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Fatigue life estimation of welded structures enhanced by combined thermo-mechanical treatment methods

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ABSTRACT

Different post-weld treatment methods are used to strengthen welded joints that are subjected to cyclic loading. Combining High-Frequency Mechanical Impact (HFMI) treatment with Tungsten Inert Gas (TIG) remelting is rather a new concept. In this paper, the fatigue lives of welded transverse attachments treated by HFMI-treatment, TIG-remelting, or the combination of both are estimated using fatigue damage modelling and finite element deletion. The change in local topography and residual stresses due to treatment are evaluated numerically and incorporated in the analysis. The local hardness is measured by a Vickers tester and incorporated by increasing the elemental ultimate strength. The analysis demonstrates the superiority of the combined treatment because of the introduced compressive residual stress and the improvement in topography. The analysis also shows that the damage is less distributed after the combined treatment than both individual treatments. Besides, the capability of the TIG-HFMI combination in treating existing welded structures with remaining embedded fatigue crack is proven. Besides, available fatigue test results on combined TIG-HFMI treatment shows that this combination gives always longer fatigue life than the characteristic fatigue lives of the treated details by any of the treatment methods. However, many aspects such as TIG arc and HFMI indenter positioning, and indentation and fusion depth should be taken into consideration when the combined treatment is to be applied to existing structures.

1. Introduction

Fatigue appears as one of the most challenging issues for designers and structural engineers dealing with welded steel structures. Therefore, a lot of research have been conducted on methods that can increase the fatigue strength and extend the expected service life of the critical welded details. These methods are called "local methods" because their effects are localized to an area around the weld toe. They act on counteracting the detrimental welding effects that weaken the welded area such as residual stress after welding or local stress risers [1]. The local methods are branched into two families depending on their main influence: methods that change the stress distribution near the toe to create beneficial compression field like High-Frequency Mechanical Impact treatment (HFMI treatment), or methods to improve the weld toe topography to decrease the stress concentration factor such as Tungsten Gas remelting (TIG).

Both the aforementioned methods (i.e. TIG-remelting and HFMI-treatment) have their own pros and cons. For instance, despite its capability in introducing compressive residual stresses, HFMI-treatment may induce defects such as cold laps in some cases [2]. On the other hand, TIG-remelting sometimes causes softening in the heat-affected zone after remelting [3], and it can even introduce detrimental tensile residual stress [4]. It can also induce undercuts at the position of the newly formed well toe [5,6]. Therefore, combining TIG-remelting with HFMI-treatment guaranties the introduction of compressive residual stress. Besides, HFMI-treatment can remove any formed undercut due to TIG-remelting. It also increases the hardness of the weld toe in case that TIG-remelting causes softening beforehand.

Different methods are used to estimate the service life of welded details enhanced by post-weld treatment. Al-Karawi et al. [7] used weight function and Paris law to estimate the fatigue life of cracked welded details treated by a single HFMI indenter. Despite the good matching between the analysis and the experimental results, the propagation analysis was conducted on the expected crack path. The same authors used a relationship between the fatigue life and the stress range after incorporating some measured parameters (e.g. residual stress and toe radius) which were introduced by TIG-remelting in fatigue life estimation [6]. A local strain approach led to a remarkable agreement

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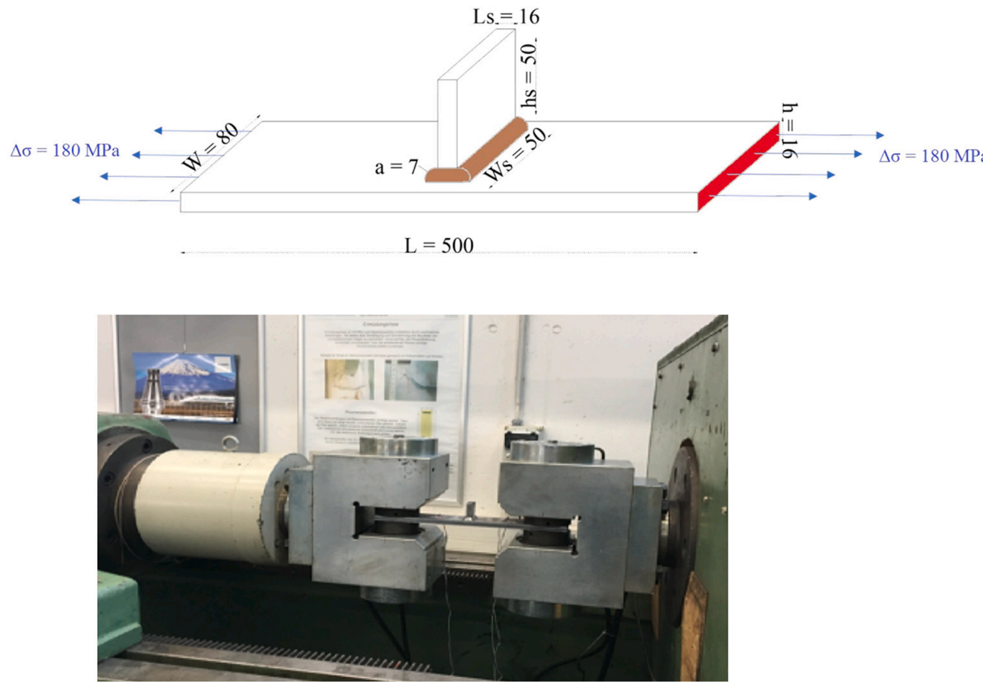

Fig. 1. T: Geometry of the studied specimen [mm] B: Fatigue testing rig.

Table 1
The chemical and mechanical properties of both steel and welds [6].

	Chemical content				
	Si	C	Mn	P	S
S355 %	0.05	0.23	1.6	0.05	0.05
C6 LF %	0.73	0.03	1.51	0.01	0.01

	Mechanical properties		
	Ultimate strength	Yield strength	Elongation
	MPa	MPa	%
S355	575	355	22
C6 LF	557	459	31

Table 2
Welding and TIG remelting parameters [6].

Welding parameters (Modelled weld toe radius = 0.67 mm)				
Weld run	Current (A)	Voltage (V)	Speed (mm/s)	Heat input (KJ/mm)
1	240	28.3	5.8	0.9
2	235	28.3	5.8	0.95

TIG remelting parameters (Modelled weld toe radius = 5.39 mm)			
Current (A)	Voltage (V)	Speed (mm/min)	Heat input (KJ/mm)
12	270	100	1.8

with the experimental results of welds improved by peening [8]. However, the analysis was conducted only on one single point at the weld toe with no crack proportion.

Takahashi and Fueki [9] used the threshold stress intensity concept to examine the capability of needle peening in life extension of cracked butt-welds. Herein, only a qualitative assessment was conducted without estimating the fatigue life. Leitner et al. [10] conducted an intensive study on different assessment methods such as fracture mechanics and strain accumulation approaches. The residual stress due to both welding and HFMI-treatment were incorporated by altering the mean stress. Despite the intensive work, it was concluded that more analysis was required to incorporate the prolongation in the initiation period after HFMI-treatment.

The choice of life assessment methods depends on different factors like the existing flaw size, the desired accuracy, the available inputs, and the applied loading level. Kumar et al. [11] conducted a review of the literature on fatigue life estimation methods of steel joints. Besides, Manai et al. [12] presented a framework proposing different assessment methods for different scenarios. This framework is generic and works for any post-weld treatment method. Safe life approaches were found to be suitable when the structure is crack-free. On the other hand, damage tolerance approaches were found to be more fitting to calculate the remaining life of structures containing cracks.

