THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Fatigue life extension in existing steel bridges

High-Frequency Mechanical Impact treatment and Tungsten Inert Gas remelting in life extension and fatigue crack repair of welded steel structures

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Cover:
[The figure shows the High-Frequency Mechanical Impact indentor and the Tungsten Inert Gas arc which are used to treat existing welded structures]

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ABSTRACT

This thesis investigates the performance of improved welds with two post-weld treatment methods for application on existing structures. High-Frequency Mechanical Impact (HFMI) treatment and Tungsten Inert Gas (TIG) remelting were used for fatigue life extension of welded structures. Axial fatigue testing was conducted on transversal non-load-carrying attachment treated via the investigated methods. Furthermore, more than 250 test results on different treated welded details were collected, sorted and analysed. HFMI-treatment was found to give a significant fatigue life extension even with the presence of cracks up to 2.25 mm. On the other hand, the efficiency of TIG-remelting was also proven when the crack was completely eliminated after remelting. Even if a small part of the crack remains after remelting, fair fatigue life could be expected. However, it is recommended to use HFMI-treatment or TIG-remelting only when the crack inspection is negative before and after treatment respectively.

Complimentary studies showed that the investigated methods induced compressive residual stress, increased the smoothness of the weld toe, increased the local hardness and changed the angular distortion status locally. Moreover, TIG-remelting changed the microstructure in both the fusion zone and the heat-affected zone. HFMI-treatment changed the crack orientation, induced compressive plasticity at the crack tip and caused crack narrowing or even closure. However, these effects were less significant for deeper cracks. Moreover, some practical aspects of the treatment application were investigated. Unlike treating new structures, TIG-electrode should be placed at the weld toe to secure that the maximum fusion depth corresponds to the crack plane. On the other hand, HFMI-indentor should be slanted more toward the base metal than the weld to avoid unintentional crack opening. Moreover, the IIW recommendations for both HFMI-treatment inclination and indentation depth could be extended to cracked structures.

The aforementioned investigated parameters (i.e. residual stress, distortions, local hardness and toe's smoothness) were incorporated in fatigue life predictions for both treatment methods. The base metal S-N curve was used to predict the life of specimens treated via TIG-remelting, while Paris law was used to track the crack propagation of HFMI-treated details. The results corresponded well with fatigue test results. Combining TIG-remelting with HFMI-treatment resulted in welds with higher fatigue strength because of the combined effects of crack closure via TIG-remelting and compressive plasticity via HFMI-treatment.

Keywords: HFMI, Peening, TIG-remelting, TIG-dressing, Life extension, Post weld treatment, Crack retrofiting, Crack detection, Linear elastic fracture mechanics, Strain gauge, fatigue crack, LEFM, Micro-hardness, Concentration factor, Gain factor.

Preface

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HASSAN AL-KARAWI

list of publications

This thesis is based on the work contained in the following papers:

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- Al-Karawi, Hassan, Asma Manai, and Mohammad Al-Emrani. ”A Literature review for the state of the art, fatigue life extension of welded structures by peening and TIG dressing .” (2019).

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1 Introduction

1.1 Background

After world war II, numerous amount of bridges were built in order to meet the need in road and railway networks. Therefore, traffic authorities in Europe are dealing with many bridges which are structurally deficient, functionally obsolete and in need of repair and upgrading. The collected data from 17 railway administrations show that more than two-thirds of the railway bridges in Europe are older than 50 years, half of them are even older than 100 years [1]. In France, more than 50 % of 20000 bridges need to be repaired, while more than 20 % of the bridges are structurally deficient. In Hungary, an urgent repair is needed for more than 50 % of the main highway and secondary bridges [2]. There are two strategies to deal with ageing structures; the first is to replace the old bridge by a new one. Another option is to upgrade the bridge and repair any existing damage.

Bridge upgrading is more preferred than constructing new ones to avoid the high expenses associated with new bridge construction, demolishing the existing bridge and traffic interruption. Moreover, environmental concerns and inconvenience to the public are greater for constructing new bridges. The main factors associated with bridge maintenance during the service life of the structure are the structural damage, the errors during design or production stages, the changes in design codes, the desire to increase the traffic load and the deterioration of one of the bridge critical components. This deterioration can be either instantaneous due to unexpected loading or progressive and takes time.

Out of the studied 161 failed metallic bridges, fatigue and fracture appear to be the most critical failure mode constituting more than 45% of the total cases [3]. Therefore, the fatigue limit state (FLS) should be taken into consideration when designing steel or steel-concrete composite bridges. Fatigue is progressive damage evolves when the bridge is subjected to repeated loading lower than the material's capacity. This damage accumulates and causes crack formation which can propagate and causes failure in the structure if not treated. Considering the millions of load cycles which the bridge components are bearing, fatigue is usually the governing criterion in the design of steel bridges as it limits the design load to a lesser value than both the ultimate and the service limit states.

When welding was introduced in Europe for joining steel components instead of riveting prior to world war II, many welded truss bridges were constructed. Nowadays, welding is by far the most predominant joining method used in steel bridges. The first failure due to fatigue was reported in Germany in a truss bridge in the 1920s. Fatigue fracture was then observed in many steel bridges and in some cases, the fracture was brittle and sudden. This drew the attention of bridge engineers and researcher to fatigue of welds. In the 1960s, the American Association of State Highway and Transportation official AASHTO introduced fatigue design provision. The stress range concept and the detail categories were then introduced in the 1970s [4]. Two decades later, a whole section was devoted to the problems of fatigue in steel structures in the Eurocode [5]. At the beginning of the 21st century, recommendations for the design of welded steel structures was released by the International Institute of Welding IIW [6].

Despite being the most predominant joining method, welding usually induces unfavorable tensile residual stresses in the heat-affected zone. Furthermore, geometrical stress concentrations are obtained where the stress flow in the element is disturbed due to geometry change such as welded stiffener. Moreover, weld defects such as undercuts, spatter or inclusions usually exist in the weld toe region. Fatigue process consists of two stages: crack initiation and propagation. In welded structures, the crack initiation phase is negligible and relatively shorter than the propagation stage. Cracks can initiate either from the weld toe and propagate through the base metal or from the weld root and propagate through the weld body.

Because of the aforementioned challenges related to welded joints, several weld repair methods were developed and investigated in many test programs. The choice of the method is dependant on many factors such as the circumstance of fatigue cracking, the availability of the required skills and operators, and the crack size. Drilling a hole at the crack tip to stop the crack propagation is one of the most popular methods. Sufficient hole diameter is required to arrest the crack, usually greater than 25 mm. Therefore, crack inspection is needed to specify the crack tip location. In addition, it can be plugged with a tightened bolt to introduce compression forces, and cause further crack retardation. However, the crack, in this case, should be large in size, usually through-thickness crack.

Re-welding is another well-known method which can be used for long crack reparation. The material first is removed by grinding, then it is filled with weld material. Thus, the whole crack is replaced by welds. Usually, the new weld exhibits the same fatigue strength of the original uncracked weld [7]. However, this method has deleterious effects on the mechanical proprieties of the material. There is also a risk that the crack is blurred or smeared while the material is removed. Re-welding may also induce undesired tensile residual stress and distortions due to the extreme heat input. Nevertheless, these effects can be counteracted through mechanical impact to introduce compressive residual stress.

Anther method aims at reducing the nominal stress range by increasing the plate area is to attach a splice plate. This can be used to restore the properties if the member is heavily corroded. These splices are attached to the main plate by bolting or less preferably by welding. However, this introduces a source of stress concentration and affects the fatigue strength. Furthermore, this method requires good accessibility to the crack position and requires traffic shut down temporarily. It also increases the mean stress by increasing the self-weight.

All the aforementioned methods (crack arrest hole ,re-welding, splice plate) are applicable for repairing through-thickness cracks or at least cracks deeper than 5 mm [8]. On the other hand, there are other family of methods that aims at repairing shallower cracks such as grinding, impact treatment and remelting. These methods are specified in the IIW recommendations on post-weld improvement of steel and aluminium structures [9]. These methods are classified into two categories based on their effect: stress concentration reducers and residual stress improvers. In the former one, the aim is to reduce or remove the local stress concentration by providing a smooth transition between the material and the weld face by either fusion or grinding.

In comparison with Tungsten Inert Gas (TIG)-remelting, grinding is a slower method, especially when applied on hard material, which also causes wear in the used tool. Moreover, it is more demanding for the operator than TIG-remelting [10]. Furthermore, the fatigue strength of TIG-remelted details is found to be longer than these of ground details [10, 11]. In TIG-remelting, the non-consumable tungsten electrode is protected by an inert gas such as argon. This technique aims at creating a weld pool, remelting the vicinity of the weld toe, removing any existing defect, providing a transition between the weld and the base material and thereby, reducing the stress concentration. Moreover, it influences the microstructure of the material and modifies the residual stress level at the weld toe. The depth of fusion and the radius of the new weld toe can be optimised by controlling the heat input which is dependant on the remelting speed, voltage and welding current.

The second category of the surface treatment methods comprises the residual stress improvers which aim at reducing the tensile residual stress in the heat-affected zone or even introducing compressive residual stress by an impact tool. High-Frequency Mechanical Impact (HFMI) treatment has emerged as a new and user-friendly weld improvement method for fatigue enhancement. This enhancement is due to the combined effects of introducing compressive residual stress by surface cold working, increasing the weld toe radius which reduces the sharpness of the welds and strain hardening of the steel which prolongs the crack initiation life. Moreover, HFMI-treatment removes the local stress raisers at the weld toe such as undercuts. HFMI-treatment can be given by different brand names such as Hammer Peening (HP), Ultrasonic peening (UP), Pneumatic Impact Peening (PNP), Needle Peening (NP), Ultrasonic Impact Treatment (UIT) and High-Frequency Impact Treatment (HiFIT). The latest produces finer surface finish because of the smaller spacing between the alternate impacts [12].

Both HFMI-treatment and TIG-remelting can be used for either increasing the fatigue resistance of new built welded structures or repairing in-service structures which have been subjected to fatigue damage. In the latter case, cracks may already have formed at the weld toe. HFMI-treatment, in this case, aims at closing up the crack surfaces via cold working while TIG-remelting causes full or partial fusion of the crack surfaces. The performance of the treated structures is dependant on the treatment quality, the treated geometry, the steel quality, the load level, the stress ratio and last but foremost, the existing damage or crack in the structure due to previous fatigue loading.

Despite being promising, the available knowledge on the efficiency of HFMI-treatment and TIG-remelting in fatigue life extension of welded structures and retrofitting existing cracks are still limited. Moreover, fatigue life prediction of treated structures which is an important input for traffic authorities is still to be explored. Therefore, the thesis in hand mainly aims at studying the efficiency of both HFMI-treatment and TIG-remelting in fatigue life extension of existing structures via experimental and analytical investigations. A special focus is directed toward the mechanisms and the causatives of fatigue life extension. Moreover, light is shed on the potential benefits of combining TIG-remelting with HFMI-treatment on fatigue strength.

1.2 Objectives

The overall aim of this thesis is to investigate the efficiency of HFMI-treatment and TIG-remelting in fatigue life extension of existing welded steel structures subjected to fatigue loading. The following research objectives have been identified for this thesis:

1. Studying the potential effect of HFMI-treatment in fatigue crack repair and fatigue strength enhancement of welds, and identifying the limits of using this method with respect to prefatigue loading and existing damage.
2. Studying the potential benefit of using TIG-remelting in fatigue life extension of existing welds and crack removal, and identifying the maximum crack size could be tolerated before TIG-remelting application.
3. Comparing the fatigue behaviour of treated new (virgin) and existing structures, and identifying the similarities and the differences.
4. Providing simple but rather relatively accurate fatigue life calculation tools of both HFMI-treated and TIG-remelted details.
5. Investigating the mechanisms behind fatigue life extension using HFMI-treatment and TIG-remelting and comparing these mechanisms for both methods.
6. Investigating the possibility of combining these methods and studying the potential effect of such combination on fatigue life extension.
7. Proposing practical guidelines for engineers and traffic authorities who deal with existing steel structures regarding both of these methods.

1.3 Methodology

The work presented in this thesis comprises literature reviews, fatigue testing, experimental investigations, numerical and analytical models. The literature review shed the light on the published fatigue test results of prefatigued welded details treated by HFMI-treatment or TIG-remelting. Axial fatigue tests were conducted on non-load carrying transverse attachment detail in order to enhance the available knowledge on fatigue life extension.

Moreover, several supportive investigations such as crack detection, local geometry scanning, residual stress investigation, hardness testing, metallurgical analysis and optical microscopy were carried out to explore the mechanisms behind life extension and to compare the efficiency of the studied methods. Moreover, the results obtained from fatigue testing together with published results extracted from the literature were analysed to determine the allowable crack size and pre-fatigueing number of cycles before the application of HFMI-treatment or TIG-remelting. Practical guidelines on how HFMI-treatment should be applied for existing cracked welds were studied via numerical analysis. Moreover, local stresses due to external loading were also obtained by numerical analysis with the effective notch stress approach. In addition, crack propagation study was performed with linear elastic fracture mechanics to estimate the fatigue life of HFMI-treated structures. For TIG-remelted details, damage model was adapted in order to incorporate the several investigated parameters (e.g. residual stress, local hardness, stress concentration factor, clamping stress) in fatigue life prediction.

1.4 Limitations

- The thesis includes only constant amplitude fatigue tests in both as-welded state and after HFMI-treatment and TIG-remelting. Therefore, fatigue life estimations are not valid for variable amplitude loading.
- The thesis focuses on crack repair and retrofitting of existing structures. Therefore, implementation of the studied treatment methods in the design of new structures is out of the scope of this thesis.
- The damage model used for fatigue life prediction of TIG-remelted details is only valid when the structures are crack-free after remelting.
- The elastoplastic finite element analysis used for studying the effect of HFMI-treatment on crack closure id rather simple and does not take into account the dependency on strain rate.
- No analytical or numerical prediction of residual stress is presented in this work. Moreover, residual stress relaxation due to cyclic loading is not taken into account in fatigue life predictions.

1.5 Outlines

Section 1: This section gives a general background to the topic and defines the problem statements in the form of objectives.

Section 2: The state of the art of fatigue life extension on welded steel structures by HFMI-treatmenat and TIG-remelting are presented in this section.

Section 3: The potential benefits of both treatment methods in fatigue life extension are explored in this section. In addition, fatigue test results are presented for combined treatment (TIG-remelting followed by HFMI-treatment). This section extracts results from paper I, II. These results together with test results presented in **Section 2** are analysed and compared against standards & recommendations in Paper IV.

Section 4: Supportive experimental and numerical investigations on the mechanisms of fatigue life extension are conducted in this section which are extracted from papers I, II and III.

