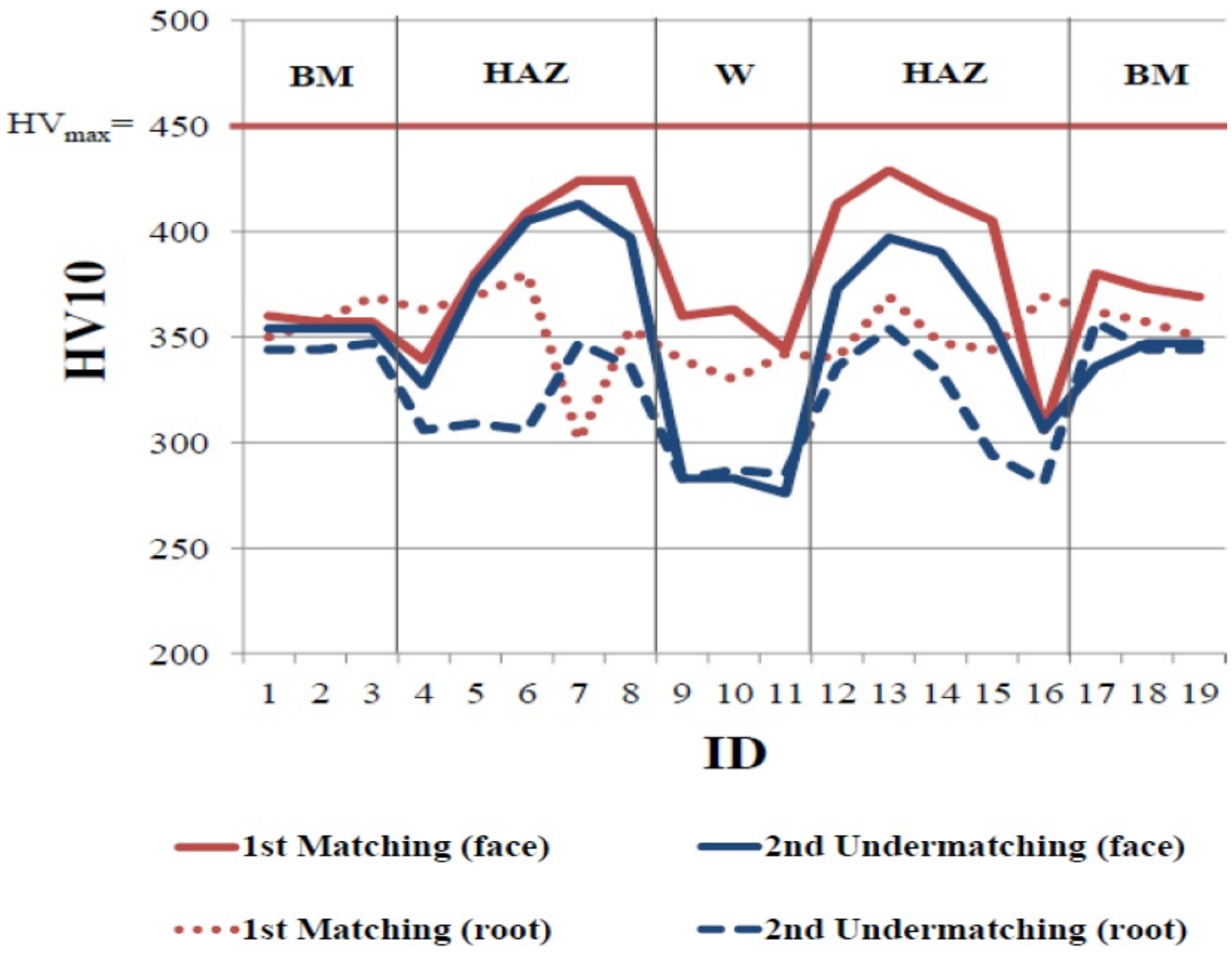


**Fig. 14.** Hardness distribution of the matched and undermatched welded joint. Reprinted with permission from Gáspár and Balogh // *Production Processes and Systems*, **6** (2014) 1. © 2014 OSZK.

hardness profile of the two cases of experiments performed; one for a matching and the other an undermatching welded joint. One can observe that the hardness of the matching joint was 350-360 HV, which is 60-70 HV lower than the hardness of the undermatching welded joint. However, the maximum hardness was 450 HV in both cases with 400 HV at peak in both cases. The lack of homogeneity increases with the growth of the strength, which could result in failure during in-service of the joint.

