THE ANALYSIS OF CASE STUDIES HELPS TO PREPARATION AND EVALUATION OF HIGH STRENGTH STEEL FATIGUE STRENGTH IMPROVING PROGRAMS FOR POST-WELD TREATMENT METHODS

Illés Sas
Technical Director, Elektro-MontőrING Ltd,
H-5100 Jászberény, Monostori str. 1., e-mail: sasilles@gmail.com

János Lukács
Full Professor, Institute of Materials Science and Technology,
Faculty of Mechanical Engineering and Informatics, University of Miskolc
H-3515 Miskolc, Miskolc-Egyetemváros, e-mail: janos.lukacs@uni-miskolc.hu

Abstract
Numerous researchers conducted work on the fatigue strength improvement of high strength steels welding joint by applying different post-weld treatment on it, in the last decade. These research works based on different approaches to compare the post-weld treated welding joints fatigue strength with the as welded condition or with another post-weld treatment processes. These methods are limitedly applied based on practical experiences, however significantly different results were presented in research studies. To compare the different post-weld treatment fatigue strength improvement results on high strength steels, experimental program should be performed. The aims of this article are summarizing the most relevant information for our experimental work based on analysed case studies, and proposing program setup method for evaluation different post-weld treatment process results.

Keywords: *high strength steels, fatigue strength improvement, post-weld treatment, weld geometry improvement, residual stress condition improvement, experimental program*

1. Introduction

Fatigue properties of welded structures are today a bottleneck for the introduction of high strength steels in high-performance, lightweight welded structures (Gáspár, 2016; Dobosy, 2017; Mobark, 2020; Sisodia, 2021). This caused by high strength steels increased sensitivity to notches and weld discontinuities and/or defects compared to mild strength steels, which limits the use of high strength steels in fatigue loaded structural components. Based on International Institute of Welding (IIW) recommendation (Hobbacher et al., 2009), there is little or no increase in fatigue strength of welded high-strength steel assemblies in the as-welded condition. Welding introduces geometrical notches and metallurgical modifications which give rise to local stress concentrations, and the thermo-metallurgical treatment of the filler metal and the heat affected zone (HAZ) leads to high residual component stresses or huge distortion values of the assembly (e.g., construction of steel structures or pipelines). Currently, it is necessary to apply post-weld treatment to gain increased fatigue strength when introducing high strength steels in structural applications where fatigue is the cause of failure (Ästrand et al., 2016). There are several methods which are used in industry shown in *Figure 1*, where the most available ones are marked with green colour. In the most bottom block of *Figure 1* “LTT welding” means Low Transformation Temperature welding whose details can be found in the literature (Harati et al., 2017; Igwemezie et al., 2022).