Section 5: In this section, fatigue life prediction is conducted using both damage model and fracture mechanics are presented. The section is an adaption from papers I, II.

Section 6: The main findings and conclusions are summarised in this section.

2 The state of the art

Fatigue is a progressive localised permanent damage occurs in the structure when it is subjected to repetitive loading. In steel bridges, fatigue usually occurs in the welded joints because of their susceptibility to crack formation. This is attributed to the high stress concentration at the weld toe, the tensile residual stress raising in cooling stage, and welding induced imperfection such as undercuts. Several post-weld treatment methods have been developed to increase the fatigue strength and prolong the fatigue live of welded structures. These methods are divided into two categories based on their effects. In the first category, the tensile residual stresses are eliminated or even replaced by compressive residual stresses such as HFMI-treatment. On the other hand, the main beneficial effect of the methods in the second category is reducing the shardpness of the weld toe to reduce the local stresses, TIG-remelting is an example on these methods.

2.1 High-Frequency mechanical Impact

As mentioned earlier, HFMI-treatment mainly aims at introducing compressive residual stress at the weld toe by inducing permanent plastic deformations. Single or multiple indentors are used to generate these deformations. In addition to the induced residual stress, HFMI-treatment causes a remarkable increase in the local hardness and thereby, tensile strength increases locally. It also reduces the sharpness of the weld toe and removes the existing weld defects. The International Institute of Welding (IIW) has dedicated a whole document on recommendations for the HFMI-treatment. Herein, the maximum possible improvement number of fatigue classes (FAT) reaches 8. Moreover, milder fatigue strength curves are proposed with a slope of 5 instead of 3 which was proposed for as-welded details [12].

Four main factors influencing the fatigue class improvement due to HFMI-treatment: plate thickness, steel strength, stress ratio and maximum applied stress are considered in the recommendations [12]. However, HFMI-treatment efficiency depends also on other factors such as indentor's radius, treatment speed, number of indentors as they affect the resulted geometry, and indentation depth. Both might affect the induced compressive residual stress. Moreover, the angle of incidence of the indentor with respect to the weld toe is an important parameter as it reduces the risk of folds observed after HFMI-treatment. However, it is found to have a little effect on residual stress distribution [13–16].

HFMI-treatment can be used for either enhancing the fatigue life of new built structures (virgin structures) [17–23] or for repairing in-service structures (prefatigued structures) subjected to fatigue loading. Günter et al.[24] found that treating transverse attachments by ultrasonic impact indentor after pre-fatigue loading of 75-90% of the estimated as-welded fatigue life (obtained from the characteristic S-N curve) caused a life prolongation by a factor of 2.5. Kudryavtsev et al.[25] concluded that fatigue strength of treated prefatigued samples was larger than the those for the treated virgin ones. However, Zhang et al.[26] found that the efficiency of peening decreases as the prefatigue number of cycles increases.

The existing crack size before HFMI-treatment application has a significant effect on fatigue life. Leitner et al.[27] studied the effect of HFMI-treatment on cracked longitudinal attachment and recommended not to apply this treatment when the crack is deeper than 0.5 mm. On the other hand, Branco et al.[28] & Fisher et al. [11, 29] concluded that HFMI can treat cracks up to 2.5 & 3 mm deep respectively. Maddox et al.[30] found that fatigue crack initiated from the weld root after HFMI-treatment because of the significant strength enhancement at the weld toe. Houjou, Fukeri and Takahashi [31–33] created artificial cracks to represent the prefatigue loading stage and they concluded that HFMI-treatment efficiency decreases as the crack size increases.

The collected test results of HFMI-treated different details are shown in Figure 1. The collected data includes test conducted on treated HFMI specimens with and without previous fatigue loading donated with red and black colours respectively. No distinction was made between the data based on their crack size in the figure. In most of the cases, the red circles which corresponded to prefatigued treated details are lying to the top of the design curves which facilitate the capability of HFMI-treatment to extend the fatigue life of prefatigued structures. Besides, in some cases, prefatigued specimens endure longer than new treated specimens as in [25].

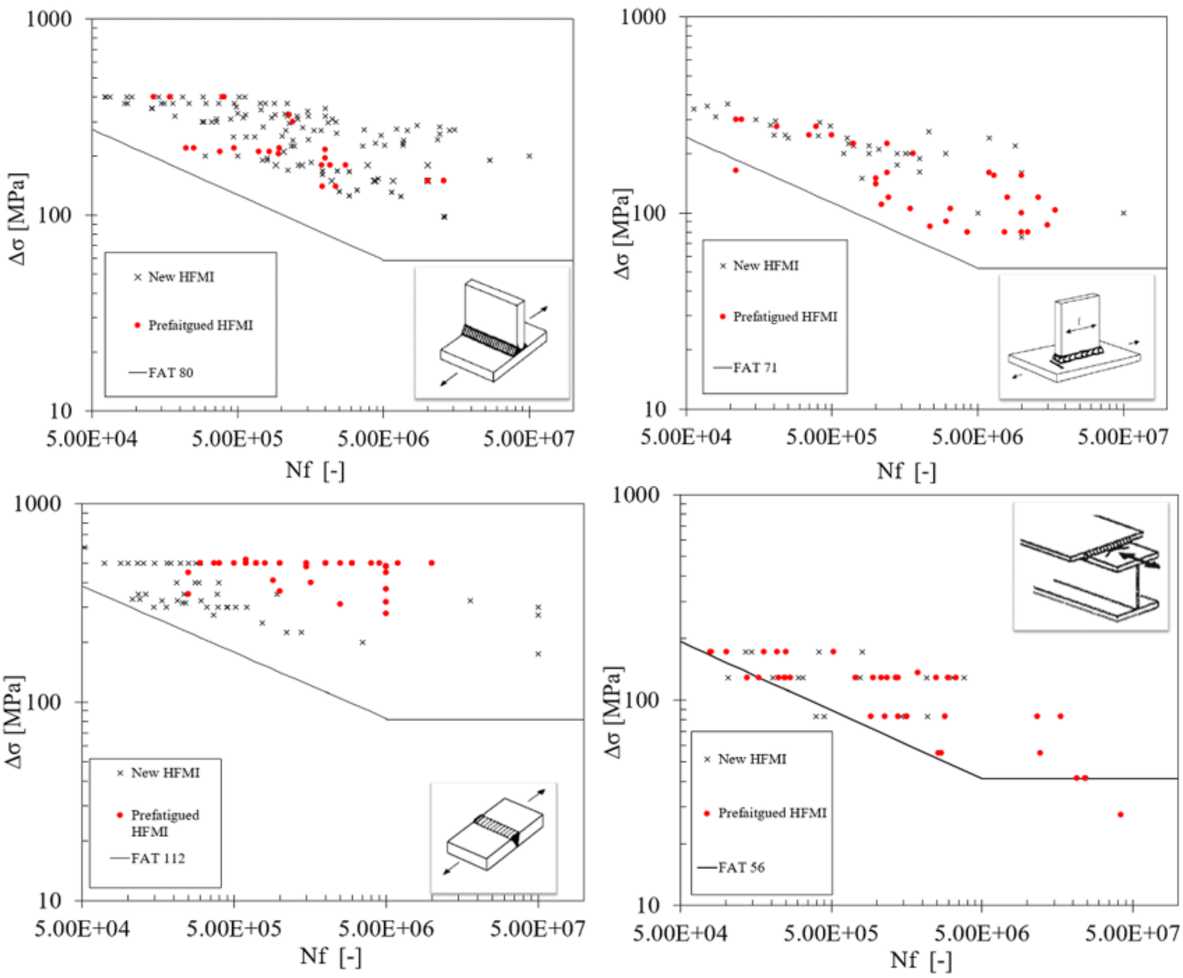

Figure 1: Fatigue test results of new & prefatigued HFMI-treated details

When applied to cracked structures, HFMI-treatment rarely causes crack removal. Nonetheless, Zhang et al. found that HFMI-treatment caused a change in crack orientation with an angle α which is dependant on the crack size. By comparing the fracture surfaces of HFMI-treated specimens with and without prefaitgue loading, parallel plastic deformations because of compressing the existing cracks were found in the former case. On the contrary, these kinds of deformation did not exist when the structure was not prefatigued, and only stamp-like impressions were found at the weld toe [26].

2.2 Tungsten Inert Gas remelting

As stated earlier, TIG-remelting aims at removing the flaws existing at the weld toe and increasing its radius through remelting the material at the toe's vicinity. Unlike HFMI and grinding, TIG-remelting is a thermal treatment method which induces heat to fuse the steel and the original weld. Similarly to HFMI-treatment, this method have been used extensively to enhance the fatigue strength of new built structures [10, 34–42]. The efficiency of TIG-remelting, in this case, is mainly dependant on the resulted toe geometry and the change in local hardness. Unlike radius which always increases after TIG-remelting, the local hardness might increase or decrease depending on the microstructure of the heat-affected zone and the heat input of the treatment.

There are a few pieces of research on the use of TIG-remelting to repair existing structures. Nascimento et al. [43] investigated the effect of several TIG repair on thin-walled butt welded plates, and found that the efficiency of treatment decreases as the number of successive repair increases. The efficiency of TIG-remelting was found to be dependant on both the fusion and the crack depth [44]. Root failure was obtained in most of the tested specimens in [11], which demonstrated the high strength of the TIG-remleted toe. However, this was only guaranteed when the crack was completely removed, which is the case when the fusion depth is greater that the crack depth. The collected test results for both new built and cracked specimens are shown in Figure 2. Remarkably, the vast majority of the specimens are lying above the characteristic S-N curves of the as-welded details.

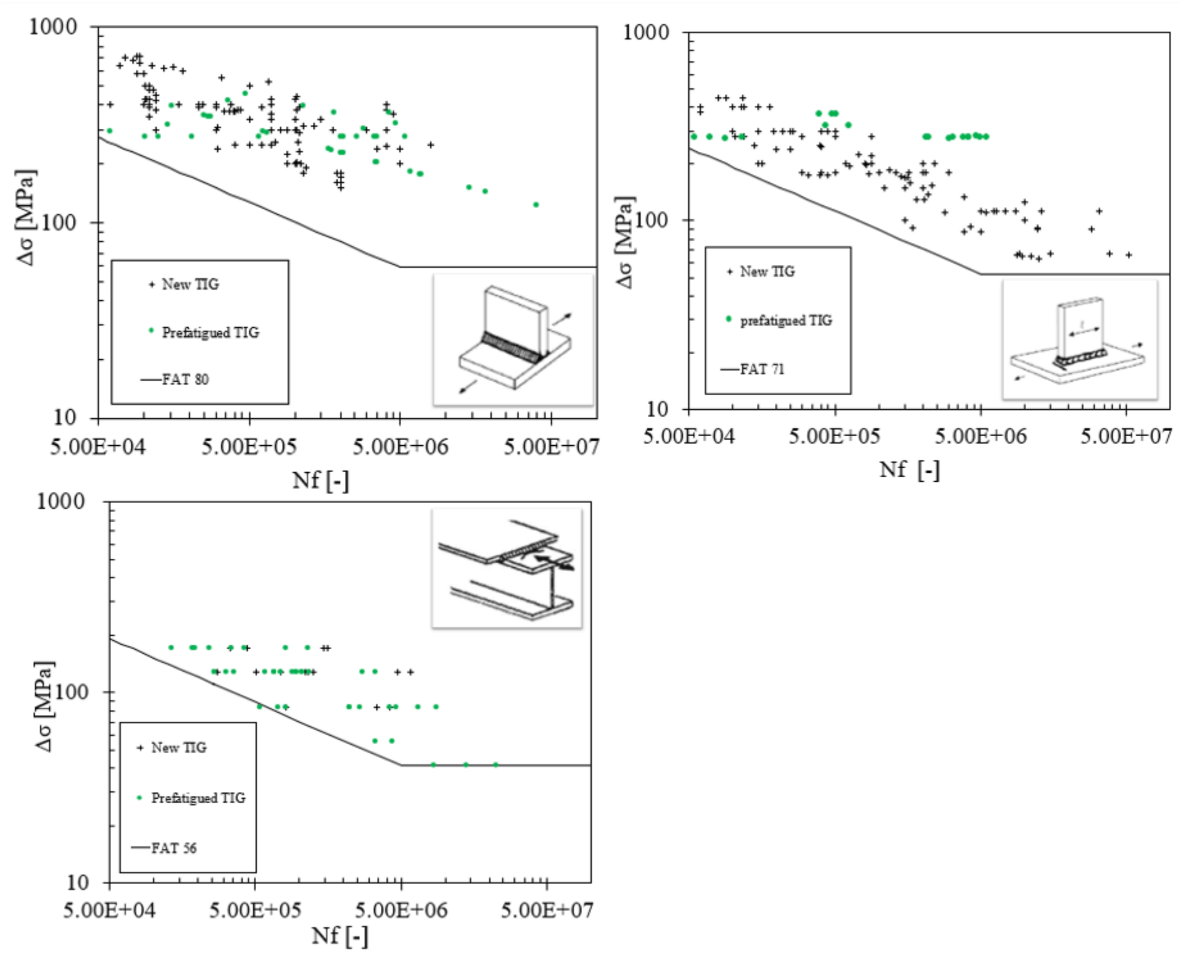

Figure 2: Fatigue test results of new & prefatigued TIG-remelted details

Combining HFMI-treatment after fusing the steel by TIG-remelting was rarely studied in the literature for enhancing fatigue strength of new transverse and longitudinal attachment [19, 20, 45]. In all of them, the results were better than individual treatment as it improves on both residual stress and geometry improvement. Nonetheless, it has never been applied -to the best of the author's knowledge- on existing structures.

3 Experimental investigation on fatigue life extension

3.1 Fatigue testing

Fatigue testing program consisting of seven series was produced on 16 mm non-load carrying transverse attachment, see Table 1. The specimens in series B were used to find a correlation between the crack size and the stiffness drop measured by attached strain gauges at the weld toe. It was found that 25% drop in the local strain measured by any gauge is equivalent to 0.6-1.2 mm crack. Afterwards, the specimens in series E, F and G were tested until 25% drop in the strain. These specimens were called 'prefatigued specimens' and the number of cycles required to reach this percentage in each series is given in Table 2.

The weld toes of the specimens in series D and E were treated by HiFIT indentor.

