Review

Francois Njock Bayock*, Paul Kah, Belinga Mvola, and Pavel Layus

Experimental review of thermal analysis of dissimilar welds of High-Strength Steel

<https://doi.org/10.1515/rams-2019-0004>

Received May 3, 2018; accepted Oct 4, 2018

Abstract: Dissimilar welding offers exiting benefits for a wide range of engineering applications, such as automotive bodies, piping systems of nuclear power plants, health equipment. The main advantages of dissimilar welding applications are weight reductions, lower costs, unique properties combinations, and improved energy-efficiency. The properties of dissimilar weld depend on the type of welding process used, the accuracy of the process parameters control, the characteristics of the base metal and the heat treatment procedures. The current study reviews the scientific literature on the topic of thermal analysis of dissimilar high-strength steels (HSS) welding. The review of experimental data was carried out to analyze the variable heat input effect on dissimilar welds. The results indicate the welds mechanical properties irregularity and reduction in toughness and tensile strength due to uneven changes in the microstructure. Furthermore, post weld heat treatment (PWHT) often resulted in the formation of intermetallic compounds whose properties are dependent on the duration of treatment. The research results can be used to optimize the heat input of the HSS welding process.

Keywords: High-Strength Steel, Dissimilar Weld, Heat Treatment, GMA Welding Process, Thermal Distribution, PWHT

1 Introduction

Industrial enterprises are increasingly starting to use dissimilar welded joints of high-strength materials in the manufacturing of their products. Dissimilar joints can im-

prove not only product quality and bring cost benefits, but also enable innovative design and provide enhanced structural stability [1]. It is also clear that the mechanical, thermo-mechanical and microstructural properties of materials used in dissimilar welding, play an essential role in the determination of the optimal parameters for a welding process [2–5]. On the other hand, regardless of the welding process, of the introduced heat input will influence the metal during the welding process and also after welding is complete.

A suitable weld depends mainly on the heat source parameter for it to conceal these mechanical characteristics, microstructures. In addition to the heat source, there are also parameters such as the geometry of the weld joint, the filler metal, and the welding process to be applied.

In gas metal arc welding (GMAW) of HSS, the microstructure and mechanical properties of the welded joint are determined by the chemical composition of the weld and the base material, and by the cooling rate, especially in the heat-affected zone (HAZ). The latter depends mostly on the heat input, weld geometry and the thermophysical properties of the metal. Comparative analysis of the HAZ microstructure of HSS shows the dependence of the mechanical properties of the weld on the welding conditions and especially on the heat input [6–10]. All these parameters have a direct effect on the thermal characteristics of the weld joint for dissimilar materials.

This study aims to review analyses of thermal treatment (e.g., heat input during welding and post weld heat treatment) of dissimilar welds of HSS structures produced using different welding processes. Improved understanding of the effects of heat treatment will enable better control of the mechanical properties (hardness, yield strength, and tensile strength), metallurgical compounds and microstructure (martensite, bainite, and ferrite morphology) in the weld joint structure.

The material characteristics and alloy composition of HSS are presented, and the principles underlying the chemical composition of such steels, the manufacturing processes used in HSS production and the weldability of the steels are explained. This knowledge provides the basis for analysis of heat input and posts weld heat

*Corresponding Author: **Francois Njock Bayock:** Laboratory of Welding Technology, Lappeenranta University of Technology, P.O. Box 20, 53851, Lappeenranta, Finland;
Email: Francois.Njock.Bayock@lut.fi

Paul Kah, Belinga Mvola, Pavel Layus: Laboratory of Welding Technology, Lappeenranta University of Technology, P.O. Box 20, 53851, Lappeenranta, Finland

treatment, and study of their effects on the mechanical, metallurgical and microstructural characteristics of the weld [11].

2 Background of high-strength steel

Different types and grades of HSS were developed. Steels using yield point (R_e) above 355 MPa are referred to as HSS. Different classifications were put on the market according to the high values of the mechanical characteristics. For those values of high tensile strength ranging from 450 to 800 MPa are considered to be advanced high-strength steel. And that with high tensile strength values above 960 MPa, are classified as ultra-high strength steel [4].