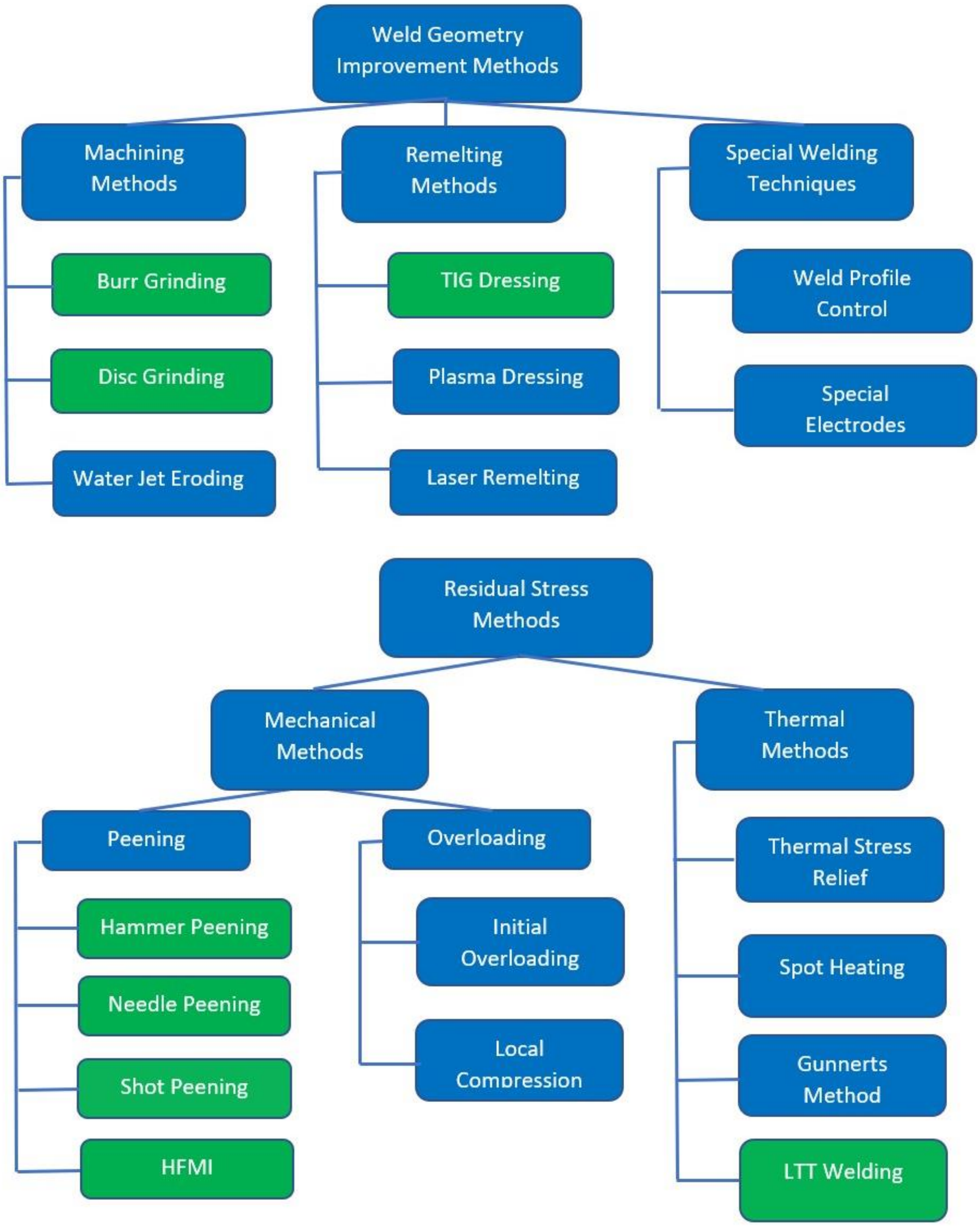


Figure 1. *Overview of different weld improvement techniques – top part: weld geometry improvement methods; bottom part: residual stress methods* (Leitner et al., 2020)

An overview regarding usage and to some extent, fatigue assessment and the increase of fatigue strength, are given in the IIW guidelines for improvement techniques (Hobbacher et al., 2009; Haagensen et al., 2013).

Research efforts over the last years have been conducted to assess an increase in the fatigue life of high strength steel structural elements, using different post-weld treatment methods in regions where the weld toe is critical. However, applying post-weld treatment in production gives additional costs in terms of treatment process time, equipment, as well as staff. In our days, practical experiences show the weld geometry improvement methods are still more utilized in high strength steel welding construction post-weld treatment rather than residual stress concentration methods. This finding originates more from the characteristics of post-treatment technologies than from the geometrical dimensions of the structures and the effects of the treatments on the integrity of the structures; whilst the post-treatment of welding joint is close correlation with the structural integrity (Koncsik, 2019; Koncsik, 2021) of both the welding joint and the welded structural element. Considering the production cost and quality assurance – in other words technological stability – of post-weld treatment processes, it is reasonable to compare not only the improvement achieved compared with as weld condition than also the different processes are interesting to compare.

The aims of this article are summarizing the most relevant information for our experimental work based on reviewed and analysed case studies, and proposing experimental program setup method for evaluation different post-weld treatment process results.

2. Review of experimental programs

Research studies from last decades were reviewed to analyse the experimental programs of fatigue strength improving post-weld treatment methods. Based on analysed 19 research studies several interesting findings were detected what support to prepare our experimental program proposal for comparing post-weld treatment of high strength steel welding joint. Reviewed research reports applying different post-weld treatment methods on welding joints of high strength steels with different experimental specimens presented in Appendix. 60 investigational specimens were published in reviewed studies and 46 from these are focused on high strength steels welding joint fatigue strength improvement. As review analysis result shows in Table 1, the most of reviewed studies focused on high frequency mechanical impact (HFMI) post-weld treatment. Furthermore, important that the reviewed studies are mainly focused to compare the as-weld condition with one to three applied fatigue strength improvement post-weld treatment methods. None of them is comparing the full range of post-weld treatment of high strength steels welding joint. The reviewed research studies also apply other post-weld treatment methods for high strength steel welding joints fatigue improvement which are not industrialized such level as *Table 1* presented methods.