Table 1: The specimens series

Series	Number	Function	Specimens	Stop criteria
A	12	Investigating the strength of the as-welded specimens	1-10, 12-13	Failure/Run-out
B	3	Crack detection and calibration	14-16	50-80% drop in strain
C	2	Investigating the HFMI effects on existing cracks	17-18	50-80% drop in strain
D	8	Investigating the strength of virgin HFMI-treated specimens	21-28	Failure/Run-out
E	7	Studying the life extension by HFMI-remelting	29-35	Before treatment: 25% drop in strain After treatment: Failure/Run-out
F	7	Studying the life extension by TIG-remelting	36-42	Before treatment: 25% drop in strain After treatment: Failure/Run-out
G	5	Studying the life extension by TIG-HFMI-treatment	43-47	Before treatment: 25% drop in strain After treatment: Failure/Run-out

Single indentor tool with a 3 mm diameter was used, the inclination angle of indentor's axis with respect to the base plate surface was fixed to be 60-70°. Besides, the toes of the specimens in series F and G were treated by tungsten electrode. The electrode was fit at the weld toe to secure that the maximum fusion depth corresponds to the crack plane. Subsequently, 5 mm diameter HiFIT indentor was used to treat the specimens in series G. Larger diameter was used in order not to lose the benefit of radius improvement achieved by the preceding TIG-remelting.

Fatigue test results of all as-welded and treated specimens are given in Table 2 & Figure 3. The characteristic design curves of as-welded, HFMI-treated and TIG-remelted transverse attachment were donated by solid lines in the figure. The as-welded specimens showed relatively high fatigue strength, while most of the treated specimens ran-out after 10 millions cycles when tested under stress range of 150 MPa. Remarkably, all as-welded and HFMI-treated specimens failed at the weld toe, while all TIG-remelted and TIG-HFMI-treated specimens failed at the base metal from the clamping position. The obtained characteristic fatigue strengths (FAT) for as-welded, virgin HFMI-treated and prefatigued HFMI-treated specimens were found to be 125, 180 and 165 MPa respectively. No FAT value could be assigned for both TIG-remelted or TIG-HFMI-treated specimens as their weld toes did not fail.

3.2 Gain factor in fatigue life

Figure 1 & 2 showed clearly that the two studied treatment methods can be applied to existing structures as for virgin structures. However, using the S-N curves to evaluate the efficiency of these methods does not take into account different important factors such

Table 2: Fatigue tests results

Test	Specimen	$\Delta\sigma$ MPa	N Cycles	Test abort criterion	Test	Specimen	$\Delta\sigma$ MPa	N Cycles	Test abort criterion
As-welded (series A)									
A1a	1	119	1.00E7	Run-out	A4	4	145	1.08E6	Toe failure
A1b	1	143	2.15E6	Run-out	A5	5	175	7.57E5	Toe failure
A2a	2	114	7.85E6	Run-out	A6	6	170	6.85E5	Toe failure
A2b	2	125	1.04E7	Run-out	A7	7	165	8.59E6	Toe failure
A2c	2	140	8.00E6	Run-out	A8	8	160	9.87E6	Toe failure
A2d	2	132	2.75E6	Run-out	A9	9	150	1.13E6	Toe failure
A2e	2	145	8.84E5	Toe failure	A10	10	150	1.60E6	Toe failure
A3a	3	132	2.53E6	Run-out	A12	12	150	3.25E6	Toe failure
A3b	3	139	3.10E6	Toe failure	A13	13	150	2.42E6	Toe failure
Virgin HFMI-treated (Series D)									
D21a	21	180	1.00E7	Toe failure	D26	26	150	4.41E6	Toe failure
D21b	21	180	9.12E5	Run-out	D27a	27	150	1.00E7	Run-out
D22	22	150	4.32E6	Toe failure	D27b	27	180	1.38E6	Toe failure
D23	23	150	5.82E6	Toe failure	D28a	28	150	1.00E7	Run-out
D24	24	150	2.19E6	Toe failure	D28b	28	180	1.00E7	Run-out
D25a	25	150	1.00E7	Run-out	D28c	28	210	1.03E6	Toe failure
D25b	25	180	3.88E6	Toe failure					
Prefatiging stage (Series E)									
E29P	29	150	5.64E6	25% Strain drop	E33P	33	150	1.91E6	25% Strain drop
E30P	30	150	8.93E5	25% Strain drop	E34P	34	150	7.67E6	25% Strain drop
E31P	31	150	1.49E6	25% Strain drop	E35P	35	150	8.35E5	25% Strain drop
E32P	32	150	1.40E6						
Prefatigued HFMI-treated (Series E)									
E29a	29	150	1.00E7	Run-out	E32c	32	180	2.14E6	Toe failure
E29b	29	180	1.89E6	Toe failure	E33a	33	150	1.00E7	Run-out
E30a	30	150	1.00E7	Run-out	E33a	33	210	8.25E5	Toe failure
E30b	30	180	2.76E6	Toe failure	E34a	34	150	1.00E7	Run-out
E31	31	150	1.00E7	Run-out	E34b	34	150	2.95E6	Toe failure
E32a	32	150	1.00E7	Run-out	E35a	35	150	1.00E7	Run-out
E32b	32	150	1.00E7	Run-out	E35b	35	210	3.78E5	Toe failure
Prefatiging stage (Series F)									
F36P	36	150	1.92E6	25% Strain drop	F40P	40	150	5.68E5	25% Strain drop
F37P	37	150	8.15E5	25% Strain drop	F41P	41	150	6.42E5	25% Strain drop
F38P	38	150	7.66E6	25% Strain drop	F42P	42	150	2.22E6	25% Strain drop
F39P	39	150	1.27E6	25% Strain drop					
Prefatigued TIG-remelted (Series F)									
F36a	36	150	1.00E7	Run-out	F38c	38	220	7.41E5	Clamp failure
F36b	36	180	1.00E7	Run-out	F39a	39	150	1.00E7	Run-out
F36c	36	110	1.00E7	Run-out	F39b	39	220	2.49E5	Clamp failure
F36d	36	250	2.43E6	Clamp failure	F40a	40	150	1.00E7	Run-out
F37a	37	150	1.08E7	Run-out	F40b	40	250	7.29E5	Clamp failure
F37b	37	180	1.00E7	Run-out	F41a	41	150	1.00E7	Run-out
F37c	37	220	1.80E6	Clamp failure	F41b	41	250	3.34E5	Clamp failure
F38a	38	150	2.00E7	Run-out	F42a	42	150	1.00E7	Run-out
F38b	38	180	1.03E6	Run-out	F42b	42	250	1.41E6	Clamp failure
Prefatiging stage (Series G)									
G43P	43	150	5.64E5	25% Strain drop	G46P	46	150	7.18E5	25% Strain drop
G44P	44	150	8.94E5	25% Strain drop	G47P	47	150	1.35E6	25% Strain drop
G45P	45	150	1.49E6	25% Strain drop					
Prefatigued TIG-remelted (Series G)									
G48a	48	220	1.00E7	Run-out	G51a	51	150	1.00E7	Run-out
G48b	48	250	2.45E5	Clamp failure	G51b	51	200	1.42E6	Clamp failure
G49a	49	180	1.49E5	Run-out	G52a	52	180	5.65E5	Run-out
G50a	50	150	1.00E7	Clamp failure	G52b	52	220	2.41E5	Clamp failure
G50b	50	220	1.52E6	Run-out					

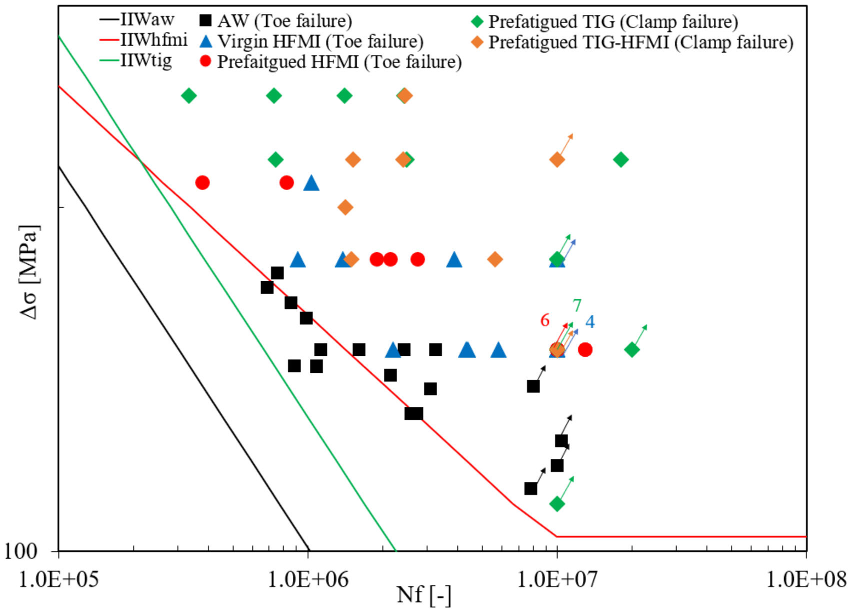

Figure 3: Fatigue test results of as-welded and treated specimens

Table 3: Fatigue life extension data groups

HFMI	Crack detection before HFMI-treatment	Prefatigued number of cycles is described	Group 1.1
		Prefatigued number of cycles is not described	Group 1.2
	No crack detection before HFMI-treatment	As-welded fatigue life is described	Group 2.1
		As-welded fatigue life is not described	Group 2.2
TIG	Crack detection before TIG-remelting	Remaining crack inspection after TIG-remelting	Group 3.1
		No remaining crack inspection after TIG-remelting	Group 3.2
		No crack inspection after TIG-remelting	Group 3.3
	No crack inspection before TIG-remelting		Group 4.1

as plate thickness, R-ratio, steel strength and loading history (i.e. prefatigue number of cycles or crack size). Therefore, another evaluation method was introduced to incorporate these factors.

Fatigue test results given in Table 2 together with more than 250 test results obtained from several articles presented in section 2 were used to evaluate the efficiency of both treatment methods in fatigue life extension of existing structures. The collected HFMI test data were classified into two main groups depending on the availability of crack size before the treatment. The first group which comprises tests with available crack size were classified into two main subgroups depending on the availability of prefatigue number of cycles. The crack size was not available in the second group which was classified into two main subgroups depending on the availability of as-welded fatigue life.

Similarly, the collected TIG test data was also classified into two main groups depending on the availability of crack size before treatment. Since TIG-remelting aims at removing the crack fully or partially, the first group was categorised into three main subgroups depending on the crack removal. In the first one, cracks were inspected after remelting and the crack size was determined. No cracks were found after remelting in the second subgroup. Besides, no crack detection was conducted after remelting for the third subgroup. Furthermore, no crack detection was conducted after or even before TIG-remelting in the second group. These categorizations are illustrated in Table 3.

Two gain factors with reference to fatigue life were introduced. The first one G_1 denotes the ratio between the life of the repaired specimens N_{Ext} to the prefatigue number of cycles before treatment N_{Pre} normalised to the ratio between the characteristic lives of the treated detail $N_{IIW,Ext}$ to the as-welded detail $N_{IIW,AW}$, see Equation 1. In order to incorporate the test results at which the prefatigued number of cycles were not reported, another gain factor was defined by replacing the prefatigue number of cycles N_{Pre} with the characteristic life of the as-welded detail $N_{IIW,AW}$ as donated in Equation 2. The characteristic lives were obtained from the S-N curves of different details according to the IIW recommendations [6, 9].

$$G_1 = \frac{N_{Ext}/N_{pre}}{N_{IIW,Ext}/N_{IIW,AW}} \tag{1}$$

$$G_2 = \frac{N_{Ext}/N_{IIW,AW}}{N_{IIW,Ext}/N_{IIW,AW}} \tag{2}$$

Test data for which the size of cracks before HFMI-treatment was reported (Group 1.1 & 1.2) can be used to study the dependency of HFMI efficiency on crack size. Gain factors G_1 & G_2 were plotted against the crack size in Figure 4 & 5 respectively. Treatment was successful so that virgin HFMI-treated strength detail could be reached when the existing crack is shallower than 2.25 mm. The obtained scatter in gain factor is not solely attributed to crack detection precision. This is evident as the data at which cracks were created artificially are also widely scattered despite being precisely determined.

The dependency of the defined gain factors in equation 1 & 2 on the remaining cracks

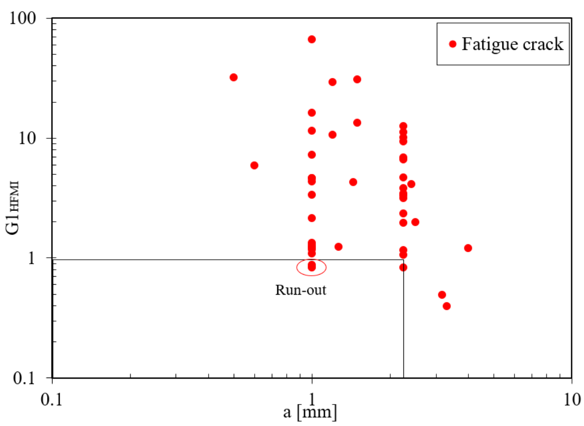

Figure 4: Gain factor *G1* against depth of fatigue crack repaired by HFMI-treatment for Group 1.2

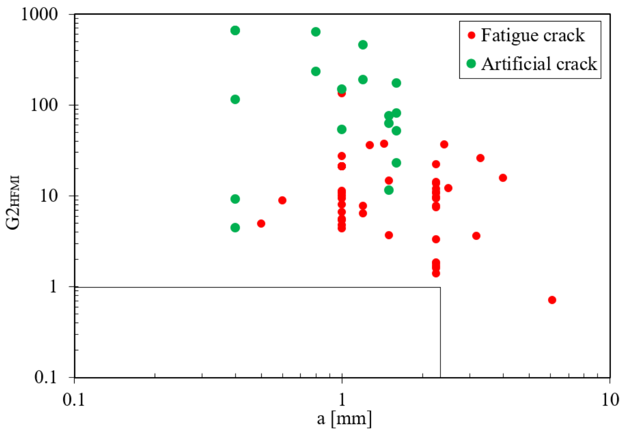

Figure 5: Gain factor *G2* against depth of crack repaired by HFMI-treatment for Groups 1.1 & 1.2

after TIG-remelting were plotted in Figure 6 & 7. The figures show that the gain factors were significantly larger than 1.0 when the crack was completely removed. This causes crack initiation outside the weld toe; indicating the high fatigue strength of the weld toe region. Furthermore, fair fatigue life extension can also be achieved even with the presence of 2.25 mm crack.

The allowable prefatigue number of cycles before each treatment methods were studied by plotting both gain factors against the prefatigue period normalised to the characteristic as-welded fatigue life, see Figure 8. More than 99% of the collected data lie outside the risk region which indicates that TIG-remetling or HFMI-treatment can restore at least the characteristic fatigue life of the treated detail. It is mention-worthy that the collection included test data with root failure which demonstrates that there is no need to account for root failure when taking a decision about fatigue life extension using these methods. Moreover, the evaluation did not consider the partial factors in fatigue strength which increase the safety margin.