2.1 High-strength steel classification

High-strength steels are grouped based on chemical composition, production method, and the heat treatment process. In the production of high-strength steels or improving others properties, the different alloying composition like carbon (C), Manganese (Mn), Nickel (Ni), Chromium (Cr), Molybdenum (Mo), Vanadium (V), Niobium (Nb), Copper (Cu), Titanium (Ti) or Boron (B) are added with the aim of increasing strength, but increased alloying is not cost effective. Heat treatment is applied to attain desired mechanical characteristics such as tensile strength, yield strength, ductility, and notch toughness to meet the requirements of the relevant standards and specifications. Common heat treatments include normalizing followed by tempering. Highly resistant steels can be classified according to the mode of production. Many production companies developed quenched and tempered (QT) steels, Induced Plasticity steel (TRIP) or thermo-mechanical control Process (TMCP) and many others. This process offers higher strengths with lower carbon equivalent, therefore, better weldability. In automotive engineering, the mechanisms of a controlled transformation of the microstructure have proved particularly interesting because they allow the creation of steels with a favorable combination of mechanical strength and formability. Figure 1 shows a selection of high-strength specialty steels commonly used in automobile production, with their strength properties and ductility. Non-alloyed high-strength, fine-grained structural steel are compared. It is noted that the Dual-phase and multi-phase steels and special alloy steels offer the following advantages:

- Reduced weight while keeping strength level;
- Easy formed cold and hot;
- Good ductility with high processing speeds;
- A strong hardening with large total deformations, resulting in a high energy absorption capacity;
- Good weldability.

Their microstructure depend on the load profile, the chemical composition, the effective hardening mechanisms, and heat treatment status. Flat products made from HSS for cold forming are characterized by different property-determining microstructure states like Two-phase steels, Multi-phase steels, special alloyed steels and other (recently developed) [12, 13].

Figure 1: Example selection and properties of currently common hot-rolled high-strength steels for automotive production. G. Schulze // Heidelberg-Dordrecht. (2009). ©2009 Springer Verlag.

2.2 Filler material classification

The choice of filler materials in welding depends on the minimum requirements for the mechanical properties of the base material. To prevent metallurgical notches, filler materials should be used that allows production of a weld metal with mechanical-technological properties that are comparable to those of the base material [2]. Table 1 presents a recommended series of base material features (yield point, type of production) and corresponding elements of filler materials [14].

The most critical parameter in the welding of structural steels is the temperature-time curve. Therefore, the excessive welding heat input degrades HAZ properties by two possible scenarios: A tendency to hardening through martensite formation, thus leading to possible cold cracking, and a tendency to recombine integrated hydrogen and thus to the formation of hydrogen-induced cracking. The

Table 1: Recommendations for base material-filler material allocations with fine-grain structural steels. G. Schulze // Heidelberg-Dordrecht. (2009). ©2009 Springer Verlag.

Base material		Filler material		The chemical composition of solid wire
Yield point [N/mm ²]	Production	Welding Process	Code for yield point	
275	N,M	E	38, 42	-
		G		G3Si1
		S		S3
355	N,M	E	38, 42	-
		G		G3Si1
		S		S3Si
420	N,M	E	42, 46	-
		G		G3Si1, G4Si1
		S		S3Si, S4Si
460	N, M, Q	E	46, 50	-
		G		G4Si1
		S		S4Si
500	M, Q	E	50	1NiMo
		G		G3Ni1
		S		S2Ni1Mo
550	Q	E	55	1NiMo
		G		-
		S		-
620	Q	E	62	Mn1NiMo
		G		-
		S		-
690	Q	E	69	Mn2NiMo
		G		-
		S		-
890	Q	E	89	Mn2NiMCrMo
		G		-
		S		-

Q – Quenched and tempered fine grain structural steels;
Q M – Thermomechanical rolled fine grain structural steel;
Q N – Normalising rolled fine grain structural steels and the unalloyed.
Q E – Manual arc welding, **G** – Gas metal Arc welding, **S** – Submerged arc welding.

method used to assess the need for pre-heating is based on the carbon equivalent value (C_{EV}). Accordingly, all structural steel standards from the EN 10025 series contain unique tables detailing, for each material, the extreme acceptable amount of carbon equivalents depend on the material thickness. If the exact equivalent of a batch exceeds these specifications, preheating should be considered.