Table 1. *Number of applied post-weld treatment methods in reviewed case studies*

Weld geometry improvement methods			**Residual stress methods**			
Burr grinding	**Disc grinding**	**TIG dressing**	**Hammer peening**	**Needle peening**	**Shoot peening**	**HFMI**
2	N/A	3	N/A	N/A	1	37

Examples – in other words frequently applied cases – of welded joints suitable according IIW recommendation (Hobbacher, 2009) for weld toe improvement methods are shown in *Figure 2*. In these cases the improvement of fatigue life is considered only from the viewpoint of weld toe. If there existing further imperfections on the root only the origin of the failure shifted from a weld toe to the root therefor fatigue life of the welding joint cannot significantly be improved by post treatment.

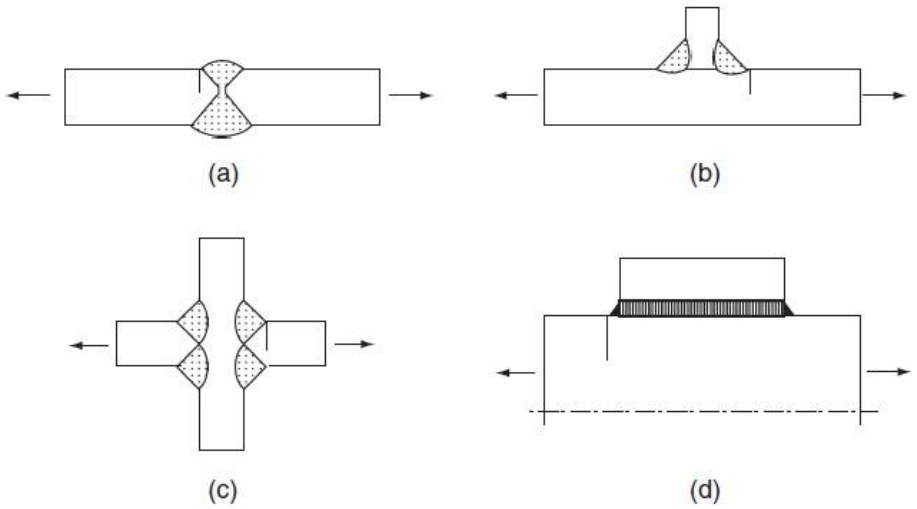


Figure 2. *Examples of joints suitable for improvement* (Hobbacher, 2009)

Some of welding joints where root cracking might occur are shown in *Figure 3*. In these cases, which are similarly frequently applied cases, significant improvement of fatigue strength is obtained if full penetration weld or extra-large throats should be used where possible. Improvement of incomplete root penetration should be verified by fatigue testing or by (finite element) analysis (Hobbacher, 2009).