The combination of TIG-remelting and HFMI-treatment has been rarely studied in the literature [6,13–15]. In all these publications, the combination shows significant potential in strengthening the different studied welded details. Nonetheless, there is no research work -as far as the author knows- on estimating the fatigue life of welded structures enhanced by the TIG-HFMI combination. For this reason, the paper in hand contributes to the fatigue life estimation of welded detail enhanced by this innovative combination using fatigue damage calculations and finite elements deletion. The effect of the remaining cracks after treatment is also covered in this paper. A special light is thrown on some practical aspects that should be considered when applying this innovative combination.

2. Materials and methods

The study is conducted on transverse attachment detail. These kinds of details are important to provide stability for steel structures against buckling. The studied specimen together with the fatigue test rig are shown in Fig. 1. The specimens are made of S355 structural steel, and C6 LF low manganese emission metal-cored wire is chosen to be the filler material for welding. The mechanical proprieties and the chemical composition are given in Table 1. These specimens are selected because there is an available report with several treatment methods such as HFMI-treatment, TIG-remelting, and a combination of both, together

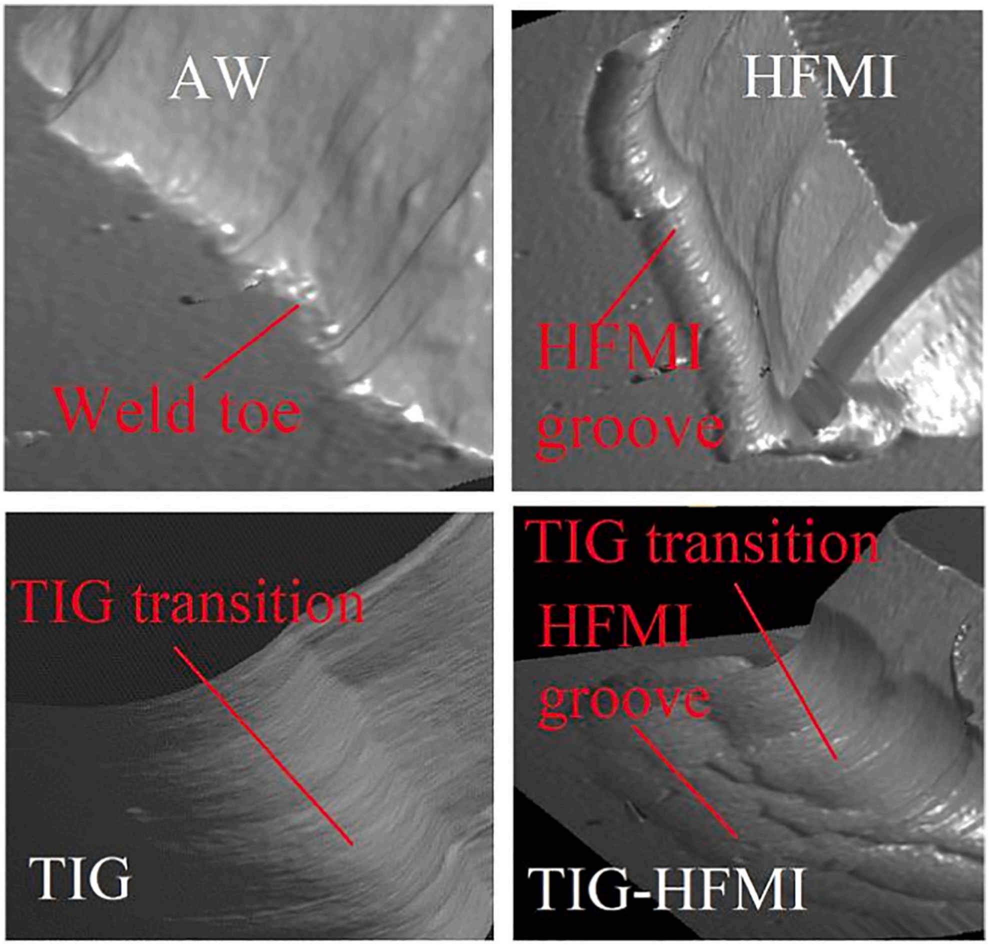

Fig. 2. Profiles of as-welded and enhanced details using different post-weld treatment methods.

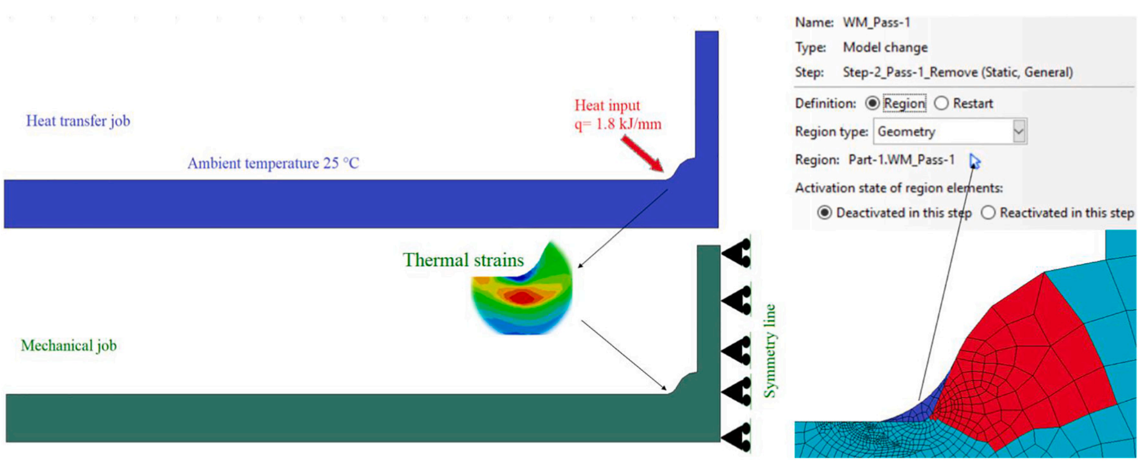

Fig. 3. Description of the finite element model used to obtain the residual stresses after TIG-remelting.

with some fatigue test results [16]. The treated specimens are subjected to pulsating membrane stress using $R = 0.29$, and a stress range = 180 MPa. The membrane stress is applied to the wings of the specimens. The test is aborted when the crack reaches half the specimen's thickness.

Several specimens are treated by TIG-remelting. Tungsten electrode is used to remelt the material at the toe's vicinity. Relatively high heat input is applied to maximize the fusion depth. Followingly, the second side is treated. TIG parameters are selected to fall within the range of the recommended values [5], see Table 2. Some of these specimens are treated by a single HFMI indenter with a diameter ∅ = 5 mm. The inclination of the indenters is 60–70 degrees. This also falls within the recommended range [2]. Other specimens are only treated by a single HFMI indenter with a diameter ∅ = 3 mm without previous TIG-remelting. A close look at the weld toes after post-weld treatment is shown in Fig. 2.