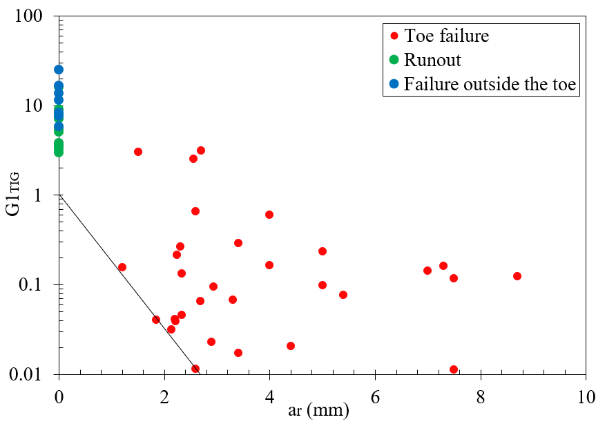

Figure 6: Gain factor *G1* against the prefatigued life before TIG-treatment normalised to the characteristic as-welded life for Groups 3.1 & 3.2

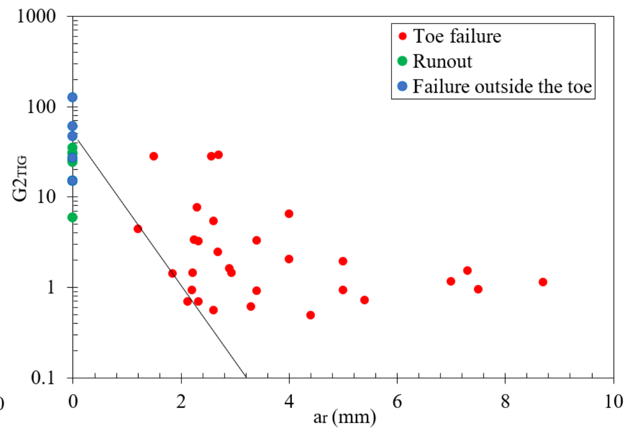

Figure 7: Gain factor *G2* against the prefatigued life before TIG-treatment normalised to the mean as-welded life for Groups 3.1 & 3.2

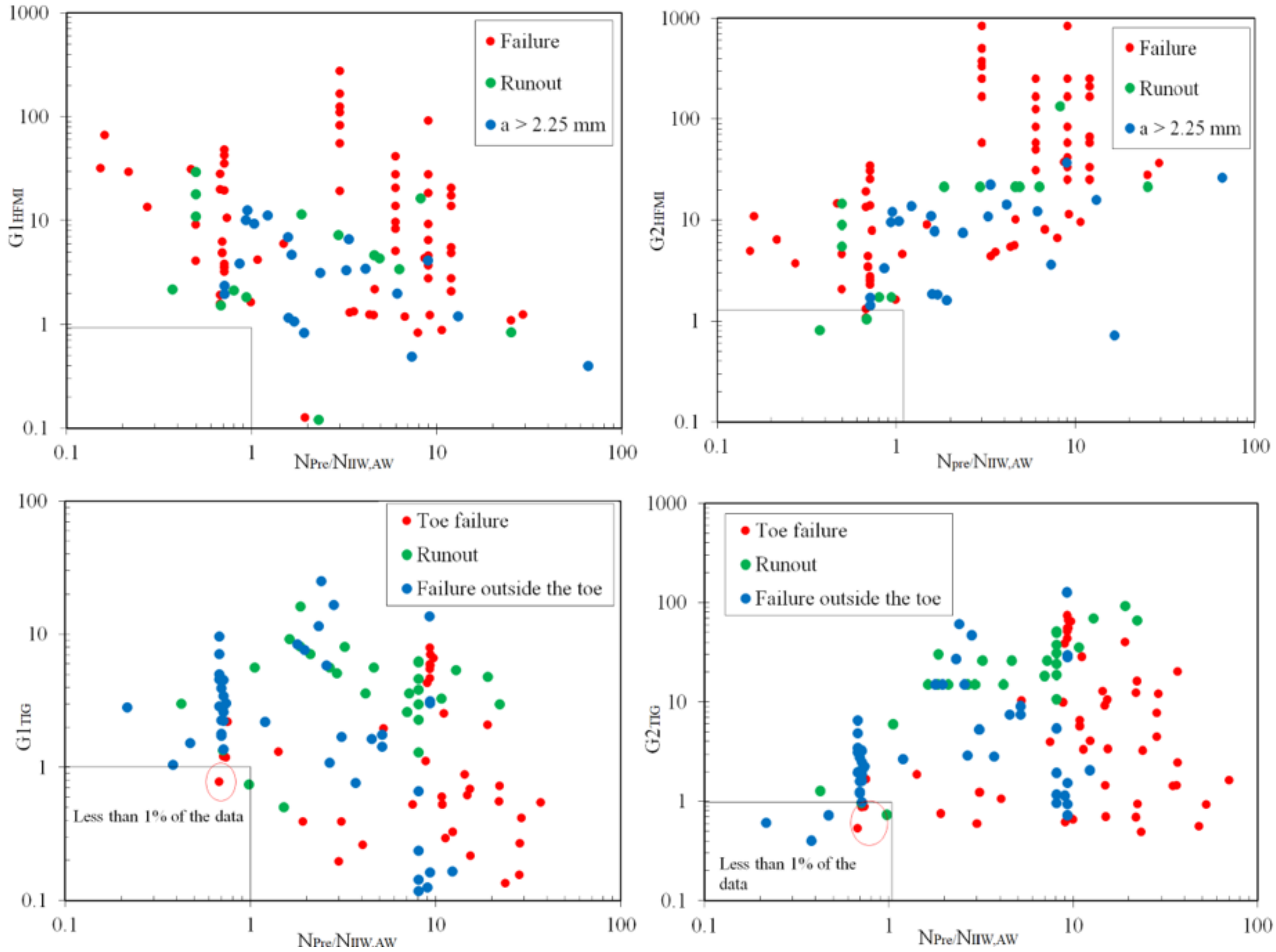

Figure 8: Gain factors against the prefatigued life before HFMI-treatment & TIG-remelting normalised to the characteristic as-welded life from IIW recommendations

It is recommended to preced the treatment by non-destructive testing 'NDT' in order to estimate the crack size. The used NDT should have the capability of detecting crack of 2 mm deep with high probability of detection. However, the crack size could be larger than the estimated value. Accordingly, HFMI-treatment is suggested to be used solely when the NDT is negative (i.e. reveals no crack). Moreover, TIG-remelting is proposed when NDT is positive before remelting and negative after remelting. Meaning that full crack removal should be guaranteed by either crack detection or conducting a metallurgical analysis on similar detail type treated under similar TIG-arc parameters. Moreover, it is suggested to follow TIG-remelting by HFMI-treatment as the characteristic life of HFMI-treatment is often longer than TIG-remelting especially in high cycle fatigue regime. The shown flowchart in Figure 9 is proposed when taking a decision regarding weld treatment.

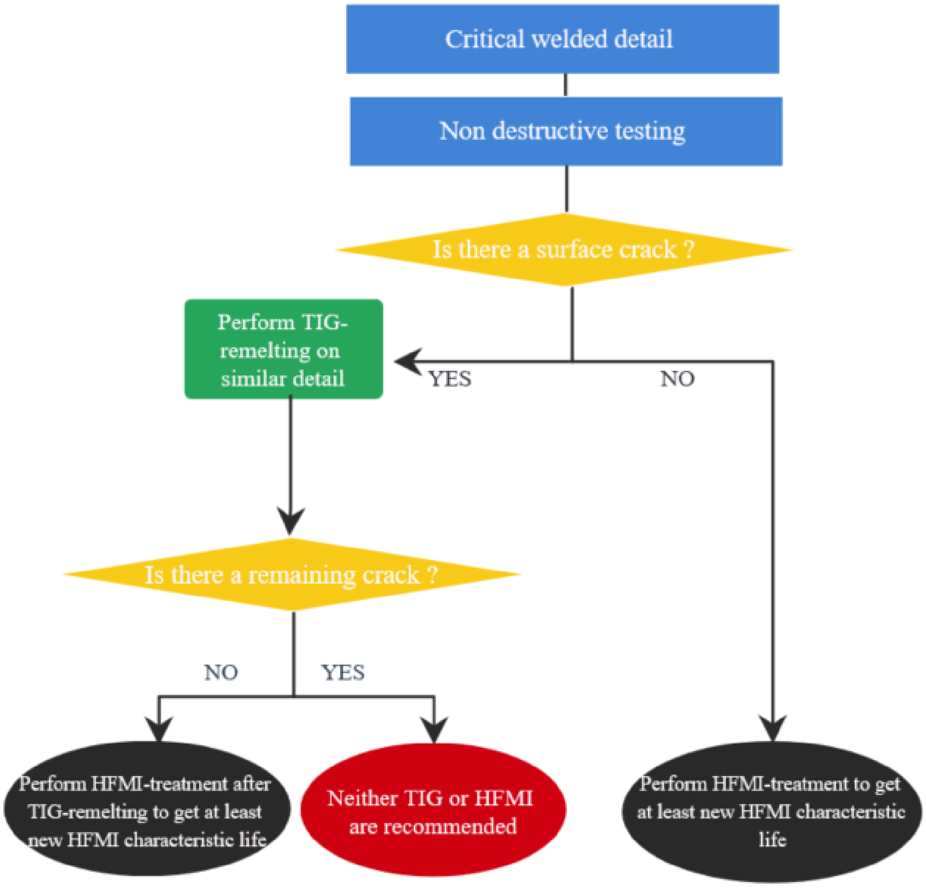

Figure 9: Fatigue life extension flowchart

4 Supportive investigations on fatigue life extension

Weld imperfections such as undercuts, and sharpness such as weld convexity increase the local stresses. Thermal expansion and contraction during welding induce residual stresses. The relatively high heat causes softening or hardening in the weld and in the heat-affected zone. Moreover, cracking consumes a portion of fatigue life. Deep understanding of the mechanisms of weld improvement is a prerequisite to assess these treatment methods and incorporate these mechanisms in fatigue life prediction of the repaired structures. These mechanisms work on counteracting the aforementioned welding's and loading's detrimental effects.

4.1 Local topography investigations

Because of the importance of local geometry in evaluating the efficiency of the studied treatment methods, they were scanned by a 3D laser scanner before and after treatments

Table 4: The geometrical parameters of the tested specimens before and after treatments

Status	AW		HFMI		TIG		TIG-HFMI	
Geometrical parameter	Toe radius	Undercut heigh	Toe radius	Groove depth	Toe radius	Undercut heigh	Toe radius	Groove depth
Mean [mm]	0.67	0.004	1.2	0.26	5.09	0.150	5.39	0.14
Standard deviation [mm]	0.31	0.03	0.29	0.13	0.73	0.10	2.44	0.06
Variation coefficient [-]	0.46	8.74	0.24	0.51	0.14	0.67	0.45	0.41
Population size [-]	20660	20660	1331	1653	150	1581	334	351

(i.e. HFMI-treatment, TIG-remelting, combined TIG-HFMI-treatment). Three geometrical parameters were studied: weld toe radius, undercut height and HFMI groove depth, see Figure 10, 11 & Table 4. Significant reduction in the variation coefficient of toe radius was observed after all studied methods which demonstrates the treatment uniformity.

The average groove depth of HFMI-treated specimen was 0.26 mm which is in accordance with the recommended range [12]. TIG-remelting caused a more significant increase in the toe radius with a factor of seven. However, fitting the electrode at the weld toe to secure that the position of maximum fusion corresponded to crack plane caused a larger undercut at the resulted toe position. Moreover, larger HFMI-indentor was used for combined TIG-HFMI-treatment (i.e. 5 mm diameter instead of 3 mm) in order not to lose the increase in toe radius achieved by the preceding treatment (i.e. TIG-remelting). Enlarged views of are shown in Figure 12.

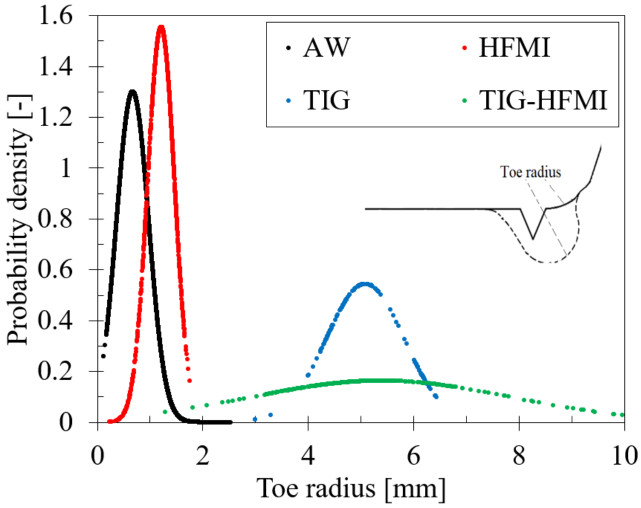

Figure 10: Normal distribution of weld toe radius before and after treatments

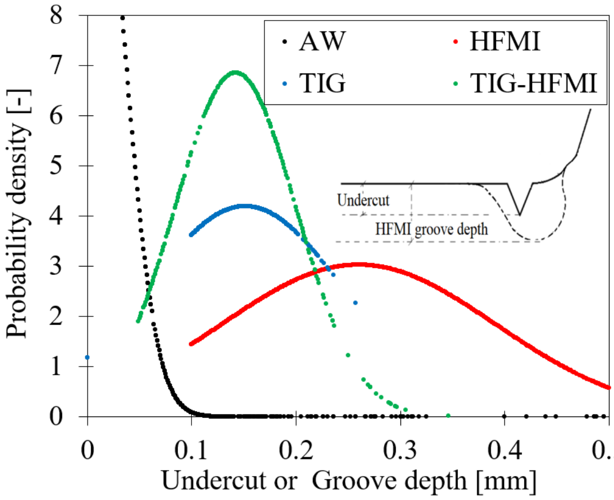

Figure 11: Normal distribution of undercut height (for AW & TIG) and groove depth (for HFMI & TIG-HFMI)

The effect of the increased weld toe radius on the stress concentration factor was studied numerically using the commercial software ABAQUS CAE 2017. The effective notch stress can be calculated using a reference toe radius of 1 mm in as-welded condition and the average real toe radius of + 1 mm after treatment [46]. Different fatigue strength values would be assigned for each treatment method if the concentration factors are to be used for fatigue strength assessment using effective notch method [47]. However, this is out of the scope of the work in hand.