The temperature-time curve during welding is influenced by the heat input, the relative thermal efficiency of the selected welding process, the sheet thickness, the pre-heating temperature, and the weld shape. Thus, with fusion and resistance welding, quick heating to a specified

peak temperature occurs followed by significantly slower cooling. This process is schematized in Figure 2, and the interaction of the above influencing factors on the HAZ in fine grain structural steels is illustrated. The cooling rate is the parameter that influences the mechanical properties in the coarse grain HAZ (CGHAZ).

The combination of C_{EV} and sheet thickness only indicates the need for pre-heating, it does not, however, define the pre-heating temperature. In order to determine this value, further parameters must be considered. Figure 3 presents the carbon equivalent for the different constitu-

Figure 2: Parameters that affect the mechanical properties of the CGHAZ. With the $t_{8/5}$ cooling time between 800 and 500°C, F_2 , F_3 weld factor for two or three-dimensional heat dissipation, k relative thermal efficiency, U , I (voltage and welding current). Reprinted with permission from Roos *et al.* // Heidelberg-Dordrecht. (2011). ©2011 Springer Verlag.

Figure 3: Comparison of the carbon equivalent value (CEV) of the constitution of steel internal composition, EN 10025-3, -4, and -6 with unalloyed steel structures, EN 10025-2. Reprinted with permission from Schulze // Heidelberg-Dordrecht. (2009). ©2009 Springer Verlag.

tion of high strength steel internal composition (EN 10025-3, -4, -6).

When welding thick sheets (> 6 mm), the heat dissipation occurs in three dimensions, the heat applied by the arc dissipates in the sheet surface and the direction of the sheet thickness.

3 Weldability of high-strength steels

Welding two pieces of different mechanical characteristics and microstructures require a certain number of objectives to be achieved. To have a weld of good quality, it is necessary to reduce as much as possible the thermal defects (hot and cold cracks), the mechanical defects (stress, hardness

defect), and defects of the microstructure (hydrogen crack). The weld should have specified values of yield strength, ductility, notch toughness, and the weld should behave appropriately in different uses. When welding the HSS, from the melting zone to the HAZ, all this part is susceptible to high hardness values. When welding the HSS, from the melting zone to the heat affected zone (HAZ), all this part is susceptible to high hardness values. High values of hardness can lead to cracking defects, leading to defects in the weld joint. It would be precious to evaluate the equivalent carbon to determine the appropriate characteristics of the filler metal to identify the more consistent cooling process.

The weldability of HSS and its behavior concerning heat input and PWHT, together with the dependence of the weldability on the base material and the type of welding process will next be considered.

4 Thermal behavior in dissimilar welding of HSS

In the welding process using dissimilar HSS, several parameters are scrupulously taken into account before the operation itself. The geometrical parameters of the weld joint, the chemical characteristics of the base materials, the choice of the filler metal. After that comes the parameters of the heat sources and the cooling rate, which are functions of the speed of the welding process, the voltage, and the current intensity. It is a link between the heat source that depends on the parameters mentioned above and the cooling time. The combination of the two parameters has effects on the mechanical characteristics and microstructures of the weld joint.

First, the mechanical and microscopic behavior of the weld joint will be examined by considering the different sources of heat, and then the results of research into post-weld thermal treatments will be addressed.

4.1 Heat input conditions

In his work, Pirinen *et al.* [6] studied strength, elongation, and hardness of HSS weld manufactured with Shielded Metal Arc Welding (SMAW). Figure 4 shown the plates welded were 8 mm thick HSS (ASTM E112-10) produced by quenching tempered, and thermos-mechanical controlled process (tensile strength 821–823MPa). Welding was done with a 15% CO₂ +85% arc shielding gas and Autrod 13.51 electrode. The dependence on heat input of the strength, elongation, and hardness in the HAZ was determined. It

was found in Figure 5a, b that an abnormal value of heat input will disturb the strength then elongation of the weld joint.