In this paper, the commercial software ABAQUS CAE is used to conduct the numerical analysis needed for the stress evaluation after treatment (i.e. HFMI-treatment, TIG-remelting or combination of both)

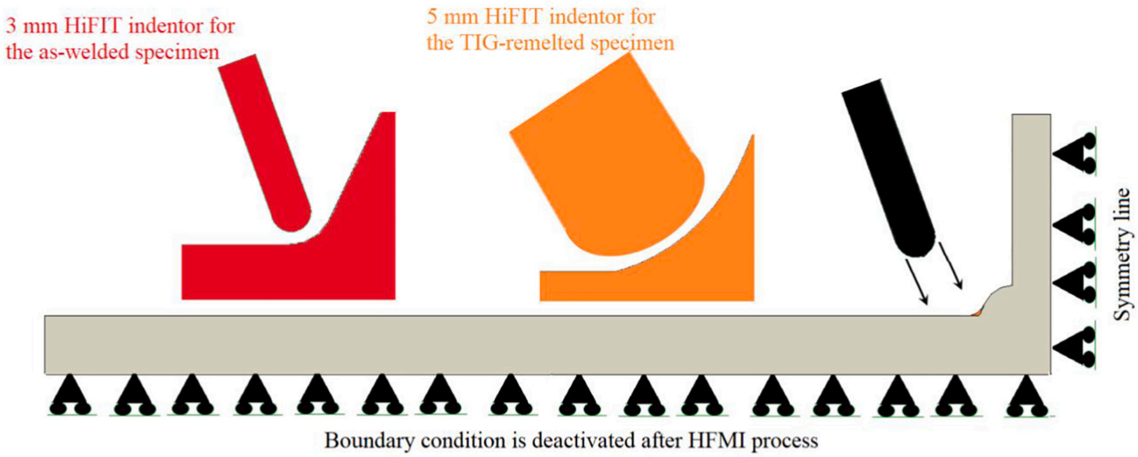

Fig. 4. Description of the HFMI-treatment model.

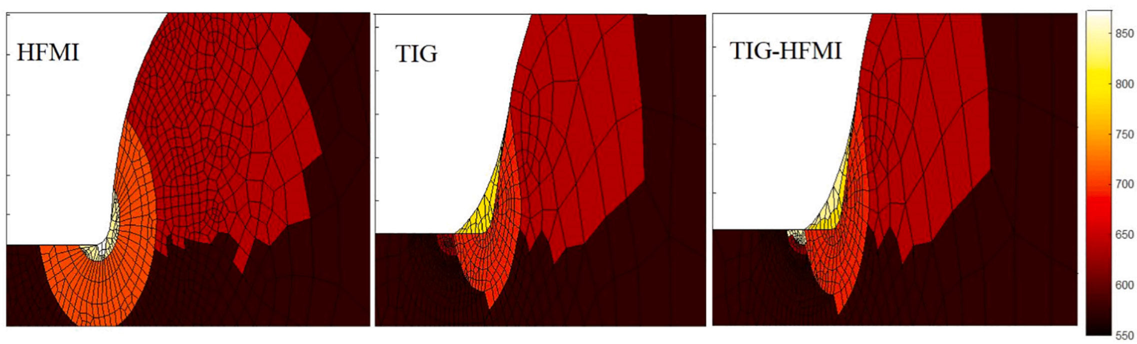

Fig. 5. Distribution of the local ultimate strength $\sigma_{u,L}$.

and after load application. Thermo-mechanical simulations are conducted to evaluate the residual stresses introduced by TIG-remelting. Abaqus welding interface (AWI) is used to generate the required steps and relate the temperature distribution obtained from the thermal analysis to the strains due to thermal expansion and contraction in the mechanical analysis [17]. The required temperature-dependent material proprieties such as yield strength, thermal conductivity, heat capacity and Young's modulus of the weld and the S355 steel are obtained from [18]. The input parameters for the thermal job are given in Table 2.

In order to reduce the computational effort, a 2D model is adopted to simulate the TIG torch under plane strain conditions. Benefiting from the symmetry line, half of the geometry is modelled to reduce the analysis time. The applied thermal and mechanical loads and boundary conditions are shown in the model described in Fig. 3. Four-noded linear quadrilateral elements are used to create the mesh (i.e. in Abaqus annotation: DC2D4 elements for the heat transfer analysis and CPS4R elements for the mechanical analysis). Smaller elements size of 0.1 mm is selected for meshing the area around the weld toe, while 3 mm is chosen elsewhere.

Different element groups are specified according to the material type as shown in Fig. 3. The red elements belong to the weld, while the purple elements are only activated during remelting. The rest belongs to S355 structural steel. The geometry of the weld and the TIG material (i.e. toe radius and weld height) are selected in accordance with the manufacturing process given in [6]. The heat input is selected to be 1.8 KJ/mm which lays in the recommended range [5]. The analysis is terminated when the temperature reaches the ambient temperature (25C) in all elements which indicates the end of the cooling stage.

The HFMI indenter is modelled as a rigid undeformed body. Two indenter's sizes are selected: the former has a diameter ∅ = 3 mm which is used to treat as-welded detail (i.e. with no previous residual stress from the TIG-remelting process). Since TIG-remelting aims at increasing the toe radius, a larger indenter size of ∅ = 5 mm is used to treat the TIG-remelted detail. A friction coefficient between the indenter and the body is chosen to be 0.3, and hard normal contact is defined. In addition to the symmetry line prescribed before, an additional boundary condition is included to simulate the specimen's fastening during HFMI-treatment. This boundary condition is deactivated after treatment. The displacement of the rigid body is prescribed until a depth of penetration of 0.25 mm is reached. The depth was measured on real identical specimens using depth gauge, and the results were confirmed via weld toe scanning [16]. Moreover, the optimum HFMI groove should have a groove depth of 0.2–0.6 mm [2]. Isotopic hardening plasticity material model is selected in accordance with [10]. Fig. 4 describes the model used to obtain the HFMI induced residual stress.

One load cycle is applied after residual stress determination to account for the expected relaxation after the first load cycle [19]. The further residual stress relaxation afterwards is calculated using the proposed linear relationship [20], see Eq. (1).

$$\frac{\sigma_{RS}}{\sigma_{RS\ 1cycle}} = N_i^k \tag{1}$$

Where σ_{RS} is the relaxed residual stress, $\sigma_{RS1Cycle}$ is the residual stress after applying the first load cycle, N_i is the crack initiation life, and K is an empirically evaluated exponent obtained from [19]. Herein, N_i is still unknown, so it should be assumed to a specific value and the assumption is to be checked later when fatigue life is evaluated. Afterwards, the load is applied on the deformed shapes to obtain the local distributions of the mean stress σ_{mLoc} and the stress range $\Delta\sigma_{Loc}$. The fully reversed stress range $\Delta\sigma_{ar}$ can then be calculated from Goodman mean stress correction

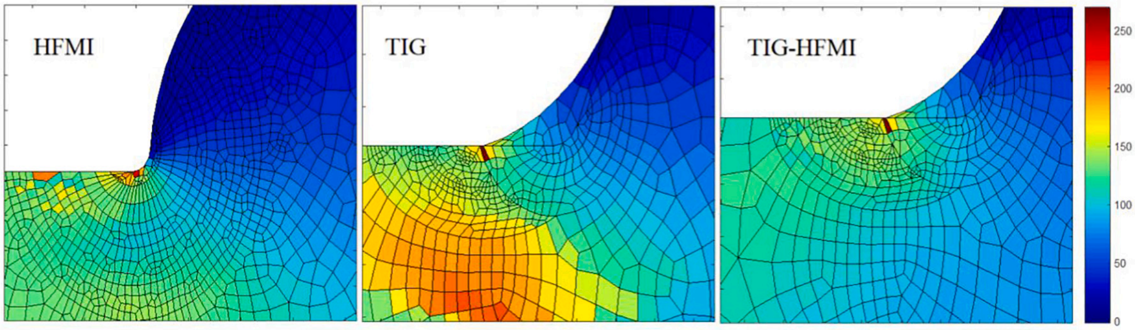

Fig. 6. Distribution of the fully reversed stress range $\Delta\sigma_{ar}$.