## 6. COMPARATIVE DISSIMILAR COMBINATIONS AND WELDING PROCESSES

In the case studies section a particular emphasis has been placed on the microstructures and the mechanical properties of the welded joints made of dissimilar metals and very few comparisons are made as regards the welding processes. This section examines the relationship between results obtained and the welding process used. Note that the use of a filler metal or not also depends on the welding process used. Resistance spot welding (RSW) for example does not use a filler metal while GMAW, laser or hybrid laser/GMAW do. In the welding of dissimilar metals, the amount of energy and heat input have a significant effect on the fusion zone between the welded metals and the heat affected zone. Laser beam welding (LBW) gives a smaller area of HAZ but can lead to very hard and brittle regions in the middle of the weld metal. The combination of processes allows advantage to be taken of the best aspects of both processes.

An example illustrates the effect of welding processes on the welding of dissimilar metals of high strength steels. Cortez et al. [37] carried out an investigation of the weld integrity of TRIP800 steel using the GMAW process and $CO_2$ laser welding. A filler metal of high strength used for the GMAW process whose designation is Mn3Ni1CrMo G according to EN ISO 16834-A. The results showed very high hardness for laser welding (LBW) due to a predominant presence of martensite in the fusion zone. The hardness was slightly above 500 HV for LBW with a peak of 600 HV, then the hardness of the GMAW welding reached up to 500 HV. A composition of bainite and ferrite was noted in both HAZ of GMAW and LBW. The fracture tests found failure in the base metal (BM) for GMAW, whereas the sample welded with LBW exhibited brittle fracture failure at the HAZ.

Table 4 compares on the basis of risk associated with a component thereof, the choice of the filler metal, the strength of the base metal and the differences of the filler metal for the main categories considered in this study. It is observed that the risk and constraints become greater when welding increasingly higher-strength steels. Moreover, it can be noted that the risk of faults (e.g. cracks, martensite) and the prediction requirement to evaluate the susceptibility to a brittle microstructure depend significantly on whether a filler metal is used. The need to predict the microstructure of different joint parts

**Table 4.** Combination of DMW of high-strength steels.

| Joining different alloys of the same type of base metal with and without filler wire | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | High-Strength Steel (HSS) | | | | | | Advanced High-Strength Steel (AHSS) | | | | Ultra High-Strength Steel (UHSS) | |
| | | BH | IF-HS | P | IS | CMn | HSLA | DP | TRIP | PM | CP | HMS-TRIP | HMS-TWIP |
| High -Strength Steel(HSS) | BH | */x | | | | | | | | | | | |
| | IF-HS | +/++ | */x | | | | | | | | | | |
| | P | +/++ | +/++ | */x | | | | | | | | | |
| | IS | +/++ | +/++ | +/++ | */x | | | | | | | | |
| | CMn | +/++ | +/++ | +/++ | +/++ | */x | | | | | | | |
| | HSLA | +/++ | +/++ | +/++ | +/++ | +/++ | */x | | | | | | |
| Advanced High-Strength Steel(AHSS) | DP | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | **/xx | | | | | |
| | TRIP | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | +/++/ +++ | **/xx | | | | |
| | PM | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | +/++/ +++ | +/++/ +++ | **/xx | | | |
| | CP | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | +/++/ +++ | +/++/ +++ | +/++/ +++ | **/xx | | |
| Ultra High-Strength Steel (UHSS) | HMS-TRIP | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | +/++/ +++ | +/++/ +++ | +/++/ +++ | +/++/ +++ | ***/xxx | |
| | HMS-TWIP | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | ++/ +++ | +/++/ +++ | +/++/ +++ | +/++/ +++ | +/++/ +++ | ***/+++ | ***/xxx |

Different base metal with and without filler wire

| | |
|---|---|
| + | Risk of element diffusion |
| + + | Selection of suitable filler wire |
| +++ | Suitable for base metal of comparable strength |

Different alloys of the same type of base metal with and without filler wire

| | |
|---|---|
| * | Risk of carbon diffusion |
| ** | Compatible filler wire |
| *** | Favour base metal of comparable strength |

Same base metal with different filler metals

| | |
|---|---|
| x | Low risk element diffusion |
| xx | Low risk for lower strength |
| xxx | Mismatch concerned of weld |

follows the same trend with the use of heat treatment.