Figure 4: The configuration of V-joint with 2 passes welded joint. Reprinted with permission from Pirinen *et al.* // *Welding International*. (2015). ©2015 Taylor & Francis.

In other work, **Tasalloti *et al.*** [16] use two basic metals with different mechanical characteristics and microstructures namely S960 and S32205. With the gas welding process, it analyzes the effects of the different values of the heat source on the compositions of the microstructure. Figure 6 shows the different effects of the heat input values in the weld zone. Figure 6a represents the heat input with 0,86kJ/mm, b represents the heat input with 0,64kJ/mm and the last Figure 6c 0,48kJ/mm. It succeeded in determining optimum heat exchange rate favorable to the good behavior of the geometry of phase transformations at the interior of the grains. For the S960, a high heat source helps move a large number of Bainite for Martensite. Figure 7a.

Löbbe *et al.*, [18] in his approach analyze the behavior of the weld joint after welding. The objective here is always to find the mechanical properties of the base materials at the level of the weld joint. It can then evaluate it by acting on the analysis of the microstructure which, they are related to the mechanical properties of the materials. It develops a new approach for reheating the joint after welding, note "hot forming with rapid heating" (Figure 8a, b). Three necessary materials are used for this process (22MnB5, ENGTS-1000-5, and Docol 1400 M). A slight change in the microstructure formation of grain size and undissolved carbide materials has been noted and was found to be excellent compared to conventional treatment. Figure 9 shows the different steps taken by the microstructure when using the new model: step 1 - quenching room temperature, step 2 - quenching at 350°C during 30s, step 3 - formation of carbides without any susceptible deformation

Frei *et al.* [19] used GMAW with Cold Metal Transfer (CMT) to evaluate the effect of low heat input on mechanical and microstructural properties of the HAZ of two high strength steels (13CrMo4-5/10CrMo9-10). The impact of the low heat source on the behavior of the microstructure of these two HSSs was determined. The analyzes were located on the CGHAZ. Compare with a higher heat source, it has been noted some incomplete microstructures transformations (austenite transformation) in this area (CGHAZ).

The weldability analysis of the dual phase of high-strength steel (grade ENGTS1000-5) using laser beam welding was studied by Alves *et al.* [20]. The assumption of the analysis is based on the heat source (0.4 kW and 2kW), and the welding speed is evaluated at the interval 20mm / s and 150mm / s. Figure 10 illustrates the method used to perform the welding and at the same time pick up the temperature profiles. The microstructure analyzes presented a hardness profile represented in Figure 11. The melting zone has the maximum value of the Hardness profile which was 530 HV; this will be justified by the fact that this zone has a high temperature, which is therefore susceptible to hot crack.

For both types of steel, this system guarantees a good quality weld compared to the conventional method. The recommended parameters for welding these materials are (P2.0 / S150).

4.2 Post weld heat treatment condition

Uzunali *et al.* [21] investigated post-weld heat treatment effects on the mechanical properties of tempered martensitic of high-strength steel welded joints. The welded joints were performed in accordance with standards EN 15609, EN 15614, steels Hardox x450 (0,11C, 0,46 Si, 1,39Mn, 0,01P, 0,002S, 0,25S, 0,25Cr, 0,07Ni, 0,017Mo) and Optim 700MC (0,064C, 0,25Si, 1,84Mn, 0,015P, 0,018S, 0,22Cr, 0,25Ni, 0,0001Mo,) were chosen due to their partially high carbon equivalent. Chemical analysis, hardness tests, and microscopic examination were implemented to assess the mechanical properties of the material before the welding process. Figure 12 shows an example of microstructure compartment during heat treatment at 450°C.

Hardness increase due to temperature distribution and cooling rate was determined only in the HAZ of Hardox 450 materials approximately 450-520 Vickers. Hardness increase due to temperature distribution and cooling rate was not defined in the HAZ of Optim700MC. The results show that Hardox450, due to its carbon equivalent ratio, can be subjected to PWHT to decrease the hardness increase in the HAZ.