Table 3
S355 structural steel mechanical properties [21].

Parameter	E	K	b	c	n	ε_f	σ_f	σ_y	σ_u
Magnitude	210	595	−0.089	−0.664	0.0757	0.7371	952	355	575
Unit	GPa	MPa	–	–	–	–	MPa	MPa	MPa

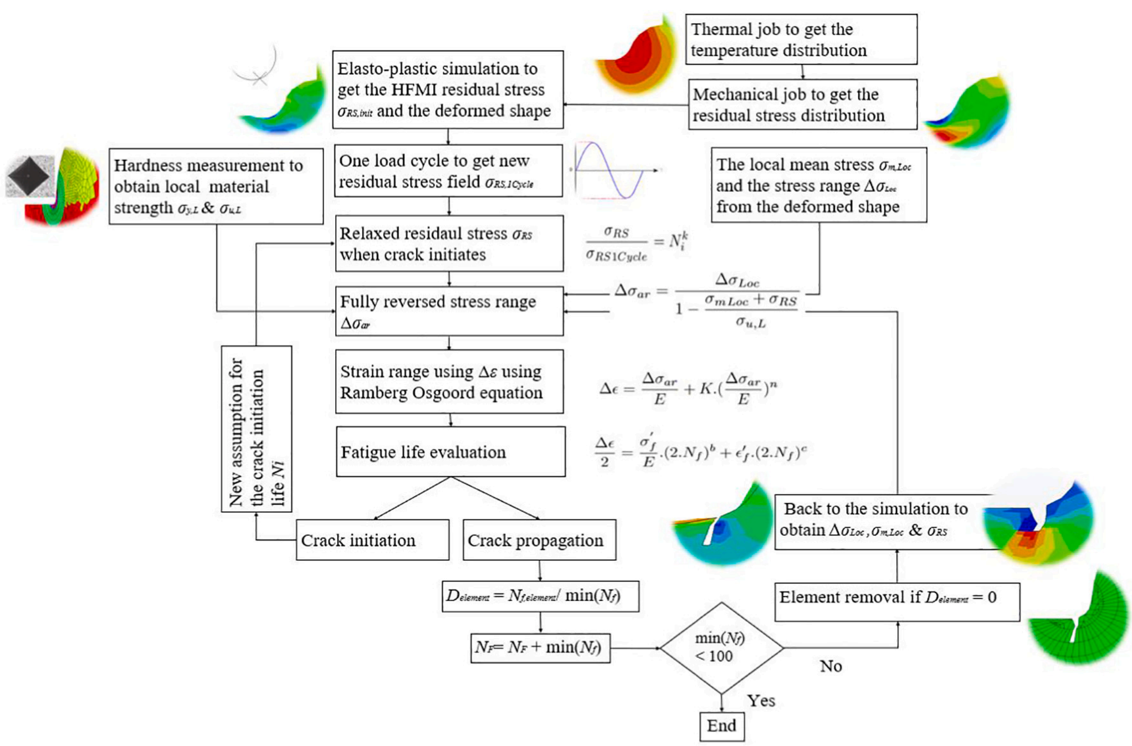

Fig. 7. Flowchart for fatigue life analysis.

given in Eq. (2). $\sigma_{u,L}$ in the equation gives the local ultimate strength obtained from the hardness measurement conducted in [16], the distributions of $\sigma_{u,L}$ after post-weld treatment are shown in Fig. 5.

The distribution of $\Delta\sigma_{ar}$ after the first loading cycle is shown in Fig. 6. Since the elemental stresses can exceed the yield limit, evaluating the local strains are necessary for fatigue life estimation. The strains can then be calculated for each finite element individually using Ramberg-Osgood relation given in Eq. (3). It is mention-worthy that the yield limit which is used to check the plastic strains in the equation is obtained locally for each finite element $\sigma_{y,L}$ from the hardness measurements.

$$\Delta\sigma_{ar} = \frac{\Delta\sigma_{loc}}{1 - \frac{\sigma_{mLoc}+\sigma_{RS}}{\sigma_{u,L}}} \tag{2}$$

$$\Delta\varepsilon = \begin{cases} \frac{\Delta\sigma_{ar}}{E} + K.\left(\frac{\Delta\sigma_{ar}}{E}\right)^n, & \Delta\sigma_{ar} > \sigma_{y,L} \\ \frac{\Delta\sigma_{ar}}{E}, \mathit{Otherwise} \end{cases} \tag{3}$$

Fatigue damage is composed of two main stages: crack initiation and propagation. In this paper, the first stage is defined as the number of cycles required to cause full damage in one of the finite elements in the generated mesh. Crack propagation, on the other hand, is indicated by full damage in subsequent elements. The endurance N_f is calculated by solving Eq. (4) numerically. σ'_f, ε'_f, b, and c in the equation are material dependent coefficients and exponents [21]. Their values for S355 structural steel are given in Table 3. The damage in the finite elements is