## 7. CONCLUSION

The objective of this study was to analyze the conditions and the quality of welded joints of dissimilar high-strength steels. After analysis of experiments carried out with different methods of fusion welding processes, the following conclusions can be drawn:

The carbon equivalent (CE) can be used to evaluate the hardenability, brittleness and solidification cracking susceptibility of the weld. In the Graville diagram, weldability prediction of advanced high-strength steels is located in Area III Welding of AHSS category steels should primarily be planned based on the manufacturing process, yield limit, thickness and expected load with controlled linear energy and preheating. It is necessary to prescribe the $t_{8.5/5}$ expected cooling time interval during welding. In heat treatment control of the DP/TRIP welds, for example, the preheating procedure improved the splash of welding to some extent. The post-heating procedure improved the mechanical properties of spot welds owing to the temper of the spot weld microstructure. This improvement is also possible for other welding processes used in the experimental cases of this study.

Due improvements in welding technology and welding procedures for dissimilar base metals, the parent metal dilution width and the HAZ range have become smaller than in traditional welding processes. The welding process has an effect on the control of the heat input and consequently the microstructure of the weld as well as the fusion zone. In GMA (MIG) welding of AHSS, for example it is important that the HAZ remains very small because, of the carbon mobility in the atoms. The cooling process in steel manufacture is very precisely controlled; something that it is difficult to duplicate in welding after heating above the critical temperature. Metals in dissimilar joints should be compatible with the welding process as well as the heat treatment.

Combinations with other types of steels with a non-equilibrium structure may lead to a weakened area. The reason is that the non-equilibrium structure of advanced high-strength steels becomes strenghtened by strain hardening, transformation hardening and controlled temperature hot-forming, which is unfavourable to welding. Pre-heat, post-heat weld and welding generate heat energy input that can causes disadvantageous changes in the microstructure. Welding of high-strength low-alloy steels (HSLA) involves the usage of undermatching, matching and overmatching filler materials, the selection of which depends on the welding process, the application of the welded joint and the obtainability of the filler material.

The alloying elements also play a fundamental role in dissimilar welding; their constitution has shown the ability to promote acicular ferrite microstructure that improves mechanical properties.

In terms of microstructural development, the use of low-alloyed filler material is beneficial to avoid excessive weld metal overmatching. The welding of advanced high-strength steels is impeded by several factors, partly because these steels are characterized by a chemical composition determining a high carbon equivalent. During their production, the steels also undergo a special heat treatment leading to the formation of a specific structure.

The application of dissimilar weld metals with different base metals with or without filler metal presents varying complexity. In the case of welding without a filler metal, it is essential to predict the effect of the alloying element, which may generate a hard microstructure component that can produce cracks. The different ways of predicting suggested in this study must be applied. Moreover, a compromise between pre and post-heat treatment must be carefully determined in order not to harm the quality of the weld. In the case of filler metal use, it is necessary to predict the structure between both the fusion zone and the risks identified and associated with different metal compositions.

## REFERENCES

[1] V.H. Baltazar Hernandez, M.L. Kuntz, M.I. Khan and Y. Zhou // *Science and Technology of Welding and Joining* **13** (2008) 769.

[2] S.T. Wei, D. Lv, R.D. Liu, L. Lin, R.J. Xu, J.Y. Guo and K.G. Wang // *Science and Technology of Welding and Joining* **19** (2014) 427.

[3] A. Santillan Esquivel, S.S. Nayak, M.S. Xia and Y. Zhou // *Canadian Metallurgical Quarterly* **51** (2012) 328.

[4] P. Russo Spena, P. Matteis, A. Sanchez and G. Scavino, In: *Convegno Nazionale IGF XXII* (Roma, Italia, 2013), p. 109.

[5] R.R. Mohanty, O.A. Girina and N.M. Fonstein // *Metall Mater Trans A* **42A** (2011) 3680.

[6] D. Bhattacharya, In: *Advanced High Strength Steel Workshop,* ed. by R.H. Wagoner and G.R. Smith (Arlington, VA, USA, 2006), p. 38.