Several two dimensional finite element models with different toe radii were created. Symmetric boundary conditions were considered at the middle of attachment to reduce the execution time. Four-node shell elements (i.e. CPS4R in Abaqus notations) were used to create the mesh and a global mesh size of 3 mm was selected. The mesh was refined

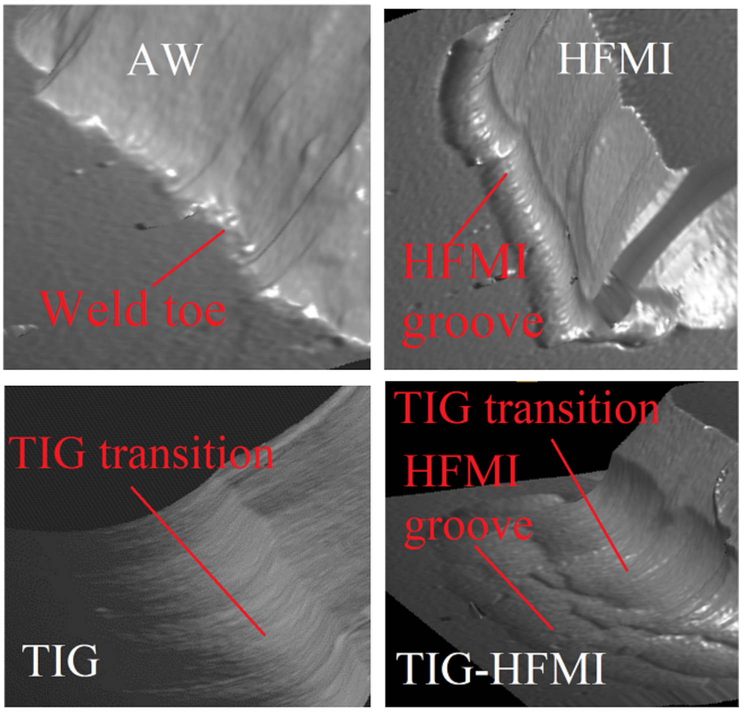

Figure 12: Weld toe profile of as-welded and treated specimens by different methods

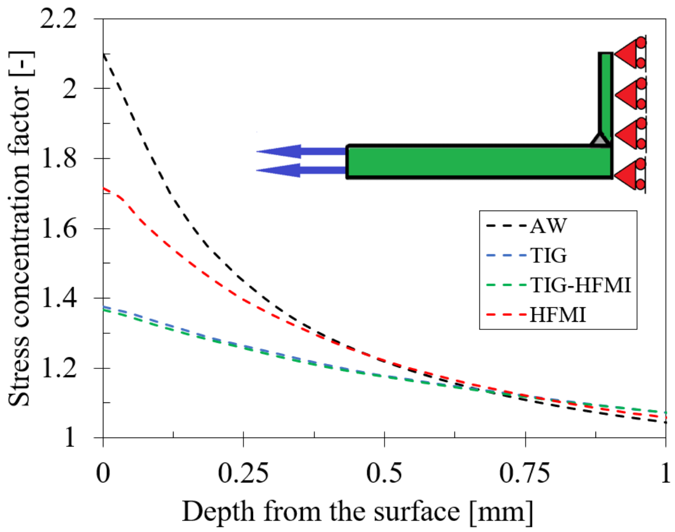

Figure 13: The elastic stress concentration factors

around the toe and 0.1 mm local element size was adapted. A reference tensile traction of 1 MPa was applied. The obtained stress concentration factor distributions in the top 1 mm of the plate thickness are shown in Figure 13.

4.2 Residual stress & distortion investigations

During welding, the welded components undergo temperature changes. The plastic straining which takes place in the welded components due to thermal contraction leads to internal stresses (residual stresses). In order to counterbalance these internal stresses, the components tend to show some displacements (e.g bending, rotation, twisting). Prior to axial fatigue testing, the specimens get fully straightened during clamping which gives rise to additional stresses called clamping stress. Residual and clamping stresses are both

Table 5: Residual stress measurement results

Status		Maximum σ_{RS} [MPa]	Depth of maximum σ_{RS} [mm]
Average	AW	-185	0.10
	HFMI	-375	0.24
	TIG	-257	0.10
	TIG-HFMI	-613	0.18
Maximum	AW	-265	0.10
	HFMI	-430	0.28
	TIG	-290	0.07
	TIG-HFMI	-738	0.18
Minimum	AW	-104	0.10
	HFMI	-330	0.18
	TIG	-209	0.07
	TIG-HFMI	-413	0.13

mean stresses which can have either beneficial or detrimental effect on fatigue life of the component depending on their sign and magnitude.

The residual stresses existing in several specimens were investigated by means of hole drilling technique. The attachment was first cut parallel to loading direction in order to provide better accessibility for the hole drilling tester. Two reference points were measured before and after cutting to check if cutting would affect the status of local residual stress at the weld toe. The two measurements were fairly similar. The holes were drilled at the weld toes of both the as-welded & TIG-treated specimens and at the edge of the HFMI groove of both HFMI-treated & TIG-HFMI-treated specimens.

The average values were plotted in Figure 14. Remarkably, compressive residual stress was found at the weld toes even in as-welded state and after TIG-remelting. Nonetheless, the magnitudes of the maximum obtained compression were significantly lager after HFMI-treatment. Moreover, the maximum obtained compression after HFMI-treatment & TIG-HFMI-treatment were found at a depth of 0.15-0.30 mm which is the depth of the HFMI groove, see Table 5 which summarises the findings.

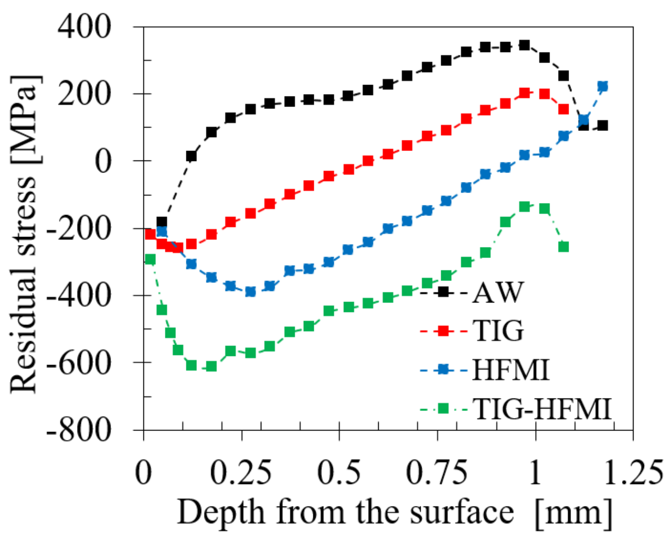

Figure 14: Average residual stress for as-welded and treated details

The angular distortions of several as-welded and treated specimens were measured at several points on two parallel lines along the specimens. Totally, 22 points were considered per specimens, and the distance between two adjacent points was 50 mm. The average values were plotted in Figure 15. Due to the high heat input associated with TIG-remelting to achieve deep fusion, relatively large distortions took place in the longitudinal direction. On the contrary, HFMI-treatment reduced the distortions level which might be explained by the additional constraint on the specimens before the treatment application. Moreover, all treated specimens exhibited a transversal twist which caused the two curves (A & B in Figure 15) to diverge from each other.

The clamping stresses were measured in some specimens via strain gauges attached

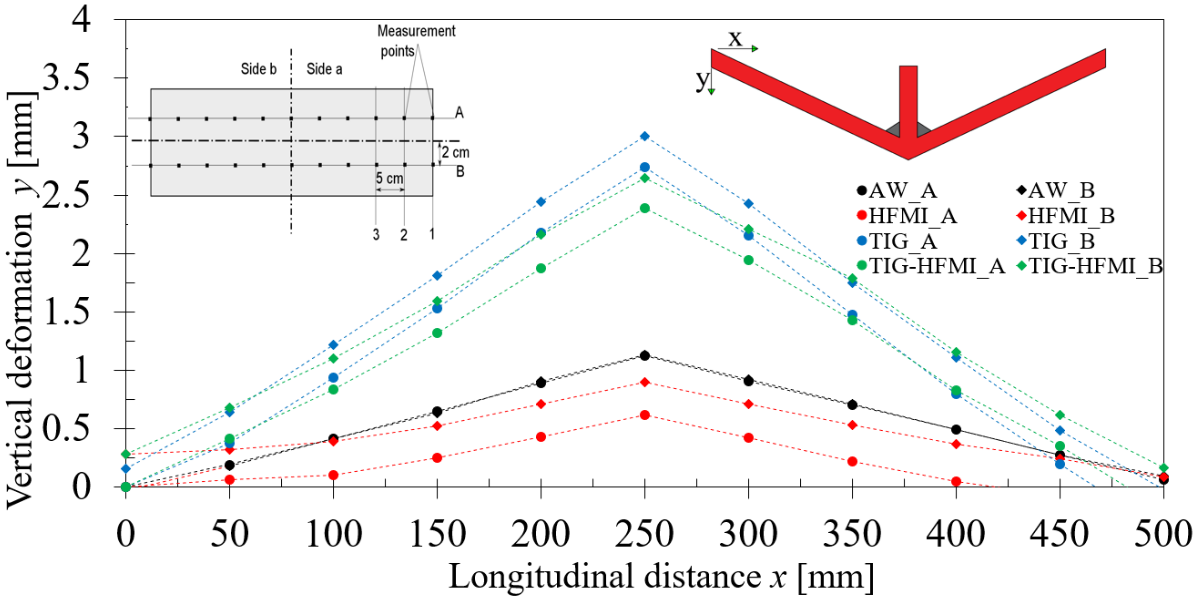

Figure 15: Measured residual stress distributions for different specimens in different states

40 mm of the welds. Therefore, the local notch stresses could not be acquired directly from the measurements. Therefore, 2D linear elastic finite element analysis was conducted to simulate the deformed specimens and the clamping process. The same external boundary conditions and mesh sizes considered in section 4.1 were used. Hard contact was assumed between the clamping jaws (i.e. the master surfaces) and the specimen's surfaces (i.e. the slave surfaces). The clamping jaws were modelled as undeformable solid objects restricted from displacement in the transversal direction ($U_x = 0$).

The vertical displacement of the top jaw U_y was prescribed to approach the specimen, while the bottom one was fixed from translation ($U_x = U_y = 0$). The results were acquired when the specimens got fully straightened. The stresses obtained from the analysis at the position of the presumable strain gauge were close to those obtained experimentally, which enabled obtaining the notch stresses from the analysis. See Figure 16 which correlates the measured angular distortions to the clamping stresses. Table 6 summarises the findings on distortion measurements & clamping stresses.

4.3 Local hardness measurement

Vickers's microhardness tester was used to obtain the hardness contour in the weld toe vicinity. Test load of 3 Kg was used, and rectangular grids were considered with a spacing of 0.5 mm both horizontally and vertically. The hardness values were extracted below the weld toes and presented in Figure 17. The hardness increased significantly at the weld toe due to HFMI indentation. Moreover, TIG-remelting caused a further hardness increase in the heat-affected zone when succeeded by HFMI-treatment with larger indentor. TIG-remelting alone did not cause the same increase in the weld toe's hardness. However, in comparison to HFMI-treatment, TIG-remelting affected deeper area.

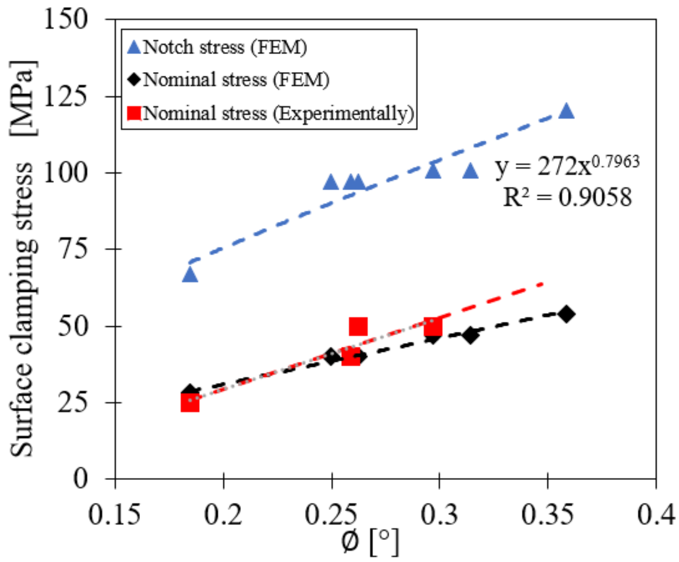

Figure 16: The correlation between the angular distortion and nominal, local clamping stresses

Table 6: Angular distortion & clamping stress results

Status		Angle [°]	Uplift [mm]	Notch stress [MPa]
Average	AW	0.29	1.25	100
	HFMI	0.23	0.99	83
	TIG	0.68	2.91	198
	TIG-HFMI	0.58	2.45	172
Maximum	AW	0.41	1.79	134
	HFMI	0.29	1.25	98
	TIG	0.71	3.09	207
	TIG-HFMI	0.59	2.57	178
Minimum	AW	0.17	0.72	65
	HFMI	0.14	0.59	55
	TIG	0.63	2.77	189
	TIG-HFMI	0.56	2.32	170

4.4 Microscopic investigations

Both HFMI-treatment and TIG-remelting are surface treatment methods which imply that their effects are local. These require a microscopic investigation to observe the microstructural change and crack behaviour after each treatment. Specimens surfaces were first prepared by cutting them parallel to the weld line and slicing the remains perpendicularly. The obtained surfaces of the slices were processed by polishing and Nital-etching with 2% for microscopic investigations.

In total, 14 slices from TIG-remelted specimens were prepared to check the adequacy and the regularity of the fusion depth. The investigation uncovered a minimum fusion depth of 1.36 mm which is larger than the existing crack size of 0.6-1.2 mm. The average fusion depth was 2.06 mm with a standard deviation of 0.17 mm; which indicated full crack removal after TIG-remelting. Figure 18 compares the obtained fusion depth for two different positionings of the TIG electrode. When the electrode was placed according to the recommendations [9] (i.e. case B), a smoother transition was achieved. However, placing the electrode right at the weld toe (i.e. case A) secures that the plane of maximum fusion depth coincided with the crack plane. Therefore, the specimens in series F & G were treated in a similar manner to case A.