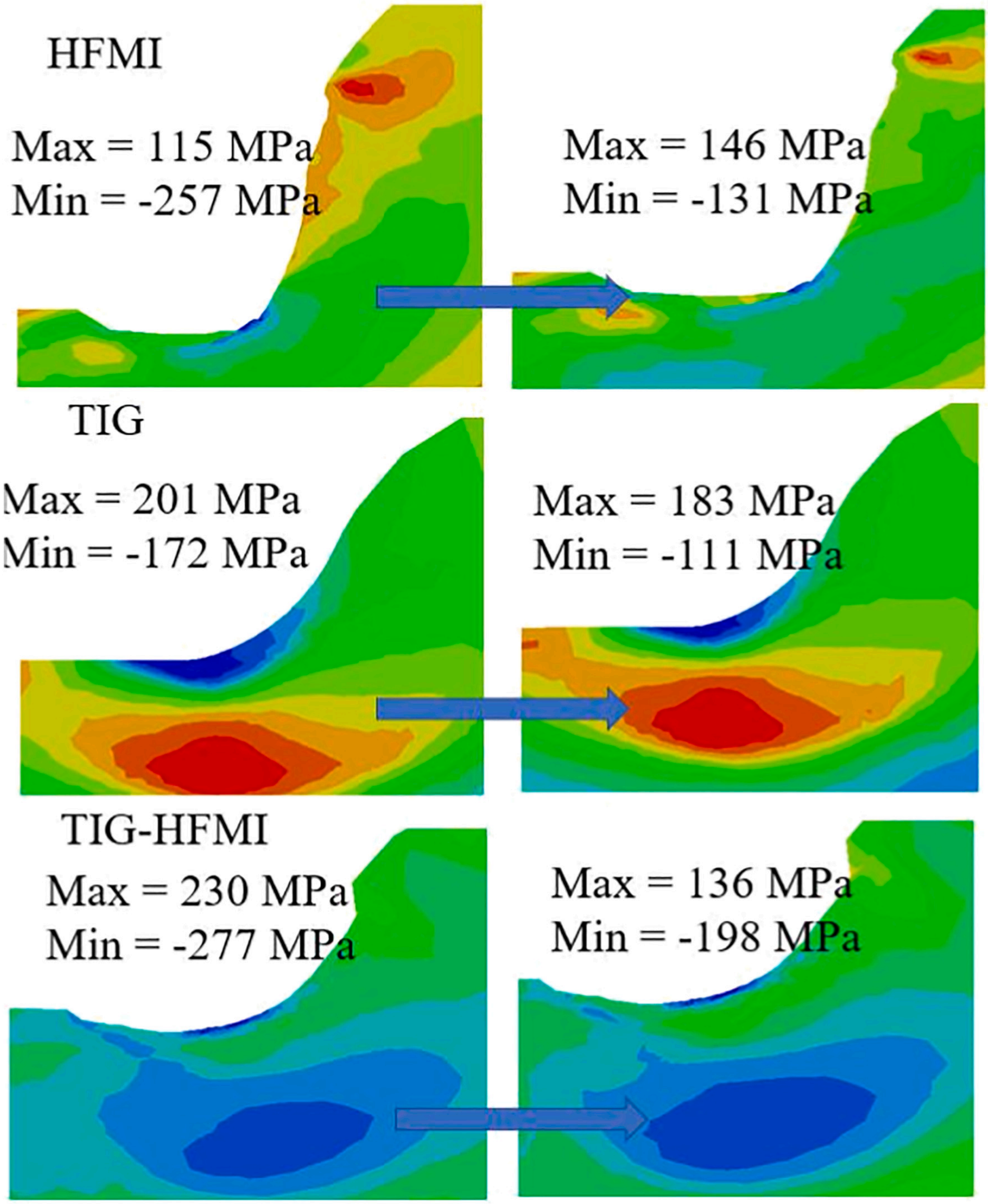

Fig. 8. Relaxation of residual stress after applying one load cycle.

calculated as the ratio between the endurance of each finite element $N_{f,\ element}$ to the endurance of the weakest element. Hence, the damage in the weakest element is equal to 1.0. The damaged element is removed, and crack propagation takes place. It should be remembered that the relaxed residual stress used to evaluate the strain is based on assuming the crack initiation life N_i. Therefore, the assumed life is compared to the obtained life, and the relaxed residual stress is changed when the difference is significant.

$$\Delta\varepsilon = \frac{\sigma_f^{'}}{E}.(2.N_f)^b + \varepsilon_f^{'}.(2.N_f)^c \quad (4)$$

The updated stress fields are acquired (i.e. residual stress, stress range, mean stress) from the FEM simulation considering the removal of the damaged element. Afterwards, $\Delta\sigma_{ar}$ is updated, and new endurance and damage values are calculated. The analysis is terminated when the number of cycles required to cause damage in any element is <100 cycles. This indicates that the remaining fatigue life is negligible. The total fatigue life is then calculated as the summation of the number of cycles required to cause damage in all removed elements. The flowchart shown in Fig. 7 summarizes the described analysis.

3. Results and discussion

The proposed model takes into account several factors which can affect the degree of fatigue life improvements such as residual stress and its relaxation. Furthermore, the deformed geometry as shown in Fig. 8

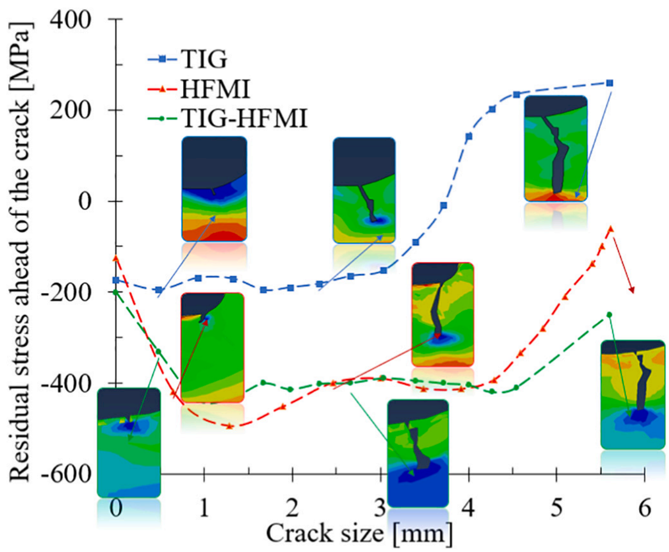

Fig. 9. Residual stress ahead of the crack.

was used in evaluating the local stress range $\Delta\sigma_{Loc}$ and the mean stress σ_{mLoc}. On the material level, the model takes into account the change in material proprieties due to welding (i.e. TIG-remelting) or cold working (i.e. HFMI-treatment) by incorporating the hardness measurements to evaluate the local yield and ultimate strength $\sigma_{u,L}$ and $\sigma_{y,L}$.

The residual stresses change continuously during fatigue loading. This change can be sub-grouped into three intervals. First, remarkable relaxation with more than 30% occurs after the first load cycle as shown in Fig. 8. Afterwards, continuous relaxation takes place during fatigue loading until crack initiation as given in Eq. (1). Subsequently, residual stress changes in conjunction with the crack propagation as shown in Fig. 9. The figures show that the combined TIG-HFMI treatment induces larger compressive residual stress than any of the individual treatments on its own even after relaxation or cracking.

The crack initiates, as expected, from the weld toe despite the introduced σ_{RS} and the reduction in the tensile stress range σ_{ar}. This confirms the results of the literature study conducted by Al-Karawi and Al-Emrani [22] which investigates the failure positions after several post-weld treatments and shows that more than 70% of the studied details fail from the weld toe. Once the crack initiates, the crack propagates to a neighboring element because of two reasons: the accumulated damage from previous steps and the high stresses at the edges of the removed elements. The damage distributions at the end of the analysis for each treatment method are shown in Figs. 10–12. Unlike the individual treatment (HFMI or TIG) distributions shown in Figs. 10 and 11, the damage distribution for TIG-HFMI in Fig. 12 is less spread and localized to fewer elements. This might be attributed to the deep compression field due to applying the HFMI-treatment on smoother topography because of the preceding TIG-remelting.

The conducted analysis described in Fig. 7 is quite simplified as it does not take into consideration several aspects. First, welding residual stress before treatment is disregarded from the analysis. This is motivated by the processes that follow welding (e.g. TIG-remelting, HFMI-treatment, relaxation) which changes the residual stress significantly. However, including welding residual stress does not take into account the phase transformation in the steel due to heat or mechanical treatment. However, the effect is indirectly included as the hardness measurement is incorporated in the definition of σ_{ar}. Furthermore, the assumed crack shape is rather simplified. The realistic crack shape is more pointed and has a tip that may influence the residual stress ahead of the crack.

The number of cycles to failure is plotted versus the size of the crack in Fig. 13. HFMI-treatment is superior because it improves both topography and residual stress. Furthermore, the combined treatment causes remarkable fatigue life enhancement which is around 40% longer than the life of the HFMI-treated detail. The obtained life after HFMI-treatment and TIG-remelting are compared to experimental results obtained from [16].