Figure 5: Heat input function of; (a) ultimate strength, (b) elongation. Reprinted with permission from Pirinen et al. // *Welding International*. (2015). ©2015 Taylor & Francis.

Figure 6: Structure of weld samples of the dissimilar weld of S960/S32205: (a) WS7.1; (b) WS8; (c) WS 9. Reprinted with permission from Tasalloti et al. // *Material Characterization*, 123 (2016). ©2016 Elsevier Inc. All rights reserved.

Figure 7: Microstructure of weld sample: (a) S960 and (b) S32205: Reprinted with permission from Tasalloti et al. // *Material Characterization*, 123 (2016). ©2016 Elsevier Inc. All rights reserved.

Figure 8: Heat process: (a) Intermittent Process Typical Cooling Cycle, (b) temps temperature of 22MnB5 Reprinted with permission from Christian Löbbbe *et al.*, // Materials, 9 (2016). ©2017 Licensee MDPI, Basel, Switzerland.

Figure 9: Microstructure analysis of 22MnB5: (a) Step 1: Quenching to room temperature; (b) Step 2: Quenching to 350°C during 30 s; (c) Formation of carbides. Reprinted with permission from Löbbbe *et al.*, // Materials, 9 (2016). ©2017 Licensee MDPI, Basel, Switzerland.

Chennaiah *et al.* [22] estimated the effect of the heat source, and PWHT on the mechanical and microstructure behavior IS 2062 and EN 1564 grade EN-GJS-800-8 welds fabricated using a MIG welding process. The variation of alloying elements and physical properties of the material did not change considerably, but the significant change occurred in the mechanical properties. In the dissimilar material, there was an increase in the tensile strength and

Figure 10: Experimental setup of the Laser welding process. Reprinted with permission from Alves *et al.* // Journal of Materials Processing Tech. ©2017 Elsevier B.V. All rights reserved.

impact strength as the heat input decreased. In addition, the process of evolution of the hardness in this case starts from the zone of fusion, followed by HAZ, towards the base metal. Figure 13 show positive effect of heat treatment for weld carried out with different heat inputs.

Both materials have different basic chemical and mechanical properties. The results after welds and heat treatments have shown that the lower the heat sources, the higher the hardness values. This phenomenon has been observed in IS2062 steel. The variation of the hardness was observed on the HAZ. The same result was obtained when the PWHT was applied. The evolution of the hardness on

Figure 11: Hardness profile of sample: P2 / S150. Reprinted with permission from Alves *et al.*, // Journal of Materials Processing Tech. ©2017 Elsevier B.V. All rights reserved.

Figure 12: The microstructure of A1 specimen (2 hours of heat treatment at 450°C). Reprinted with permission from Uzunali *et al.* // Advances in Structural Engineering and Mechanics, ASEM15 (2015). ©2015 ASEM15.

the HAZ can lead to negative effects on the mechanical characteristics of the weld joint.

Two methods of PWHT (retention and tempering annealing at the bainite transformation temperature) were used by Kucerova [23] to determine the behavior of the microstructure and the mechanical properties of the 0.4Mn 0.6Mn 42SiMn steel. 2Si 0.03Nb. A model has been developed to successively analyze the implications of the heat source on the mechanical behavior (tensile strength resulting in elongation), but also on the microstructure phase transformations (Austenite for bainite). It has been found after analysis of the results that for a heat source applied

Figure 13: Dissimilar weld of IS 2062/EN-GJS-800-8. Hardness analysis. Normal welding process, (1) Low heat input LH₁, (1) high heat input HH₁. PWHT process. (2) Low Heat LH₂, (2) High heat HH₂. Reprinted with permission from Sergio *et al.* // Material Research, 5 (2014). ©2014 MR.

to the weld joint, with an interval of 850°C to 1000°C, the reduced cooling time will have an impact on the tensile strength and its elongation. Figure 14a showed the different temperature variations and their impact on tensile strength (R_m), elongation (A) and retained austenite (RA). Based on the variations of the cooling rate, it is found in Figure 14b that the variation of the tensile strength thus resulting in elongation to a value of 930 MPa. It was possible to determine the high value of retained at more than 10%. As a function of bainitic hold temperature, a high value was observed at a temperature of 400°C. Corresponding to a value of retained of 12 %. The higher the temperature, the retained austenite values will drop to the value of 0%.