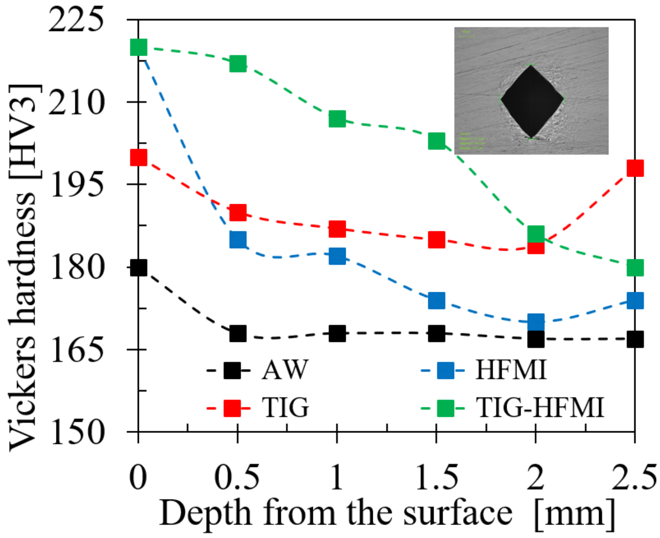

Figure 17: Vicker's hardness distribution below the weld toe

The size of the heat-affected zone was found to be similar for both welding and remelting

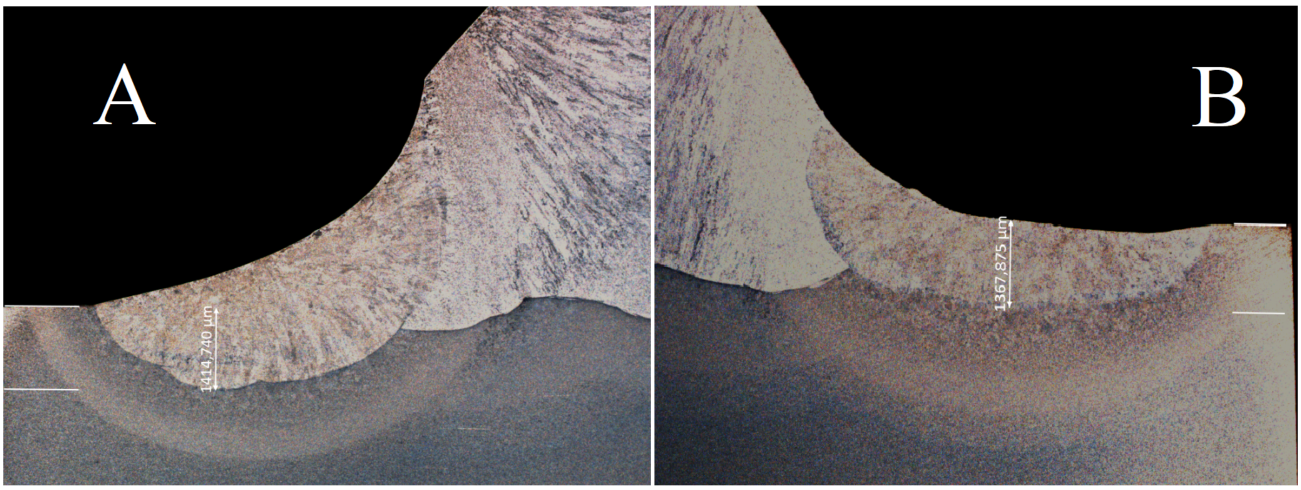

Figure 18: TIG fusion depth when the electrode was placed A: Right at the weld toe caused deeper fusion B: 2 mm off the original toe according to the IIW recommendations [9]

despite the arc size difference. This is explained by the higher heat input associated with TIG-remelting. The inspection also showed an indication on lack of fusion in the middle of the attachment. However, crack never initiated from this position as the stress concentration factor is relatively small in this area, see Figure 19. There were no significant differences between the fusion zone before and after treatment where acicular ferrite was the main constituent. The slower cooling rate after TIG-remelting caused Widmanstatten ferrite to appear instead of the allotriomorphic ferrite which existed before treatment. Furthermore, the existing bainite in the heat-affected zone was tempered after remelting because of high heat input. The interlocking nature of the acicular ferrite which replaced the bainite at the weld toe caused the increase in hardness as indicated in the previous section.

The HFMI-treated surfaces used for microscopy included 0.5-4.0 mm deep cracks. The crack width decreased significantly after HFMI-treatment (i.e. average value decreased from 0.05 mm to 0.01 mm). In some cases, the crack surfaces were so faint so they could not be distinguished from the grain boundaries indicating the crack narrowness. However, when the crack is deep, only the top part of the crack would be affected by the mechanical

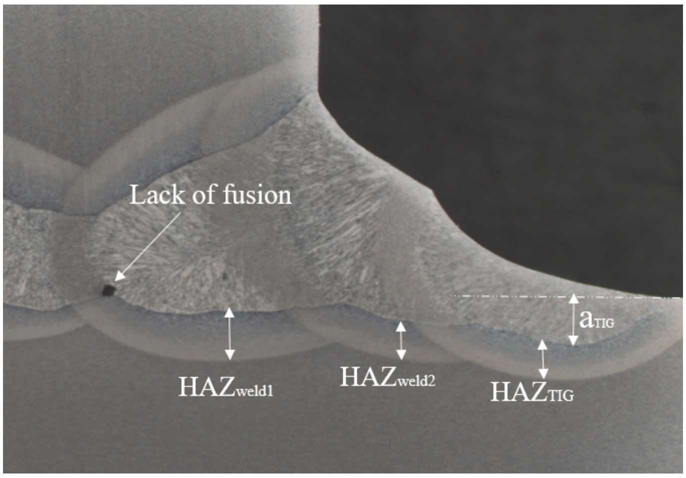

Figure 19: Microscopic investigation of the weldment after TIG remetling

impact. A change in crack orientation due to indentation was also observed in the top part of the crack. Moreover, the indentor might miss the top few micrometres of the crack. These observations are shown in Figure 20.

4.5 Numerical study on HFMI effect on cracks

Two-dimensional shell finite element model was created to study the crack behaviour after HFMI-treatment. Symmetry was considered, and only half the specimens was modelled. The translation of the specimen was prevented in both directions to simulate the specimen's fixation during HFMI-treatment. The geometrical parameters such as toe radius, throat thickness and weld angle were obtained from geometry scanning described in section 4.1. The crack was modelled as a rectangular gap in the geometry having a width of 0.05 mm as mentioned in the previous section.

The element size around the crack was selected to be 0.1 mm and a global mesh size of 3 mm was considered, see Figure 21. The element type used before in section 4.1 was used for this analysis as well. Adaptive meshing tool was used to minimise the undesired distortion of the mesh due to large deformations. The indentor was modelled as rigid undeformed body, and the displacement was prescribed so that the indentation depth reached prescribed values. The position of impact with respect to crack and the angle of treatment were also prescribed.

A friction coefficient of 0.4 was considered between both the crack surfaces, and between the indentor and the specimen's surface. This choice was motivated as the steel was not fully dry because of the applied dye penetrant to check the crack length. Johnson-Cook constitutive law was used and elastoplastic analysis was run. Several parametric studies were conducted on crack depth, indentation depth, position of peening and angle of treatment. In each study, one variable was changed and the others were kept constant. The default values of these parameters are shown in Figure 22.

The contact stresses between the crack surfaces and the average crack opening were found to be related to the crack size as shown in Figure 23. However, despite that the simulation showed the same trend to the experimental observations regarding the crack opening for cracks shallower than 2 mm, the simulation results were quite conservative. This could be traced back to the shape of the modelled crack (i.e. rectangular), which did not reflect the real crack shape (i.e. pointed). Furthermore, HFMI treatment could close the crack surfaces and change the crack orientation as shown in Figure 24. However, both beneficial effects were diminishing as the crack size increased.

Another beneficial effect of this kind of treatment is the compressive plasticity created around the crack. The maximum obtained compression was found at the crack tip for

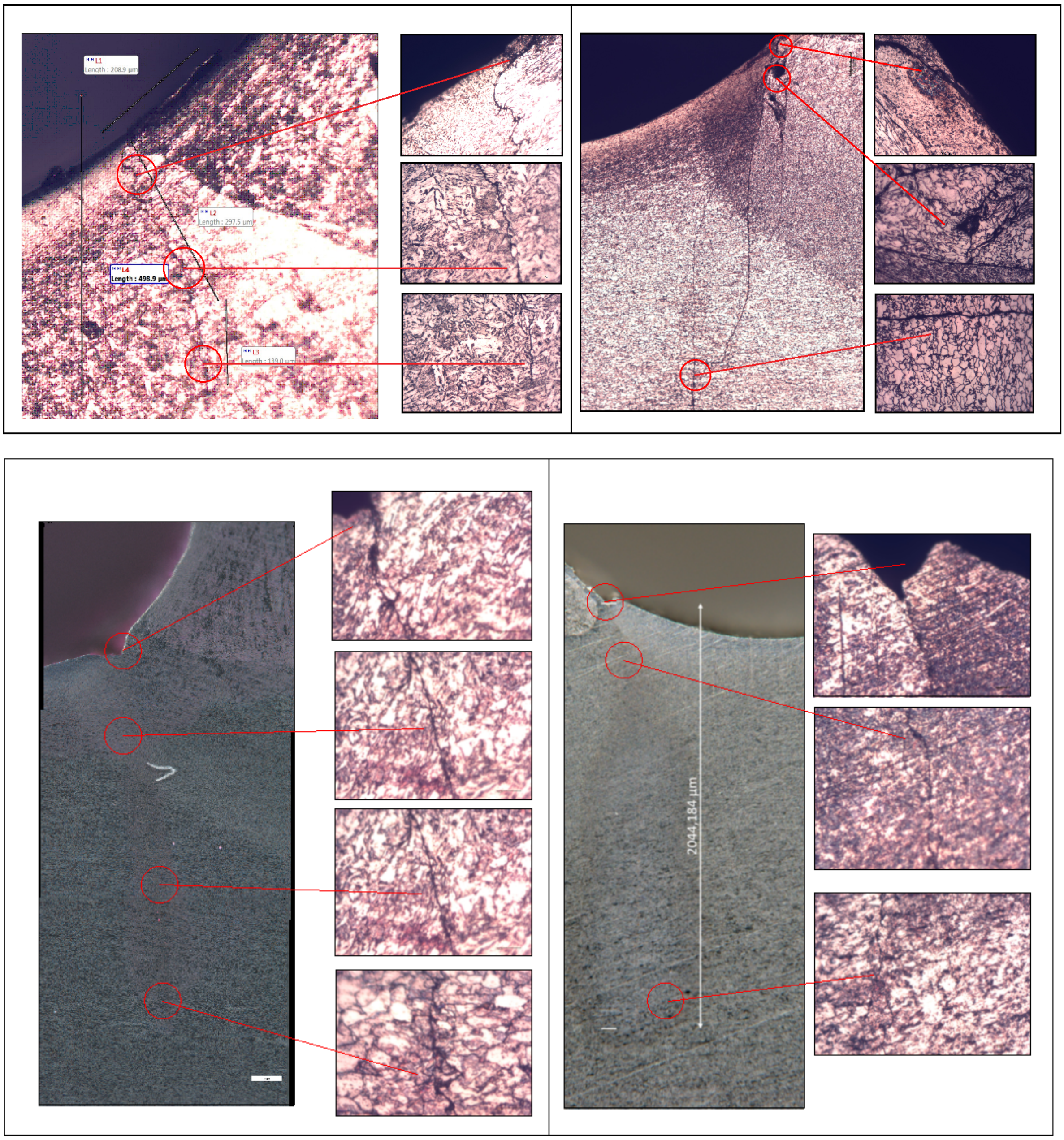

Figure 20: Observations of the cracks shapes after HFMI-treatment for different specimens
U: The change in crack orientation due to HFMI-treatment.
L: The top layer was not closed due to misalignment of the indentor.

cracks shallower than 0.75 mm, and at the surface for deeper cracks as shown in Figure 25. The size of the compressive plasticity zone was found to be inversely proportional to the crack size. No compression detected at the crack tip for cracks deeper than 1.5 mm. This limit is more conservative than the one obtained by studying the gain factor in section 3.2 which was 2.25 mm. This indicates that fatigue life extension is also conceivable even when no plasticity created at the crack tip.

When applied on new structures, HiFIT indentor inclination angle with respect to the plate surface should be 60°-80°according to the recommendations [12]. This also could be extended to cracked structures as the contact stress between the crack surfaces decreases when the angle increases, see Figure 26. Moreover, the treatment gave optimum results when the indentation depth is around 0.3 mm. Shallower indentation resulted in insuffi-

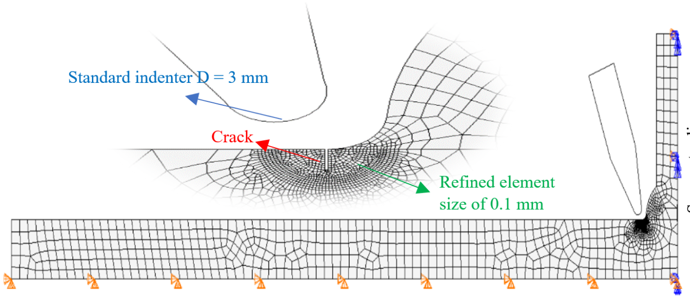

Figure 21: Elasto-plastic finite element model of cracked HFMI-treated specimen

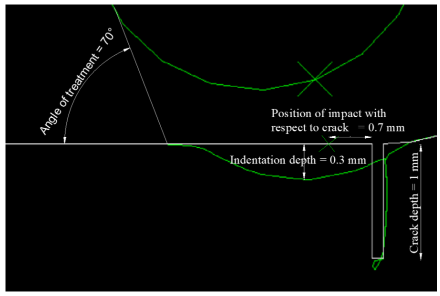

Figure 22: Default values for finite element analsys

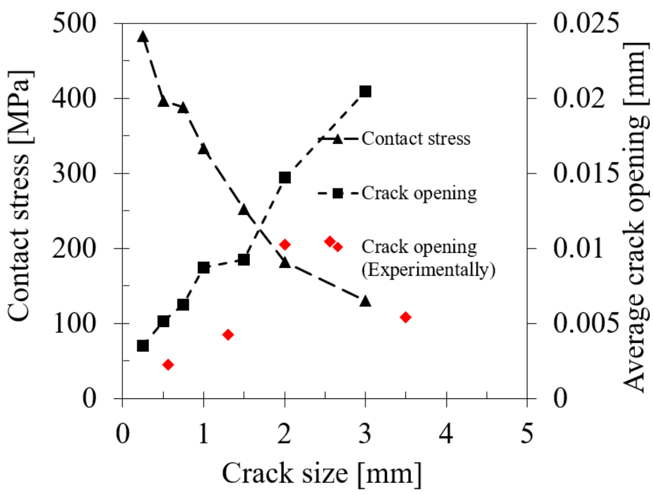

Figure 23: The dependency of contact stress and crack opening on the crack size

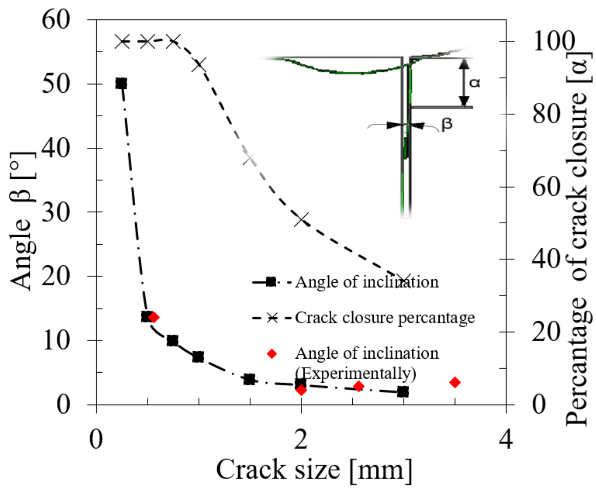

Figure 24: The dependency of crack inclination and crack opening on the crack size

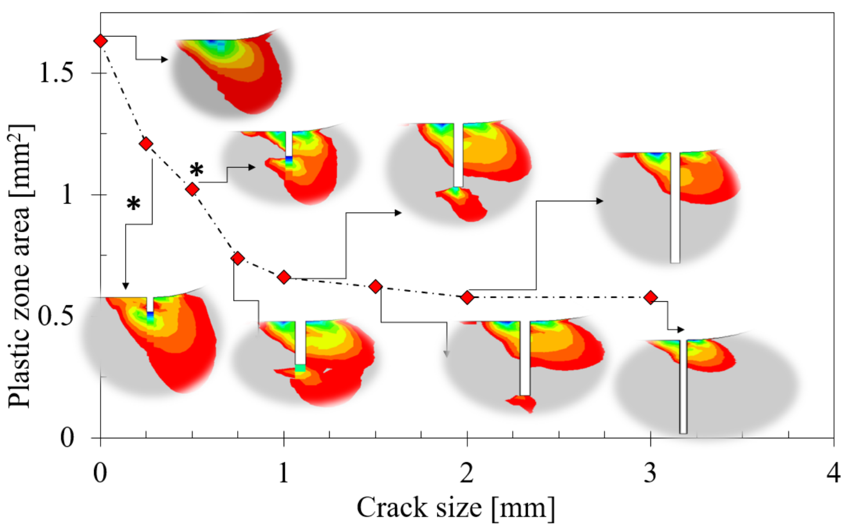

Figure 25: Effect of crack size on compressive plasticity induced by HFMI treatment

cient crack closure, while deeper indentation might also have reverse effects as shown in Figure 27. This is also similar to the recommended indentation depth for new structures [12].