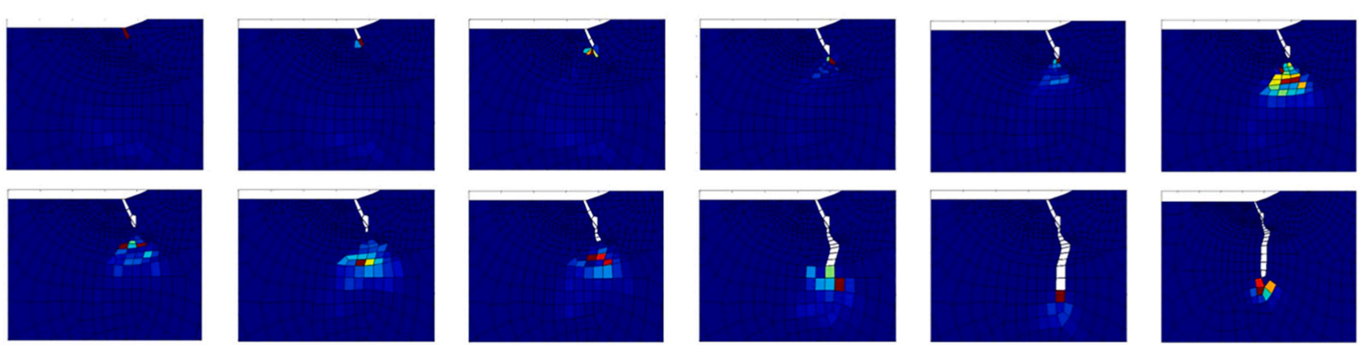

Fig. 10. Damage distributions and elements removal for HFMI-treatment.

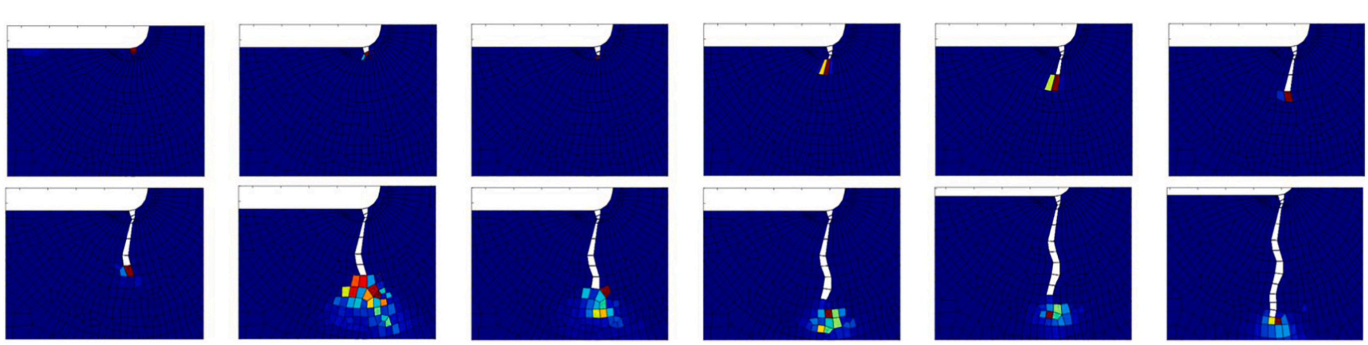

Fig. 11. Damage distributions and elements removal for TIG-remelting.

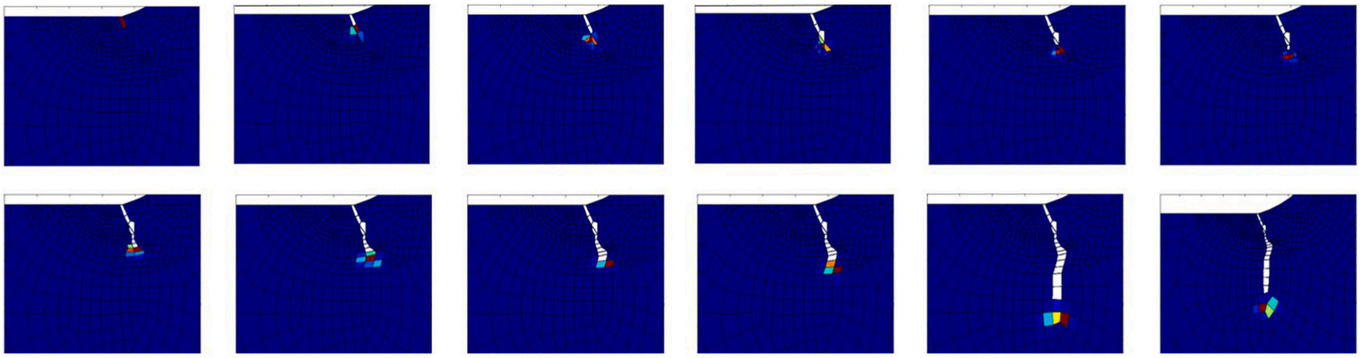

Fig. 12. Damage distributions and elements removal for TIG-HFMI combined treatment.

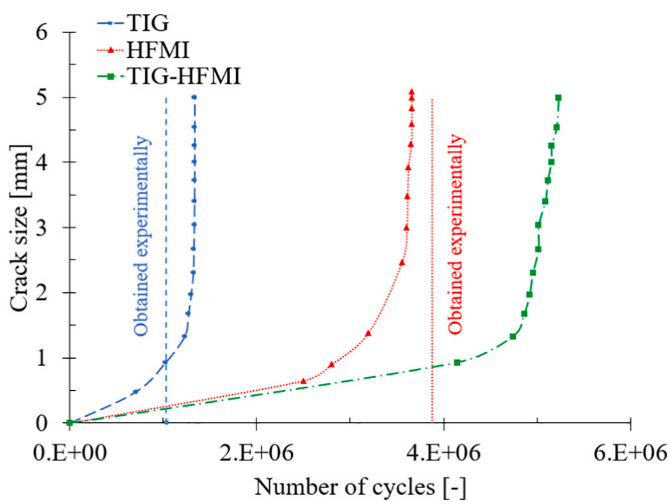

Fig. 13. Number of cycles versus crack size from the analysis, compared to number of cycles to failure obtained experimentally.

TIG-HFMI combination is rarely studied in the literature as a post-weld treatment method as mentioned in Section 1. Fig. 14 shows the available fatigue test results on transverse and longitudinal attachments. The plate thickness ranges from 8 to 20 mm, while the yield strength of the studied steel ranges from 355 to 900 MPa. All available test results lay above the design S—N curves of the treated details according to the IIW recommendations [2,5]. This indicates the efficiency of this combination in enhancing welded details. However, the few available test results urge further experimental investigation on this innovative combination.

In addition to enhancing the strength of the new-manufactured steel details, TIG-HFMI treatment can also be used to repair cracked structures. TIG-remelting can remove existing cracks, providing that the crack size is limited to a specific value [22]. HFMI-treatment removes the possibly generated undercut because of fusion and induces a beneficial compression stress field locally. This field can also retard further crack propagation.

The ability of TIG-remelting in removing cracks is dependent on both the depth of the crack and the depth of fusion, relative to each other. If the crack is deeper, part of the crack would remain after remelting. This might have a detrimental effect on the remaining fatigue life [22]. This effect may be different when combined with HFMI-treatment after remelting. In order to investigate this difference, the improvement in fatigue life of cracked details treated by either TIG-remelting or combined treatment is investigated. The evaluation differs from the procedures shown in Fig. 7 in two aspects. First, the studied detail contains a 3 mm crack. Fusion depth of 1.75 mm is selected in accordance with conducted metallurgical analysis, see Fig. 15. Therefore, several finite elements are removed underneath to simulate the remaining crack which is 1.25 mm deep as shown in the same figure. In this analysis, no relaxation of residual stresses is considered since the detail is already cracked, and the change in residual stress would be mainly attributed to crack propagation; this forms the second difference. Besides these two aspects, the rest of the analysis procedures are the same as described in Fig. 7.