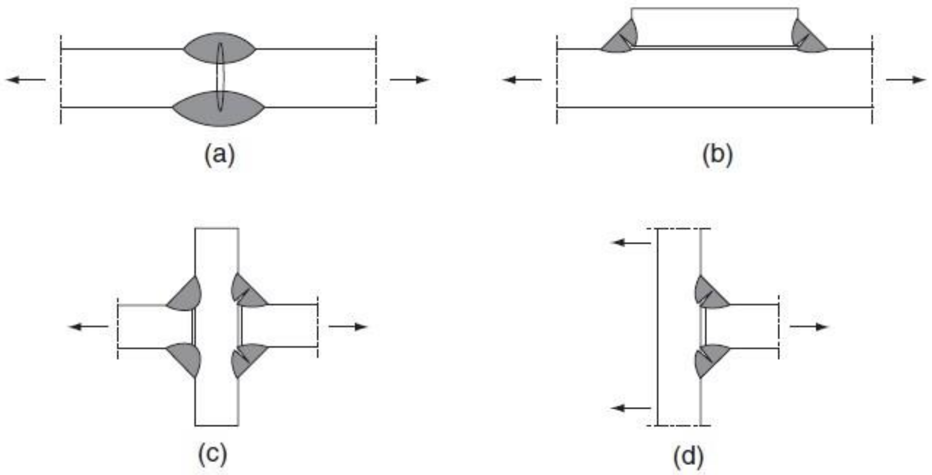
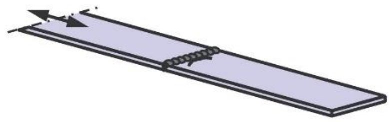
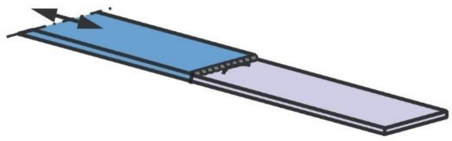
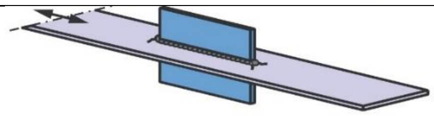
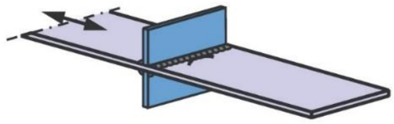
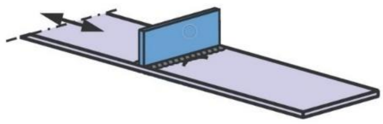
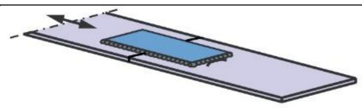
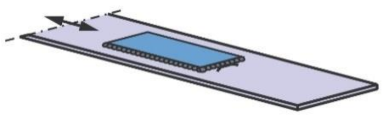


Figure 3. *Examples of joints improvement of fatigue strength limited by occurrence of the root cracking* (Hobbacher, 2009)

In the reviewed and analysed research studies applied different welding specimens can categorized according to *Figure 2* and *Figure 3* classified welding joint categories. The partial penetration butt welded joint shown in *Figure 3 (a)* were not investigated in the reviewed studies. Industrial practice also confirms in critical areas the partial penetration butt welded joints are not used in welded construction made from high strength steels because of the base materials have high sensitivity to notches and welding defects. Regarding to the IIW recommendation (Hobbacher, 2009), the research studies analysed and industrial practice, welding specimens' type could be categorized into 7 categories as shown in *Table 2*.

Table 2. *Categorization of welding specimens' type based on analysed case studies*

Welding specimen type	**Specimen setup**
Butt weld	
Butt weld with different thickness plate	
Longitudinal stiffener	
Transversal stiffener (cruciform type)	
Transversal stiffener (T joint type)	
Lap joint	
Cover plate	

Welding specimen type analysis shows that the researchers are focused on fatigue strength improvement of longitudinal and transversal stiffener type welding joint post-weld treatment, as 43 welding specimens from the 60 reviewed ones is welded as longitudinal or transversal stiffener. *Table 3* summarizes the welding specimen type analysis based on case studies. The welding specimens' type like butt weld with different thickness plate, lap joint and cover plate investigated only in few research studies, behind this fact could be that these types of welding joints are not used in critical areas of fatigue loaded high strength steel welded structures.

Table 3. *Number of applied welding specimens' type in reviewed case studies*

Butt weld	Butt weld with different thickness plate	Longitudinal stiffener	Transversal stiffener (cruciform)	Transversal stiffener (T joint)	Lap joint	Cover plate
9	1	21	11	11	3	4

Analysed results show that welding specimens welded with fillet weld (FW) is investigated 43 cases what is more than two third parts of all investigated welding specimens reviewed in this paper. Furthermore, important to note that in case of longitudinal or transversal stiffener type welding specimens could also welded by fillet weld (FW) or with butt weld (BW) what is influence the fatigue strength of the welding joint. Weld geometry of welding joint surface is influencing the fatigue strength of the welded structures it is obvious that the risk in multi-layer welding joint that the weld geometry contain notches is much higher than single layer welding technique. Therefore, other key factor what is also influencing the fatigue strength of welding joint is the welding technique in cover layer as single-layer or multi-layer technique. Analysis of case studies shows that the 56 welding specimens are welded in single layer and only 4 cases were applied the multi-layer welding technique. It is interesting result because in heavy and/or thick welded structures made of high strength steels multi-layer cover techniques are commonly used due the limitation of the heat input to ensure the right toughness of the welding joint.