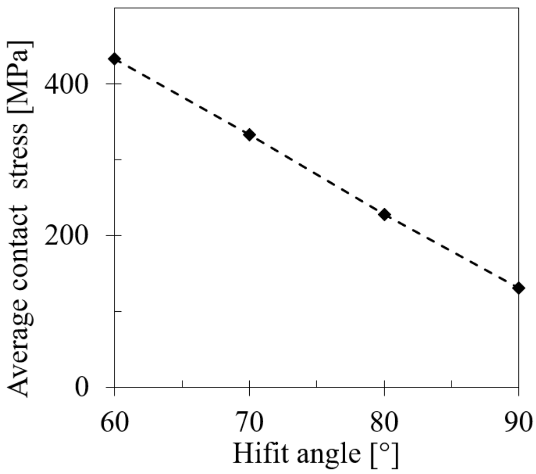

Figure 26: Hifit inclination angle effect on cracks

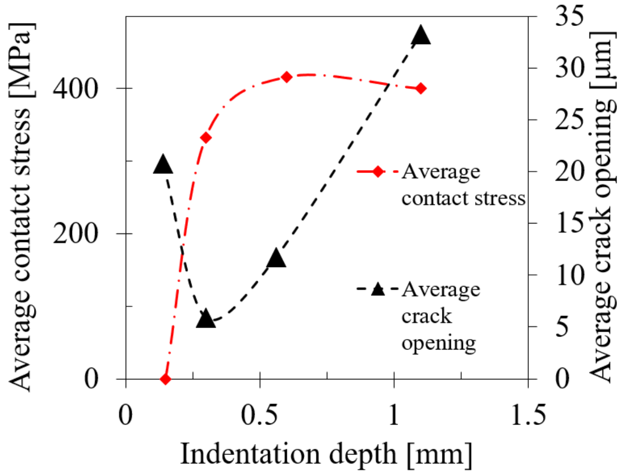

Figure 27: The indentation depth effect on cracks

When treating cracked structures, the best care should be taken to avoid opening the crack which could be the case when the indentor is slanted toward the weld more than the base metal. This might be explained by material flow away from the crack. The best crack closure was obtained when the indentor is placed 0.75 mm of the weld line. Moreover, no additional crack opening was observed even when the indentor hits the plate surface at a distance of 1.5 mm from the base metal side, see Figure 28.

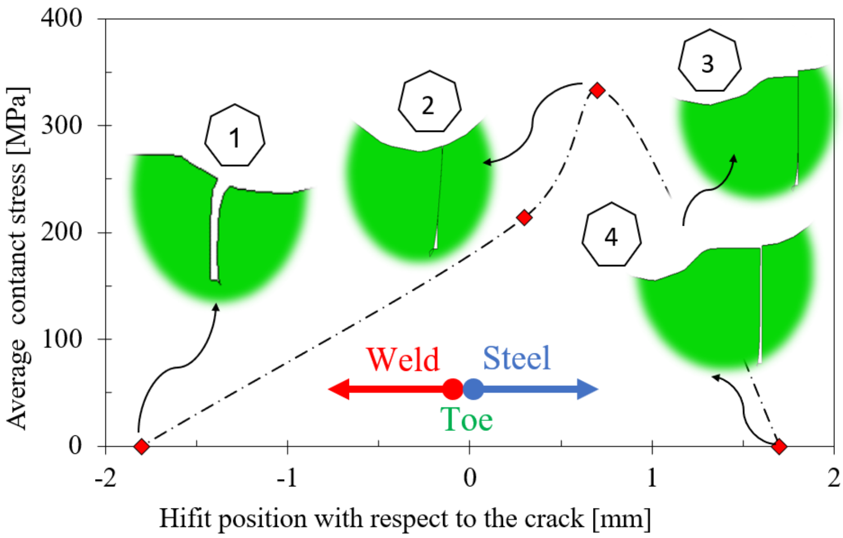

Figure 28: Effect of impact position on contract stress between the crack surfaces

5 Fatigue life extension calculations

Estimating the bridge's fatigue life after crack repair is an essential step for traffic authorities for construction and maintenance planning. Mainly, there are two calculation methods: safe life approach and damage tolerance approach. The former is applicable when the structure is crack-free. A damage model can be used if fatigue damage has accumulated at the weld toe. Nonetheless, TIG-remelting fuses the material in the weld toe's vicinity and creates a new microstructure. Therefore, no existing damage would

Table 7: Calculated fatigue lives for as-welded and treated specimens by safe life approach

Status	σ_{RS}	$\sigma_{u,l}$	σ_{Clamp}	$\Delta\sigma$	$\Delta\sigma_{ar}$	$N_{f,cal}$	$N_{f,exp}$
AW	-176	627	90	150	481	2.61E6	1.11E6-3.25E6
TIG	-219	697	198	150	279	1.16E9	1.00E7
	-219	697	198	180	345	1.08E8	1.00E7
	-219	697	198	250	583	3.01E5	3.30E5
TIG-HFMI	-293	767	171	150	268	1.79E9	1.00E7
	-293	767	171	180	281	1.10E9	1.50E6
	-293	767	171	220	371	4.66E7	1.50E6
	-293	767	171	250	450	5.56E6	2.40E6

be assumed when estimating the life of TIG-remelted or TIG-HFMI treated structures. Basquin's equation together with Goodman mean stress correction were used to incorporate the parameters investigated in section 4, see equation 3 & 4.

$$\Delta\sigma_{ar} = A\frac{K_t \times \Delta\sigma}{1 - \dfrac{\sigma_{RS} + \sigma_{clamp} + \sigma_m \times K_t}{\sigma_{u,l}}} \tag{3}$$

$$N_{f,cal} = A \times \Delta\sigma_{ar}^{B} \tag{4}$$

Where A & B are Basquin's equation parameters, and $\Delta\sigma_{ar}$ is the fully reversed stress range considering the mean stress effect. $\Delta\sigma$ & σ_m are the nominal stress range and the mean stress respectively. The residual and clamping stresses at the weld toe are given in Tables 5 & 6 respectively. $\sigma_{u,l}$ is the local tensile strength at the weld toe obtained from the hardness testing. The implementation of equation 3 & 4 is shown in Table 7. The calculated fatigue life $N_{f,cal}$ of as-welded specimens under $\Delta\sigma$ = 150 MPa was found to be 2.61 million cycles, which lie in the interval of the fatigue lives of the tested specimens $N_{f,exp}$ of 1.11-3.25 million cycles. Nonetheless, the calculated fatigue lives of TIG-remelted specimens were significantly longer than the test results due to clamping failure of all treated specimens. The calculations showed that TIG-HFMI-treatment is superior to TIG-remelting in fatigue life extension, mainly because of the introduced compressive residual stress.

Unlike TIG-remelting, HFMI-treatment does not eliminate cracks from the weld toe. Therefore, damage tolerance approach is more applicable for fatigue life extension. Accordingly , linear elastic fracture mechanics was used to study the crack propagation using Paris law. The stress intensity factors K were calculated using the weight function approach. The effective stress ratio R_{eff} was incorporated in Paris law in order to take residual and clamping stress distributions into account, see equation 5 & 6. The threshold stress intensity factor K_{th} was introduced to investigate the conditions at which the crack is not propagatable.

$$da = \begin{cases} \dfrac{C(K_{max} - K_{min})^m}{(1.5 - R_{eff})^m} \times dN & \text{if } K_{max} - K_{min} > K_{th}, \\ 0 & \textit{Otherwise} \end{cases} \tag{5}$$

$$R_{eff} = \frac{K_{min} + K_{RS} + K_{CS}}{K_{max} + K_{RS} + K_{CS}} \tag{6}$$

Where C & m are Paris law parameters. K_{max}, K_{min}, K_{RS} & K_{CS} are the intensity factors for the maximum stress, minimum stress, residual stress and clamping stress respectively. Besides, da & dN are the incremental increase in crack size and number of cycles respectively. For as-welded specimens, the initial crack size was selected to be 0.15 mm or 0.50 mm in accordance with the IIW and the British standard recommendations respectively [6] & [48]. On the contrary, the treated crack size for the prefatigued

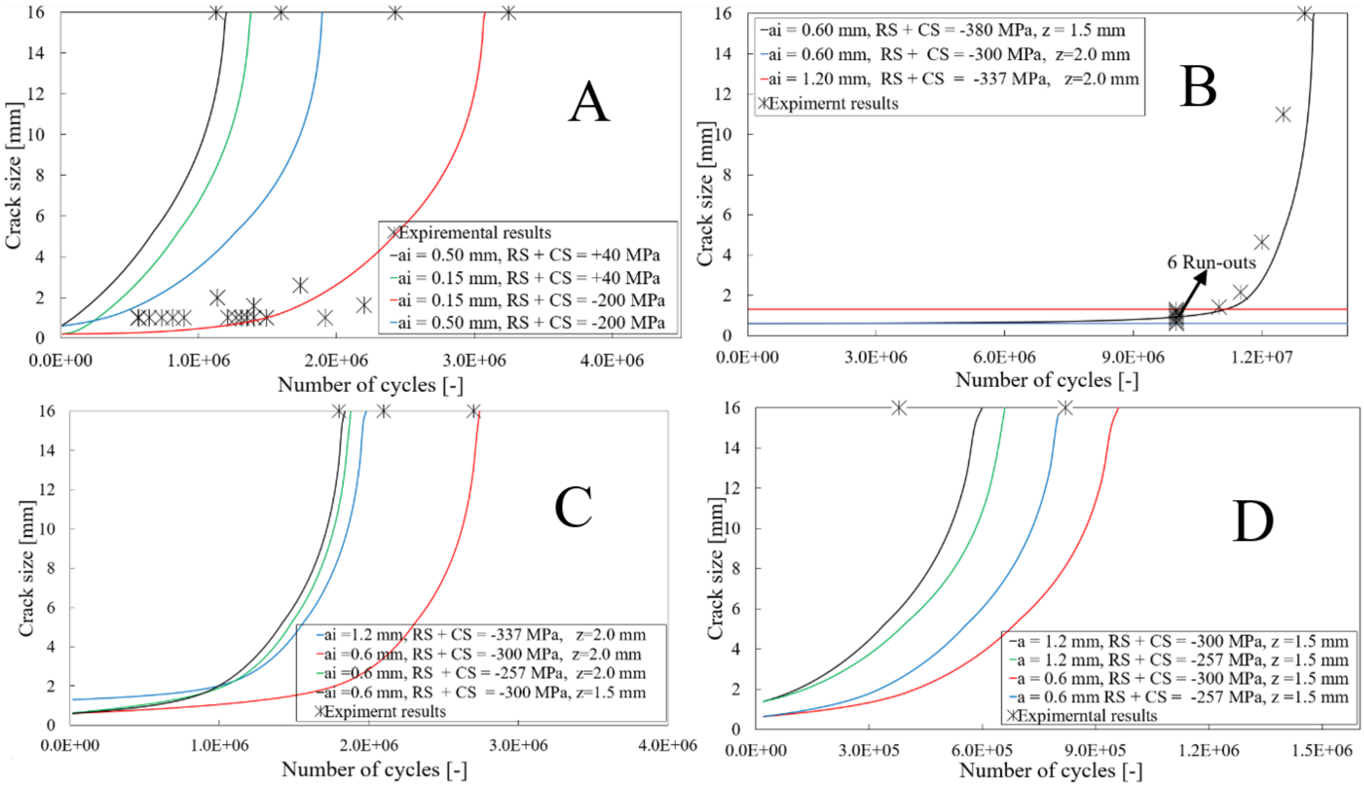

Figure 29: A: Crack propagation curves for as-welded specimen under $\Delta\sigma$ = 150 MPa
B, C, D: Crack propagation curves for prefatigued HFMI-treated specimens tested under 150, 180 & 210 MPa respectively

HFMI-treated specimens was chosen to be 0.6 mm -1.2 mm based on the crack detection results as indicated in section 3.1.

The maximum and the minimum residual and clamping stresses were considered in the analysis in order to capture the scatter in the test results. Moreover, the depth of compressive residual stresses in as-welded condition was selected to be 0.6 mm, while two depth of compression (z = 1.5 mm or 2.0 mm) was considered after HFMI-treatment, these depths were acquired from [49]. The crack propagation analysis results are shown in Figure 29. Remarkably, only 4 out of 22 experimental results were off the estimated values in as-welded condition. Moreover, 5 out of 6 specimen's fatigue lives were well predicted by the generated curves. Besides, the analysis was enabled to predict the six run-outs after 10 million cycles (i.e. in Figure 29B) by incorporating K_{th}.