For both treatment methods (i.e. TIG-remelting and combined treatment), the cracks do not re-initiate from the weld toe, but instead, they propagate upward from the remaining crack despite the tension stress field underneath. That might be explained by the closeness of the upper tip to the surface where the stress concentration factors are larger. Afterwards, the cracks propagate quickly within a few hundred cycles downwards. The damage distributions of cracked details after TIG-remelting and combined treatment are plotted in Figs. 16 and 17 respectively. In both figures, the damage is more distributed than the ones shown in 11 and 12 because cracks already exist below the surfaces.

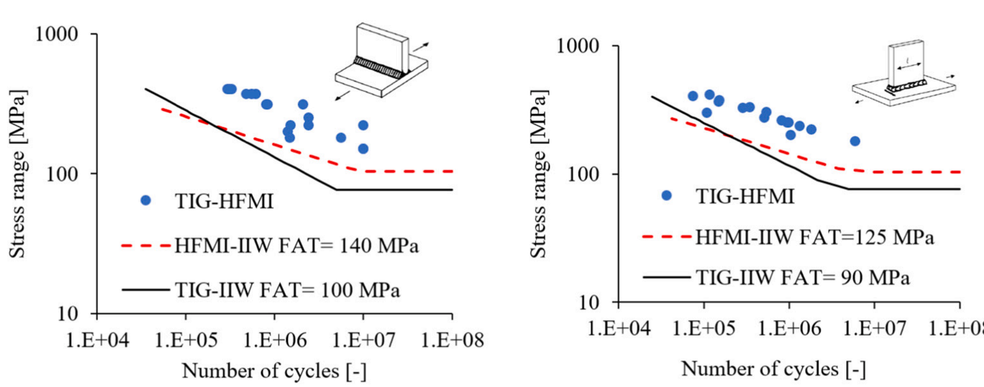

Fig. 14. Fatigue test results of transverse and longitudinal attachment [6,13–15].

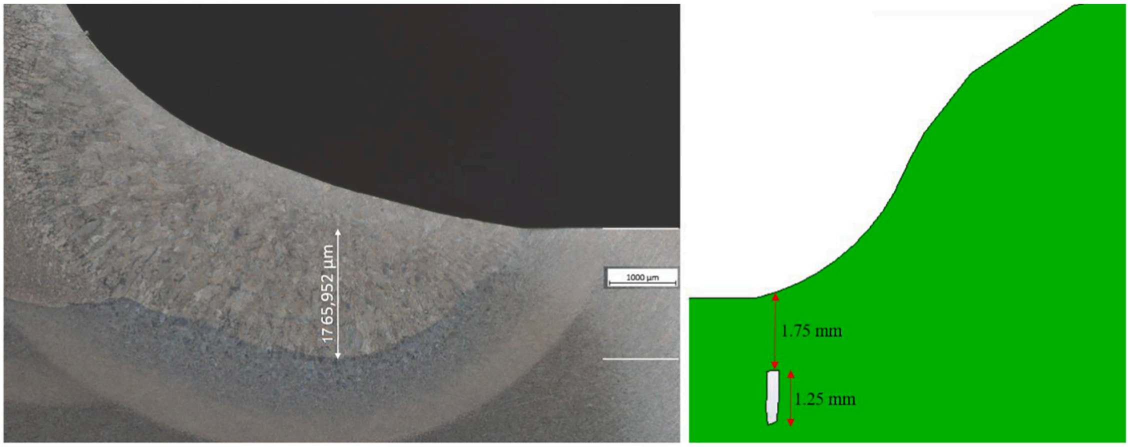

Fig. 15. TIG fusion depth R: measured metallurgically L: considered in the analysis.

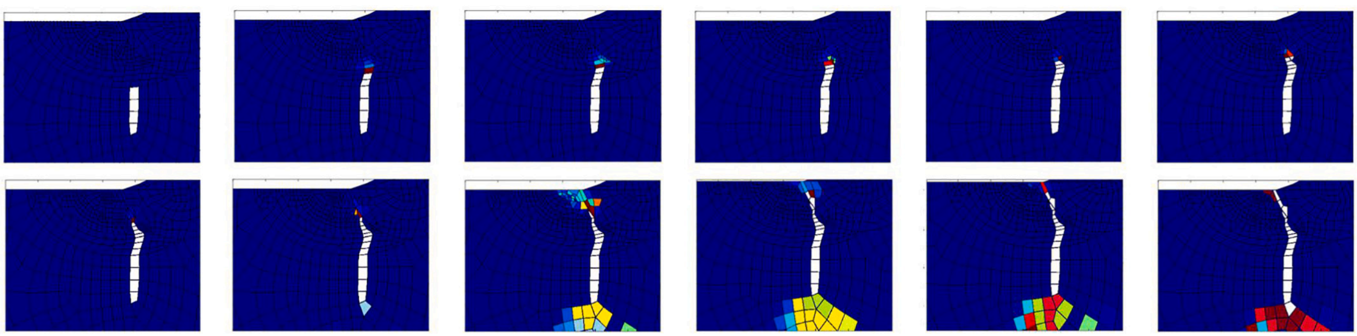

Fig. 16. Damage distribution of cracked detail and elements removal for TIG-remelting.

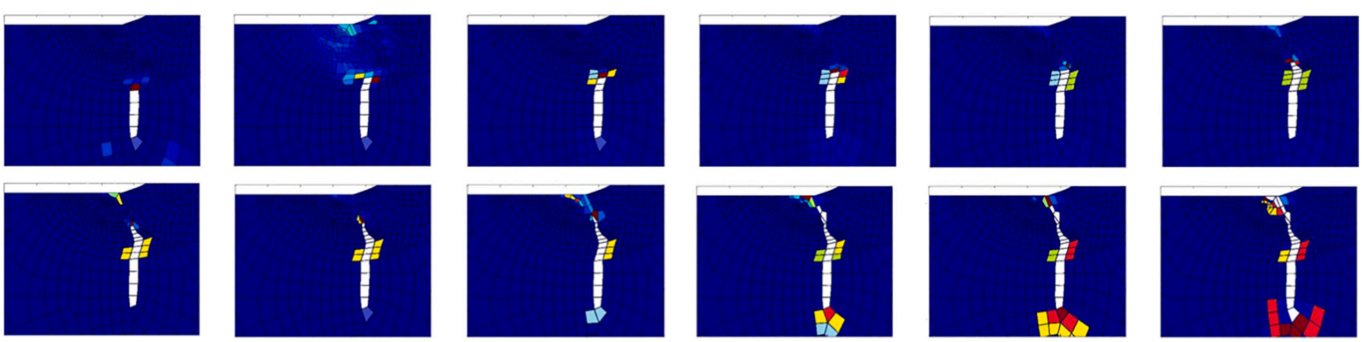

Fig. 17. Damage distributions of cracked detail and elements removal for TIG-HFMI combined treatment.

The crack propagation curves are shown in Fig. 18. The change in the curve slope indicates the switch in crack propagation from upward (i.e. toward the toe) to downward. The figure shows clearly that the remaining fatigue life after TIG-remelting is quite short (<20,000 cycles). This is because the main effect of TIG-remelting in increasing the fatigue life, which is due to the improvement in the topography at the weld toe, becomes insignificant as the crack propagates from another spot.