Weld shape imperfections influenced by the weld position also. In case of horizontal flat (PA) position welding is obvious the weld shape could be much better than in horizontal PB or PC position rather than vertical down to up position (PF). The welding position is not given in all analysed cases, however the shape of welding in FW welding joint is look like PB position welding in case of butt weld it looks like PA position welding. The welding process according to ISO 4063 (ISO, 2006) is 135, GMAW process in all reviewed cases.

Welding residual stresses are affected by welding circumstances of like free or limited deformability of the welding specimens during the welding. In welded structures the deformability of the welding joint is limited therefore higher residual stresses arise compared with free deformability welding specimens. In the case of welding the specimens under free deformability condition applying residual stress method post-weld treatment can reach better result than specimens welded under limited deformability condition. It is also not mentioned in any reviewed report that the welding was performing under which condition.

In some cases, the weld toe was removed or grinded before applying post-weld treatment in the welding joint what is also important welding condition parameters influencing the fatigue strength of the welding joint.

Based on reviewed case studies, it was started to prepare an experimental program setup proposal what is suitable to define all important details regarding the post-weld treatment of high strength steel welding joints.

3. Experimental program setup proposals

Based on the review of experimental programs can be found in case studies, influencing parameters of post-weld treatment of high strength steels welding joints were classified into three mains categories as shown in *Figure 4*. Under welding technology those parameters were classified which are influencing as basic parameters of welding process and base material. Parameters classified into welding specimens' group which are define the specimen preparation like the type and size of specimens and type of welding joint. Post-weld treatment methods and post-weld treatment parameters are classified into the post-weld treatment group.