[7] Z. Feng, In: *Workshop On Addressing Key Technology Gaps in Implementing Advanced*

*High-Strength Steels For Automotive Lightweighting* (Southfield, MI, USA, 2012), p. 10.
[8] C.M. Tamarelli, *AHSS 101 The Evolving Advanced High-Strength Steels for Automotive Applications* (Steel Market Development Institute Report, Southfield, MI, USA, 2011).
[9] V.K. Cuddy, H. Merkle, A. Richardson, O. Hudin, A. Hildenbrand, H. Richter, T. Nilsson and J. Larsson, *Manufacturing guidelines when using ultra high strength steels in automotive applications* (European Commission, Technical Steel Research Final Report, Luxembourg, 2005).
[10] Ö.N. Cora and M. Koç, In: *7th Automotive Technologies Congress* (At Bursa, Turkey, 2014), p. 12.
[11] M. Gáspár and A. Balogh // *Production Processes and Systems* **6** (2014) 63.
[12] *Computer program for welding of plate Proweld 5.3*, [Online]. Available: http://www.thyssenkrupp-steel.com/plate. Retrieved 9.5.2015.
[13] M. Toyoda, C. Thaulow and J.G. Blauel, In: *Mismatching of weld* (Mec. Eng. Publ., ESIS 17, London, 1994), p. 335.
[14] *ANSI/AWS D1.1., Structural Welding Code-Steel*, (Florida: American Welding Society, 1995).
[15] A. Umekuni and K. Masubuchi // *Weld. J.* **76** (1997) 256s.
[16] P. Nevasmaa, P. Karjalainen-Roikonen, A. Laukkanen and J. Kuoppala // *Hitsaustekniikka* **3** (2010) 4.
[17] *Eurocode 3, Design of steel structure, Part 1.8 Joints* (EN 1993-1-8, 2005).
[18] D. Kozak, N. Gubeljak and P. Konjatić, In: *2nd International Conference, Research and Development in Mechanical Industry RaDMI* (Vrnjačka Banja, 2002), p. 1.
[19] *SK 99, Swedish design code for steel structures* (Boverket: ISBN 91-7147-527-3, 1999).
[20] T. Björk, J. Toivonen and T. Nykänen // *Welding in the World* **56** (2012) 71.
[21] P. Collin and B. Johansson, In: *4th European Conference on Steel and Composite Structures* (Maastricht, 2005), p. 4. 10-89.
[22] R. J. Dexter, *Significant of strength undermatching of welds in structural behaviour* (Geesthacht, FRG: GKSS Research Center Publications, 1997).
[23] P. Collin, M. Möller, M. Nilsson and S. Törnblom, In: *International association for bridge and structural engineering symposium; sustainable infrastructure – environment friendly, safe and resource efficient*, **11** (Bangkok, 2009) p. 96.
[24] V. K. Cuddy, O. Merkle and A. Richardson, *Manufacturing guidelines when using ultra high strength steels in automotive applications* (EU Report (ECSC) R585, Brussels, 2004).
[25] B. Norman, *Weldability of Ferritic Steels* (Abington Publishing, Cambridge, 1994).
[26] S.M. Faragasso, L.F.G. Souza, I.S. Bott and J.C.F. Jorge, In: *Proc. of the 37th National Congress on Welding* (Săo Paulo, 2011), p. 1.
[27] F. Jorge Carlos, F. Sergio Maciel, G.d.S. Luís Felipe and B. Ivamí de Souza // *Welding International* **18** (2015) 138.
[28] L. E. Svensson // *Svetsaren* **54** (1999) 29.
[29] L. Karlsson, E. Keehan, H.O. Andren and H.K.D.H. Bhadeshia, In: *Proc. of the EUROJOIN* (Vienna, 2004), p. V6.
[30] H. Mohrbacher // *Adv. Manuf*. **1** (2014) 28.
[31] M.I. Khan, M.L. Kuntz and Y. Zhou // *Sci. Technol. Welding and Joining* **13** (2008) 49.
[32] I. Rak and A. Treiber // *Kovine, Zlitine, Technologije* **32** (1998) 13.
[33] M.A. Quintana and M.Q. Johnson // *Weld. J*. **78** (1999) 87s.
[34] A.J.R. Loureiro and A.A. Fernandes // *Weld. J.* **73** (1994) 225s.
[35] A. Balogh, I. Török, M. Gáspár and D. Juhász // *Production Processes and Systems* **5** (2012) 79.
[36] J.S. Seo, H.J. Kim and H.S. Ryoo // *Journal of Achievement in Materials and Manufacturing Engineering* **27** (2008) 199.
[37] V.H. López Cortéz, G.Y. Pérez Medina, F.A. Reyes Valdéz and H.F. López // *Soldag. insp. São Paulo* **15** (2010) 234.