6 Summary & Conclusions

This thesis is concerned with the study of the fatigue performance of high-frequency mechanical impact (HFMI) treated and Tungsten Inert Gas (TIG) remelted welded joints in existing steel bridges. The efficiency of both methods is investigated via fatigue testing, topography scanning, residual stress measurement, hardness testing, micrography, numerical and analytical investigations. Based on the conducted studies in this thesis, the following main conclusions can be drawn:

- Fatigue testing carried out on S355 structural steel plates with non-load carrying transverse attachment showed that the investigated treatment methods (i.e. HFMI-treatment, TIG-remelting and TIG-HFMI-treatment) significantly increased fatigue life even with the presence of 0.6-1.2 mm crack at the weld toe. Toe failure was obtained in as-welded and HFMI conditions, while TIG-remelting and TIG-HFMI-treatment resulted in base metal failure at the clamp.

- The gain factors in fatigue life were introduced and calculated for more than 250 fatigue test results. It was found that HFMI-treatment caused a significant fatigue life extension even with the presence of 2.25 mm crack. Besides, TIG-remelting resulted in a significant fatigue life extension even if a small part of the crack remains after remelting. Nonetheless, because of the inherent inaccuracies in crack detection, it is recommended to use HFMI-treatment and TIG-remelting solely when the non-destructive testing was negative before and after treatment respectively.
- All treatment methods contributed in reducing the toes sharpness, which was reflected on the stress concentration factors. The weld toe radii increased with a factor of 7 following TIG-remelting. Moreover, local hardness increased significantly after HFMI-treatment because of the local cold working.
- Despite the compressive residual stresses existed at the weld toe even in as-welded conditions, a further increase in the compression at the surface was observed after both treatment methods especially after HFMI-treatment. Bedsides, higher distortions and clamping stresses were observed after TIG-remelting due to the heat input associated with remelting.
- When applied on existing structures, HFMI indentor should be directed more toward the welds in order to avoid unintentional crack opening. Moreover, the IIW recommendations regarding the indentation depth and the indentors inclination angle with respect to the plate surface could be extended to cracked structures. The tungsten electrode should be positioned at the weld toe to secure that the maximum fusion corresponded to the crack plane.
- Fatigue lives of TIG-remelted and TIG-HFMI-treated specimens were predicted using Basquin's equation. Goodman mean stress correction was employed to incorporate the different effects induced by the treatment. The calculated fatigue lives did not contradict the test results. On the other hand, The effect of mean stresses (i.e. residual & clamping stresses) was incorporated in crack propagation calculations to predict the fatigue lives of HFMI-treated specimens. The results were in the band of the generated crack propagation curves.
- Combining TIG-remelting with HFMI-treatment was found to be superior to both individual treatments in term of the introduced compressive residual stress, toe's radius and local hardness which was reflected on the calculated fatigue lives.

7 Future work

The work conducted in this thesis, together with findings from previous studies indicated that both of the studied methods have the potential to increase the strength of welded joints. The following subjects are proposed for future research.

- Investigation of the performance of existing structures containing cracks following HFMI-treatment under variable amplitude loading. Moreover, the effects of stress ratio and maximum stress need to be further examination.
- More accurate numerical simulations for treating cracked structures using the studied methods are proposed to investigate the crack behaviour more precisely.
- Field studies on bridges in Sweden and other European countries including non destructive testing in order to study the potential fatigue life extension for each bridge.
- Investigation on the performance of treated steel with low weldability which was used for constructing old bridges.
- Studying the potential of robotising the process of fatigue life extension in term of crack detection, crack repair and monitoring the performance afterwards.

References

[1] Pantura, "Needs for maintenance and refurbishment of bridges in urban environments," 2011.

[2] I. L. K. Reid, D. M. Milne, and R. E. Craig, *Steel Bridge Strengthening: a study of assessment and strengthening experience and identification of solutions*. Thomas Telford, 2001.

[3] B. Imam and M. Chryssanthopoulos, "A review of metallic bridge failure statistics," in *Bridge Maintenance, Safety and Management: Proceedings of the Fifth International IABMAS Conference*, pp. 3275–3282, 2010.

[4] F. M. Russo, D. R. Mertz, K. H. Frank, K. E. Wilson, *et al.*, "Design and evaluation of steel bridges for fatigue and fracture–reference manual," tech. rep., National Highway Institute (US), 2016.

[5] E. C. for Standardization, "Eurocode 3: Design of steel structures. part 1.9: Fatigue," 2003.

[6] A. Hobbacher *et al.*, *Recommendations for fatigue design of welded joints and components*. Springer, 2009.

[7] R. J. Dexter, J. M. Ocel, *et al.*, "Manual for repair and retrofit of fatigue cracks in steel bridges," tech. rep., United States. Federal Highway Administration, 2013.

[8] A. Akyel, M. Kolstein, and F. Bijlaard, "Fatigue strength of repaired welded connections made of very high strength steels," *Engineering Structures*, vol. 161, pp. 28–40, 2018.

[9] P. Haagensen and S. Maddox, "IIW recommendations on post weld improvement of steel and aluminium," *IIW Doc*, vol. 13, pp. 1815–00, 2003.

[10] M. M. Pedersen, O. Ø. Mouritsen, M. R. Hansen, J. G. Andersen, and J. Wenderby, "Comparison of post-weld treatment of high-strength steel welded joints in medium cycle fatigue," *Welding in the World*, vol. 54, no. 7-8, pp. R208–R217, 2010.

[11] J. W. Fisher, A. W. Pense, R. E. Slockbower, and H. Hausammann, "Retrofitting fatigue damaged bridges," *Transportation Research Record*, no. 664, 1978.

[12] Z. B. Gary Marquis, *IIW recomendations for the HFMI treatment for imporving the fatigue strength of welded joints*. Springer, 2016.

[13] M. Leitner, M. Khurshid, and Z. Barsoum, "Stability of high frequency mechanical impact (HFMI) post-treatment induced residual stress states under cyclic loading of welded steel joints," *Engineering Structures*, vol. 143, pp. 589–602, 2017.

[14] P. Shams-Hakimi, F. Zamiri, M. Al-Emrani, and Z. Barsoum, "Experimental study of transverse attachment joints with 40 and 60 mm thick main plates, improved by high-frequency mechanical impact treatment (HFMI)," *Engineering Structures*, vol. 155, pp. 251–266, 2018.

[15] G. Le Quilliec, H.-P. Lieurade, M. Bousseau, M. Drissi-Habti, G. Inglebert, P. Macquet, and L. Jubin, "Fatigue behaviour of welded joints treated by high frequency hammer peening: Part i, experimental study," in *64th Annual Assembly & International Conference of the International Institute of Welding (IIW 2011)*, 2011.

[16] G. Le Quilliec, H. Lieurade, M. Bousseau, M. Drissi-Habti, G. Inglebert, P. Macquet, and L. Jubin, "Fatigue behavior of welded joints treated by high frequency hammer peening: Part ii," *Numerical Study, IIW Document*, vol. 13, pp. 2395–11, 2011.

[17] L. Huo, D. Wang, and Y. Zhang, "Investigation of the fatigue behaviour of the welded joints treated by tig dressing and ultrasonic peening under variable-amplitude load," *International journal of Fatigue*, vol. 27, no. 1, pp. 95–101, 2005.

[18] K. Anami, C. Miki, H. Tani, and H. Yamamoto, “Improving fatigue strength of welded joints by hammer peening and TIG-dressing, structural eng./earthquake eng,” JSCE, 2000.

[19] P. Haagensen, E. S. Statnikov, and L. Lopez-Martinez, “Introductory fatigue tests on welded joints in high strength steel and aluminium improved by various methods including ultrasonic impact treatment (UIT),” *IIW Doc*, vol. 13, pp. 1748–98, 1998.

[20] L. L. Martinez, A. Blom, H. Trogen, and T. Dahle, “Fatigue behaviour of steels with strength levels between 350 and 900 mpa influence of post weld treatment under spectrum loading,” in *Proceeding of the North European Engineering and Science Conference,(NESCO), Welded High-Strength Steel Structures, Stockholm, Edited by AF Bloom, EMAS Publishing, London*, 1997.

[21] M. Leitner, M. Stoschka, and W. Eichlseder, “Fatigue enhancement of thin-walled, high-strength steel joints by high-frequency mechanical impact treatment,” *Welding in the World*, vol. 58, no. 1, pp. 29–39, 2014.

[22] A. Abdullah, M. Malaki, and A. Eskandari, “Strength enhancement of the welded structures by ultrasonic peening,” *Materials & Design*, vol. 38, pp. 7–18, 2012.

[23] T. Ishikawa, K. Yamada, T. Kakiichi, and H. Li, “Extending fatigue life of cracked out-of-plane gusset by ICR treatment,” *Structural Engineering/Earthquake Engineering*, vol. 28, no. 1, pp. 21s–28s, 2011.

[24] H.-P. Günther, U. Kuhlmann, and A. Dürr, “Rehabilitation of welded joints by ultrasonic impact treatment (UIT),” in *IABSE Symposium Report*, vol. 90, pp. 71–77, International Association for Bridge and Structural Engineering, 2005.

[25] Y. Kudryavtsev, J. Kleiman, A. Lugovskoy, L. Lobanov, V. Knysh, O. Voitenko, and G. Prokopenko, “Rehabilitation and repair of welded elements and structures by ultrasonic peening,” *Welding in the World*, vol. 51, no. 7-8, pp. 47–53, 2007.

[26] H. Zhang, D. Wang, L. Xia, Z. Lei, and Y. Li, “Effects of ultrasonic impact treatment on pre-fatigue loaded high-strength steel welded joints,” *International Journal of Fatigue*, vol. 80, pp. 278–287, 2015.

[27] M. Leitner, Z. Barsoum, and F. Schäfers, “Crack propagation analysis and rehabilitation by HFMI of pre-fatigued welded structures,” *Welding in the World*, vol. 60, no. 3, pp. 581–592, 2016.

[28] C. Branco, V. Infante, and R. Baptista, “Fatigue behaviour of welded joints with cracks, repaired by hammer peening,” *Fatigue & Fracture of Engineering Materials & Structures*, vol. 27, no. 9, pp. 785–798, 2004.

[29] J. W. Fisher, M. Sullivan, and A. Pense, “Improving fatigue strength and repairing fatigue damage, dec. 1974,” 1974.

[30] S. J. Maddox, M. Doré, and S. D. Smith, “A case study of the use of ultrasonic peening for upgrading a welded steel structure,” *Welding in the World*, vol. 55, no. 9-10, pp. 56–67, 2011.

[31] K. Houjou, K. Takahashi, K. Ando, and H. Abe, “Effect of peening on the fatigue limit of welded structural steel with surface crack, and rendering the crack harmless,” *International Journal of Structural Integrity*, vol. 5, no. 4, pp. 279–289, 2014.

[32] R. Fueki and K. Takahashi, “Prediction of fatigue limit improvement in needle peened welded joints containing crack-like defects,” *International Journal of Structural Integrity*, vol. 9, no. 1, pp. 50–64, 2018.

[33] R. Fueki, K. Takahashi, and K. Houjou, “Fatigue limit prediction and estimation for the crack size rendered harmless by peening for welded joint containing a surface crack,” *Materials Sciences and Applications*, vol. 6, no. 06, p. 500, 2015.

[34] P. Haagensen *et al.*, "TIG dressing of steel weldments for improved fatigue performance," in *Offshore Technology Conference*, Offshore Technology Conference, 1979.

[35] L. C. Wu and D. P. Wang, "Improve the fatigue performance of welded joints with undercuts by tig dressing treatment," in *Advanced Materials Research*, vol. 472, pp. 1300–1304, Trans Tech Publ, 2012.

[36] K. Anami, C. Miki, H. Tani, and H. Yamamoto, "Improving fatigue strength of welded joints by hammer peening and TIG-dressing," *Doboku Gakkai Ronbunshu*, vol. 2000, no. 647, pp. 67–78, 2000.

[37] J. Hildebrand, I. Starcevic, F. Werner, H. Heinemann, and G. Köhler, "Numerical simulation of TIG-dressing of welded joints," in *Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, 2006.

[38] T. Skriko, M. Ghafouri, and T. Björk, "Fatigue strength of tig-dressed ultra-high-strength steel fillet weld joints at high stress ratio," *International Journal of Fatigue*, vol. 94, pp. 110–120, 2017.

[39] H. C. Yıldırım, "Review of fatigue data for welds improved by tungsten inert gas dressing," *International Journal of Fatigue*, vol. 79, pp. 36–45, 2015.

[40] S. van Es, M. Kolstein, R. Pijpers, and F. Bijlaard, "Tig-dressing of high strength butt welded connection-part 2: physical testing and modelling," *Procedia Engineering, 66, 126-137*, 2013.

[41] L. Huo, D. Wang, and Y. Zhang, "Investigation of the fatigue behaviour of the welded joints treated by tig dressing and ultrasonic peening under variable-amplitude load," *International journal of Fatigue*, vol. 27, no. 1, pp. 95–101, 2005.

[42] S. Van Es, M. Kolstein, R. Pijpers, and F. Bijlaard, "TIG-dressing of high strength steel butt welded connections–part 1: weld toe geometry and local hardness," *Procedia Engineering*, vol. 66, pp. 216–225, 2013.

[43] M. Nascimento, H. J. C. Voorwald, and J. D. C. P. FILHO, "Effects of several tig weld repairs on the axial fatigue strength of aisi 4130 aeronautical steel-welded joints," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 35, no. 3, pp. 191–204, 2012.

[44] C. Miki, T. Mori, S. Tuda, and K. Sakamoto, "Retrofitting fatigue-cracked joints by TIG arc remelting," *Doboku Gakkai Ronbunshu*, vol. 1987, no. 380, pp. 111–119, 1987.

[45] E. S. Statnikov, V. Muktepavel, and A. Blomqvist, "Comparison of ultrasonic impact treatment (UIT) and other fatigue life improvement methods," *Welding in the World*, vol. 46, no. 3-4, pp. 20–32, 2002.

[46] W. Fricke, "Guideline for the fatigue assessment by notch stress analysis for welded structures," *International Institute of Welding*, vol. 13, pp. 2240–08, 2008.

[47] M. M. Pedersen, O. Ø. Mouritsen, M. R. Hansen, and J. G. Andersen, "Experience with the notch stress approach for fatigue assessment of welded joints," in *Swedish Conference on Light Weight Optimized Welded Structures, Borlänge*, 2010.

[48] B. S. BS7910, "Guide on methods for assessing the acceptability of flaws in metallic structures, BS7910," *British Standards Institute*, 2005.

[49] H. Al-Karawi, R. U. F. von Bock und Polach, and M. Al-Emrani, "Fatigue crack repair in welded structures via tungsten inert gas remelting and high frequency mechanical impact," *Journal of Constructional Steel Research*, vol. 13, pp. 1748–98, 2020.