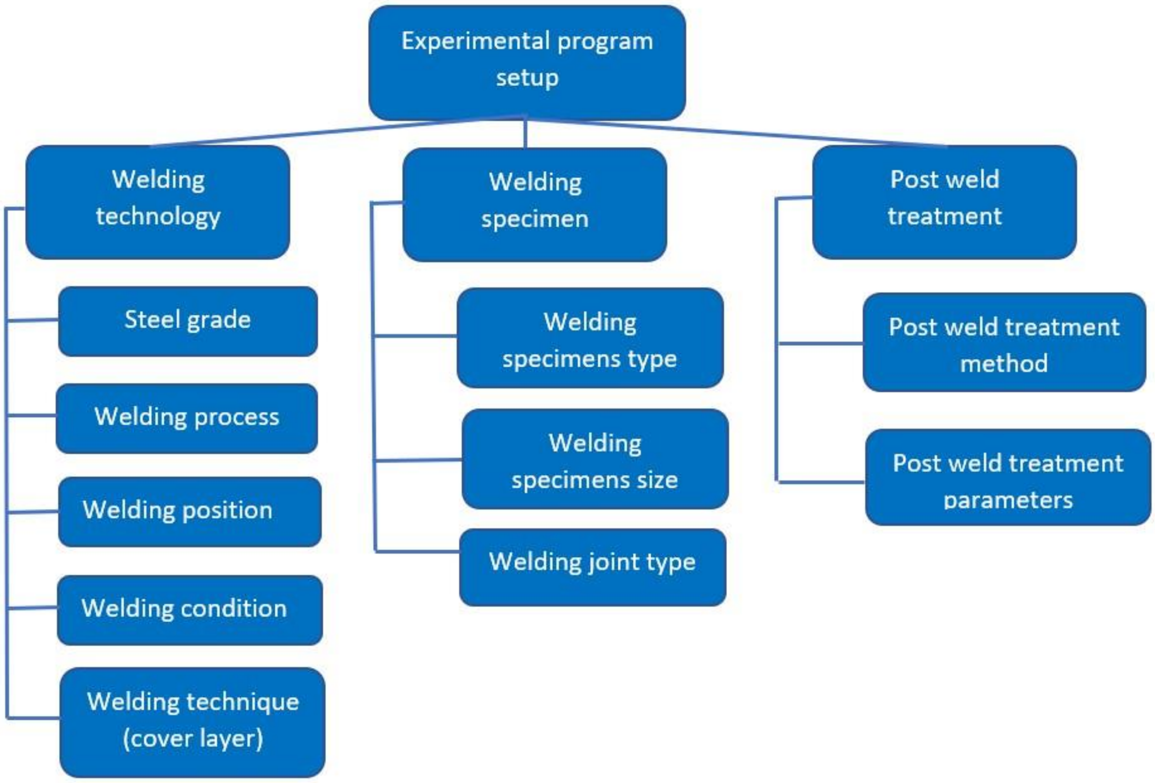


Figure 4. *Schematic diagram of experimental program setup*

Welding technology parameters, as basic parameters, are the steel grade of the inspected base material, the welding process applied during welding, the position of welding, the welding condition and the welding technique of cover layer. Important parameters under welding condition are those parameters which influenced the fatigue strength of the welded specimens, e.g., weld toe pre-machining, specimens welded under limited deformability condition, automatization level of the applied welding process. Overall, it is advised to use automatization during the welding of specimens because increasing the stability of the weld geometry is important to create same condition in each welded specimen. Butt weld, butt weld with different thickness plate and transversal stiffener could be automatized easier because more specimens can be welded in a row applying run on/out plates between the specimens. Longitudinal stiffener, lap joint and cover plate welding could be automatized only in higher level meaning robotized or cobot systems, reaching same stability in the welding process. Advised is using constant parameters in the research program planning, under the same welding technology parameters the influence of the welding specimens and/or influence of the post-weld treatment methods fatigue strength improvement could be assessed.

Welding specimen parameters are the welding specimen type (listed in *Table 2*), size of welding specimens contains the geometry of the specimens, the thickness of the plates and the welding joint type as butt weld (BW) or fillet weld (FW) what also define the edge preparation of the specimens.

Post-weld treatment parameters are the applied post-weld treatment process and the process parameters, where process parameters are defined in IIW recommendation (Haagensen et al.; 2013, Marquis et al., 2016) to each process.

The welding specimen and post-weld treatment are the variable parameters of high strength steel welding joints fatigue strength improvement research programs. Based on the target of the research program, either the welding specimen or the post-weld treatment or simultaneously booth parameters could be modified. In case of varying post-weld treatment parameters in fixed welding specimens; parameters the different treatment, costs and fatigue improvement result could be optimized. By modifying the welding specimen's parameters under same post-weld treatment circumstances, the selected methods optimum usage could be assessed from construction design point of view.

For better visualization of experimental program setup, welding specimen – post-weld treatment matrix was prepared for the most industrialized post treatment methods. Under predefined welding technology parameters proposed welding specimen post-weld treatment matrix could be used to plan the welding program based on the target of the program such us complete analysis of the treatment methods or comparing the methods in selected welding specimen type and techniques. For better visualization, the matrix also contains the cover layer welding techniques, as multi-layer (ml) or single-layer (sl) welding. In critical areas, for example after construction damages, booth weld specimen and post-weld treatment process parameters could be optimized to find solution by parallelly modifying design of welded construction and select the appropriate post-weld treatment method or parameter.

Considered the welding specimens and post-weld treatment parameters are variable parameters in most cases of research programs it is obvious idea to prepare a 2D matrix linked to the weld specimens – post-weld treatment as variables. This proposed welding specimens – post-weld treatment matrix could be utilized in research program planning and visualization of mapping of results. Consider that the cover layer welding techniques as multi-layer or single-layer has significant influence on fatigue strength of the welding joint therefore our proposal to add the welding techniques also as variable parameter to the welding specimen – post-weld treatment matrix. Based on the above-mentioned considerations, the proposed matrix format is presented in *Table 4*.

Based on the analysed research studies, the welding specimen – post-weld treatment matrix was completed and presented in *Table 4*, visualizing the coverage of the welding specimens and post-weld treatment methods. However, it is important to note that the reviewed case studies are not made under same weld technology parameters (like base material, welding condition), and welding specimen size therefore the presented matrix can be used only to show functioning of the welding specimen – post-weld treatment matrix.

Table 4. *Welding specimen – post-weld treatment matrix covered by analysed case studies (BW = butt weld, FW = fillet weld and sl = single-layer, ml = multi-layer)*

Welding specimen type	Welding joint type	Welding technique (cover Layla)	Weld geometry improvement			Residual stress reduction				
			Burr Grinding	Disc Grinding	TIG Dressing	Hammer Peening	Needle Peening	Shoot Peening	HFMI	LTT welding
Butt weld	BW	sl							■	
		ml							■	
Butt weld with different plate thickness	BW	sl								
		ml							■	
Longitudinal stiffeners	FW	sl			■				■	■
		ml							■	
	BW	sl								
		ml							■	
Transverse stiffeners (cruciform type)	FW	sl							■	
		ml								
	BW	sl								
		ml								
Transverse stiffeners (T joint type)	FW	sl			■				■	
		ml								
	BW	sl						■	■	■
		ml								
Lap joint	FW	sl							■	
		ml								
Cover plate	FW	sl							■	
		ml								

4. Conclusions

Based on the analysed nineteen research studies and sixty experimental specimens, the following conclusions can be drawn.