5 Results and discussion

The results vary according to the chemical structure of the base materials and the welding conditions. Table 2 summarizes key results obtained from the literature.

Dissimilar welding of the HSS requires a combination of several analyzes such as the geometrical parameters of the weld joint, the mechanical characteristics of the base materials after the determination of the filler metal obtained after evaluation of the carbon equivalent. The decision of the type of welding process and the value of the heat source will depend on the geometric and mechanical characteristics of the base materials. Table 3 presents some recommended welding procedures based on the mechanical components of the base material. It is noted that for

Figure 14: The effect of; (a) heating temperature, (b) cooling rate, and (c) bainitic phase temperature. Reprinted with permission from Kucerova // Metals 7 (2017). ©2017 Licensee MDPI, Basel, Switzerland.

Figure 15: (a) Heat input with strength behavior of 780 MPa (80 kgf/mm²) using SMAW (1 kgf/mm² = 9.8 MPa; 1 kgf-m = 9.8 J). Reprinted with permission from Ikawa *et al.* // Sampo Publication Inc, (1978). © 1978 Sampo Publication Inc.

HSS with a high tensile strength of 610 MPa, the widely used welding processes are as follows:

- Shielded metal arc welding;
- Submerged arc welding;
- Gas tungsten arc welding;
- Occasional use for electroslag welding.

For structural steels with a high tensile strength of 610 MPa, the widely used welding processes include Shielded metal arc welding, submerged arc welding and

gas shielded metal arc welding and occasional use for electroslag welding.

After having chosen the process of welding materials according to their high tensile strength, it is recommended to determine the parameters of the heat source. Figure 15a shows the different heat source values applicable depending on the recommended high tensile strength. It has been noted that for low values of heat source, the values of high tensile strength should be high. The same phenomenon has been observed in Figure 15b. A reduced values of a heat source has a higher energy impact value.

Table 2: Summary of experimental investigations has been done to evaluate the influence of the heat input parameter and PWHT on the microstructure and mechanical behavior of dissimilar weld structures.

Materials	Strategy	Findings	Citation
ASTM E112-10 QT, TMCP, OK Autrod 13.51 Shielded Metal Arc Welding (15% CO ₂ and 85% Ar)	Measurement of the mechanical behavior in the HAZ area of the dissimilar HSS.	• Variations in heat sources have direct implications on the mechanical characteristics of weld seams. • The heat source with a value of 1.7 can increase the hardness of the weld joint.	Pirinen <i>et al.</i> [6]
Welding Optim 960 QC and Duplex Stainless steel (UNS S32205) with austenitic filler wire GMAW 350x150x5 mm	Apply three different value heat sources and analyze the mechanical behavior and microstructure	• A higher heat source can cause high hardness of the S960 QC HAZ, resulting in hot cracks. • When the heat source is minimal, this can lead to low hardness values and some cold cracks.	Tasalloti <i>et al.</i> [16]
22MnB5, ENGTS-1000-5, and Docol 1400 M, Rapid Hot Forming Processes	Evaluate the mechanical properties and microstructure evolution during heat treatment.	• A slight change in the microstructure formation of grain size and undissolved carbide materials has been noted and was found to be excellent compared to conventional treatment. • For both types of steel, this system guarantees a good quality weld compared to the conventional system.	Löbke <i>et al.</i> [18]
13CrMo4-5/10CrMo9-10 use GMAW and Cold Metal Transfer (CMT)	Evaluate the advantages using Low heat input compared to the conventional GMAW	• It has been noted some incomplete microstructures transformations (austenite transformation) in this area (CGHAZ).	Frei <i>et al.</i> [19]
ENGTS 1000-5 use Laser beam welding between 0.4 and 2.0 kW	Using the parameters of the heat source to evaluate the mechanical behavior and microstructure of the welded structure.	• The melting zone has the maximum value of the Hardness profile which was 530 HV; this will be justified by the fact that this zone has a high temperature, which is therefore susceptible to hot crack.	Alves <i>et al.</i> [20]
Hardox 450, Optim 700MC MAG welding method	It investigated PWHT effects on the mechanical behavior of tempered of martensitic steel and high-strength steel joints.	• Hardness increasing due to temperature distribution. • The cooling rate determined only in HAZ of Hardox450 materials. • The hardness of the weld metal has not been affected by PWHT	Uzunali <i>et al.</i> [21]
EN 1564 grade EN-GJS-800-8/ MIG welding process	It estimated the heat input and PWHT, and their influences in mechanical and microstructure properties.	• Changes in the parameters of the heat source have a direct impact on the mechanical characteristics of the weld seam.	Chennaiah <i>et al.</i> [22]
42SiMn steel, Soaking hold and annealing hold	The effect of two-step heat treatment parameters on microstructure and mechanical properties.	Based on the variations of the cooling rate, the variation of the tensile strength thus resulting in elongation to a value of 930 MPa. It was possible to determine the high value of retained at more than 10%. As a function of bainitic hold temperature, a high value was observed at a temperature of 400°C.	Kucerova [23]