The case studies consist essential and applicable information belonging to both the preparation and the evaluation phases of our research program.

The experimental program setup parameters of high strength steels welding joint fatigue strength improvement methods can be classified into three groups, as follows: weld technology, welding specimens and post-weld treatment methods.

In developed and presented methodology, the welding technology parameters are functioning as basic parameters of the experimental program, and weld specimens, post-weld treatment methods are visualized in the weld specimen – post-weld treatment matrix.

This proposed methodology can be used planning the experimental research program to cover the whole type of welding specimens or to compare all most industrialized post-weld treatment methods fatigue strength improvement results. It is important to note, that the sizes of the welding specimens must be also considered to influence to the fatigue strength. Therefore, further analysis should be performed focusing on the size effect.

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APPENDIX

Reviewed case studies experimental program

(BW = butt weld, FW = fillet weld and sl = single-layer, ml = multi-layer)

No.	Reference	Steel grade	Plate thickness 1	Plate thickness 2	Welding specimen type	Welding joint type	Welding technique (cover layer)	Post-weld treatment
1	Abdulahh et al., 2012	1.4031	5	5	Butt weld	BW	sl	HFMI
2	Aldén et al., 2020	S700 MC	10	6	Transverse stiffener (cruciform type)	FW	sl	HFMI
3	Berg et al., 2014	S960	7	5	Cover plate	FW	sl	HFMI
4	Berg et al., 2014	S960	7	7	Butt weld	BW	sl	HFMI
5	Berg et al., 2014	S960	5	5	Butt weld	BW	sl	HFMI
6	Berg et al., 2014	S1100	6	6	Cover plate	FW	sl	HFMI
7	Berg et al., 2014	S1100	6	6	Longitudinal stiffener	FW	sl	HFMI
8	Berg et al., 2014	S1100	6	6	Transverse stiffener (cruciform type)	FW	sl	HFMI
9	Berg et al., 2014	S1100	6	6	Cover plate	FW	sl	HFMI
10	Berg et al., 2014	S1100	6	8	Butt weld with different thickness plate	BW	ml	HFMI
11	Berg et al., 2014	S1300	4	4	Cover plate	FW	sl	HFMI
12	Berg et al., 2014	S1300	4	4	Transverse stiffener (cruciform type)	FW	sl	HFMI
13	Berg et al., 2014	S1300	4	4	Longitudinal stiffener	FW	sl	HFMI
14	Ghahremani et al., 2015	S355	9.5	9.5	Transverse stiffener (cruciform type)	FW	sl	HFMI
15	Ghahremani et al., 2015	S355	9.5	9.5	Lap joint	FW	sl	HFMI

No.	Reference	Steel grade	Plate thickness 1	Plate thickness 2	Welding specimen type	Welding joint type	Welding technique (cover layer)	Post-weld treatment
16	Harati et al., 2020	S1300	15	15	Transverse stiffener (T joint type)	BW	sl	HFMI
17	Harati et al., 2020	S1300	15	15	Transverse stiffener (T joint type)	BW	sl	Shot Peening
18	Harati et al., 2020	S1300	15	15	Transverse stiffener (T joint type)	BW	sl	LTT Welding
19	Lefebvre et al., 2015	S690	10	10	Butt weld	BW	sl	HFMI
20	Leitner et al., 2014	S690	5	5	Butt weld	BW	sl	HFMI
21	Leitner et al., 2014	S690	5	5	Transverse stiffener (T joint type)	BW	sl	HFMI
22	Leitner et al., 2014	S690	5	5	Longitudinal stiffener	BW	sl	HFMI
23	Leitner et al., 2014	S960	5	5	Butt weld	BW	sl	HFMI
24	Leitner et al., 2014	S960	5	5	Transverse stiffener (T joint type)	BW	sl	HFMI
25	Leitner et al., 2014	S960	5	5	Longitudinal stiffener	BW	sl	HFMI
26	Leitner et al., 2020	S1100	6	6	Butt weld	BW	sl	HFMI
27	Leitner et al., 2020	S1100	6	6	Lap joint	FW	sl	HFMI
28	Leitner et al., 2020	S1100	6	6	Transverse stiffener (T joint type)	FW	sl	HFMI
29	Leitner et al., 2020	S1100	6	6	Longitudinal stiffener	FW	sl	HFMI
30	Leitner et al., 2020	S1300	4	4	Lap joint	FW	sl	HFMI
31	Leitner et al., 2020	S1300	4	4	Transverse stiffener (T joint type)	FW	sl	HFMI
32	Leitner et al., 2020	S1300	4	4	Longitudinal stiffener	FW	sl	HFMI