Table 3: Welding process with the type of welding consumables [28–32].

Welding process	Type of high-strength steel				
	490-MPa	610-MPa	690-MPa	780-MPa	980-MPa
Shielded metal arc welding	①	①	①	①	②
Submerged arc welding	①	①	①	①	②
Gas shielded metal arc welding	①	①	①	①	①
Gas tungsten arc welding	①	②	②	②	①
Electroslag welding	①	③	④	④	④

Note: ①: Widely used, ②: Used, ③: Occasionally used, ④: Not used

The consequences of a low or very high heat source compared to normal are important for the analysis of stress (cold and hot crack) and also on the microstructure (phase transformation) of HAZ of weld structures. To reduce the high risk of mechanical defects, it is often advisable to proceed to the PWHT.

6 Conclusion

This paper reviewed the literature on the topic of thermal behavior of HSS structures. It was found that different welding processes can be used to weld dissimilar steel materials (high-strength steels and stainless steels). Study of the mechanical properties and microstructure development of the weld joints is significant because the primary purpose of the welding is to actively join the two metals together as a welded structure at precise positions. It is crucial to obtain the tensile strength of the weld and the factors affecting the strength of the weld to maintain the acceptable microstructure of the weld joint. Based on the reviewed literature, a summarizing table was designed which provides a useful at-a-glance overview of current knowledge of dissimilar welding of high-strength steels. The analysis identified the resulting key aspects:

- A significant problem regarding the welding of dissimilar high-strength steels is cold cracking and material softening near the HAZ. Thus, heat input parameters should be controlled precisely during the welding process.
- It should be noted that the higher the heat input, the worse the properties of the HAZ of dissimilar welds of HSS;
- The correct category of the dissimilar HSS materials to be welded can help the manufacturer to select the best-optimized way of the joining processes. Understanding the different mechanisms found in dissimi-

lar welding of HSS will help to avoid defects such as cracks and softening;

- The heat input, the base materials, and the welding process are interlinked, and appropriate parameters are required to ensure the optimum characteristics of the weld joint. When using GMAW for HSS welds, high heat input affects the microstructure of the weld joint and the heat-affected area (causing bainitic transformation on the ferritic side and more martensite). With laser beam welding, the increase in the beam current leads to increasing depths and widths of the welds, and fully austenitic microstructure is produced in the weld zone. The consequence, there is a high cooling rate during the process. It is essential to obtain the optimal beam input current for the welding process and the desired outcome;
- When using PWHT, the weld joint may lose these intermetallic properties if the duration of the PWHT becomes long. With two HSS steels of type Hardox 450-Optim 700MC, the hardness increased due to abnormally high-temperature distribution. With decreased heat input, there is an increase in the tensile strength and impact strength. In the dissimilar welding of high-strength steel structures, suitable selection of the parameters of the PWHT process is significant to obtain specific weld joint properties.

Acknowledgement: The authors wish to express their gratitude to the Finnish National Education Agency (EDUFI), and the ENI CBC project Energy-efficient systems based on renewable energy for arctic conditions “EFREA” for their financial support.

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