No.	Reference	Steel grade	Plate thickness 1	Plate thickness 2	Welding specimen type	Welding joint type	Welding technique (cover layer)	Post-weld treatment
33	Ting et al., 2009	S700	–	–	Butt weld	BW	sl	HFMI
34	Ting et al., 2009	S700	–	–	Longitudinal stiffener	FW	sl	HFMI
35	Yang et al., 2014	S690	12	12	Transverse stiffener (cruciform type)	FW	sl	HFMI
36	Yekta et al., 2013	S355	9.5	9.5	Transverse stiffener (cruciform type)	FW	sl	HFMI
37	Hai et al., 2015	S690	15	15	Butt weld	BW	ml	HFMI
38	Dahle, 1998	S700	12	12	Longitudinal stiffener	FW	sl	TIG Dressing
39	Dahle, 1998	S900	12	12	Longitudinal stiffener	FW	sl	TIG Dressing
40	Ferreira et al., 1989	S355	4	4	Transverse stiffener (cruciform type)	FW	sl	Thermal Stress Relief
41	Ferreira et al., 1989	S355	6	6	Transverse stiffener (cruciform type)	FW	sl	Thermal Stress Relief
42	Ferreira et al., 1989	S355	12	12	Transverse stiffener (cruciform type)	FW	sl	Thermal Stress Relief
43	Ferreira et al., 1989	S355	20	20	Transverse stiffener (cruciform type)	FW	sl	Thermal Stress Relief
44	Ferreira et al., 1989	S355	4	4	Transverse stiffener (T joint type)	FW	sl	Thermal Stress Relief
45	Ferreira et al., 1989	S355	6	6	Transverse stiffener (T joint type)	FW	sl	Thermal Stress Relief
46	Ferreira et al., 1989	S355	12	12	Transverse stiffener (T joint type)	FW	sl	Thermal Stress Relief
47	Ferreira et al., 1989	S355	20	20	Transverse stiffener (T joint type)	FW	sl	Thermal Stress Relief
48	Gerritsen et al., 2013	S690	10	10	Longitudinal stiffener	FW	ml	Laser Remelting
49	Gerritsen et al., 2013	S960	10	10	Longitudinal stiffener	FW	ml	Laser Remelting

No.	Reference	Steel grade	Plate thickness 1	Plate thickness 2	Welding specimen type	Welding joint type	Welding technique (cover layer)	Post-weld treatment
50	Mecséri et al., 2020	S420	10	10	Longitudinal stiffener	FW	sl	Burr Grinding
51	Mecséri et al., 2020	S420	18	18	Longitudinal stiffener	FW	sl	Burr Grinding
52	Skirko et al., 2017	S960	8	8	Transverse stiffener (cruciform type)	FW	sl	TIG Dressing
53	Bhatti et al., 2013	S700	5	5	Longitudinal stiffener	FW	sl	LTT Welding
54	Bhatti et al., 2013	S700	10	10	Longitudinal stiffener	FW	sl	LTT Welding
55	Bhatti et al., 2013	S960	5	5	Longitudinal stiffener	FW	sl	LTT Welding
56	Bhatti et al., 2013	S960	10	10	Longitudinal stiffener	FW	sl	LTT Welding
57	Marquis, 2010	S700	8	8	Longitudinal stiffener	FW	sl	HFMI
58	Marquis, 2010	S700	8	8	Longitudinal stiffener	FW	sl	LTT Welding
59	Marquis, 2010	S960	6	6	Longitudinal stiffener	FW	sl	HFMI
60	Marquis, 2010	S960	6	6	Longitudinal stiffener	FW	sl	LTT Welding