On the other hand, the combined treatment is more efficient because of the introduced compression at remaining crack tips as shown in Fig. 18. Fig. 19 compares the fatigue life of new and cracked details treated by both methods. Remarkably, the crack effect on the combined treated detail is not significant because of the induced compression at the crack tips. However, this effect diminishes if the embedded crack is deeper than 2.25 mm as shown in Fig. 20. The figure also indicates that the introduced beneficial compressive residual stress depends on the remaining crack size and position. Therefore, further investigations are needed to explore the limitations of the combined treatment in repairing cracked structures. In the meantime, TIG-HFMI treatment is recommended when full crack closure is guaranteed.

TIG remelting is generally associated with higher cost and more skilled labour in comparison to HFMI-treatment. Therefore, it is economic to decide when each treatment is necessary. In practice, applying HFMI-treatment after TIG-remelting should not be a problem as it is easy to operate, light in weight, relatively cheap and fast in treatment. In any way, non-destructive testing (NDT) is needed to inspect the existence of the crack at the surface when the treatment is to be applied on an existing structure. One of the simplest NDT methods that can be used to reveal surface cracks in metallic structures is to apply dye penetrant, see Fig. 21. If the NDT is negative, then HFMI-treatment can be used without

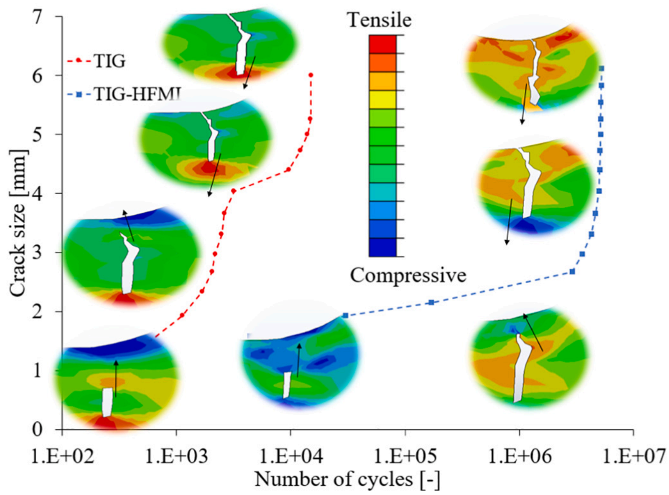

Fig. 18. Fatigue lives of details treated by TIG-remelting or TIG-HFMI treatment.

previous remelting as there is no crack to be fused. Otherwise, similar welded detail should be manufactured, and treated by TIG-remelting with specific parameters (i.e. treatment speed, voltage, current and heat input). Afterwards, metal inspection is needed to assess the sufficiency of the fusion depth in relation to the existing crack size. If the fusion depth is larger, then TIG-remelting can be applied to the structure. HFMI-treatment can then be applied to put the area under compression and remove the newly formed undercut. For other cases, when the closure of the existing crack cannot be guaranteed, further investigation on TIG-HFMI treatment is needed to verify the capability of this treatment in inducing compression at both remaining crack tips. It is noteworthy that the NDT used must be able to detect a 2 mm crack with a high probability of crack detection [23]. The flowchart in Fig. 22 summarizes the mentioned procedures.

The combined TIG-HFMI treatment should be applied with caution. In other words, some practical issues should be taken into account as follow:

- TIG remelting should never be performed after HFMI-treatment because it may eliminate the beneficial effect of HFMI-treatment (i. e. compressive residual stress relief).
- Large HFMI indenter size should be used to preserve the improvement in the local topography achieved by remelting, see Fig. 23.

Here are some additional recommendations when the combined treatment is to be used to treat existing details that may contain cracks:

- Tungsten arc should be placed right at the weld toe even if this practice leads to new undercut formation. However, deeper fusion would be guaranteed. Thereby, this would lead to a higher possibility of crack removal. Nonetheless, the IIW recommends directing the electrode more toward the base metal to get the optimum shape and avoid new undercut formation [5]. However, full crack removal, if crack exists, should be prioritized over weld shape optimization, see Fig. 24.
- HFMI indenter must be inclined to the base plate as shown in Fig. 25. The position of impact should not be a problem if the structure is

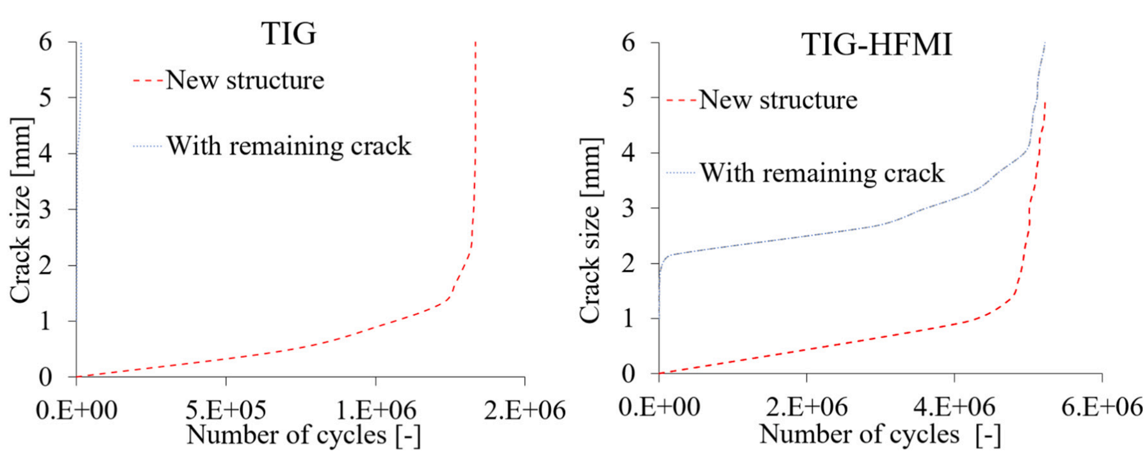

Fig. 19. Comparison between fatigue life of new and cracked details treated by TIG-remelting and combined treatment.

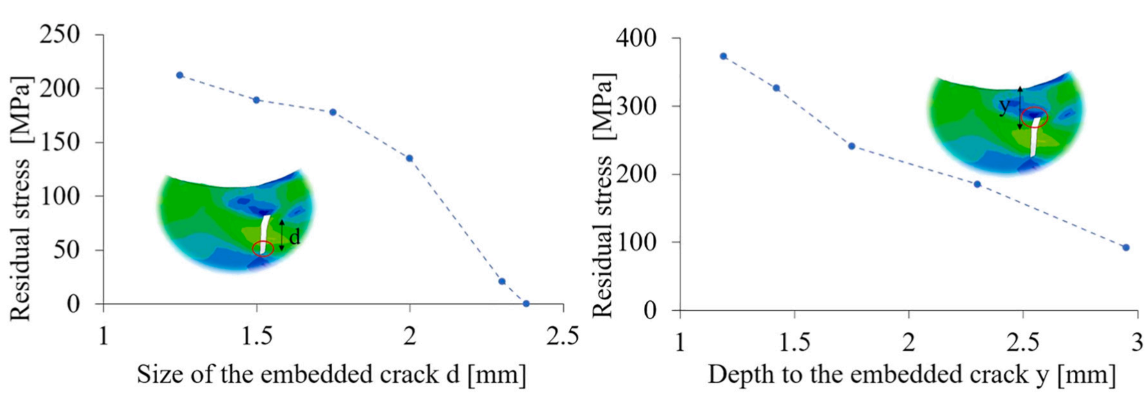

Fig. 20. Embedded crack size effect on the compressive residual stress.

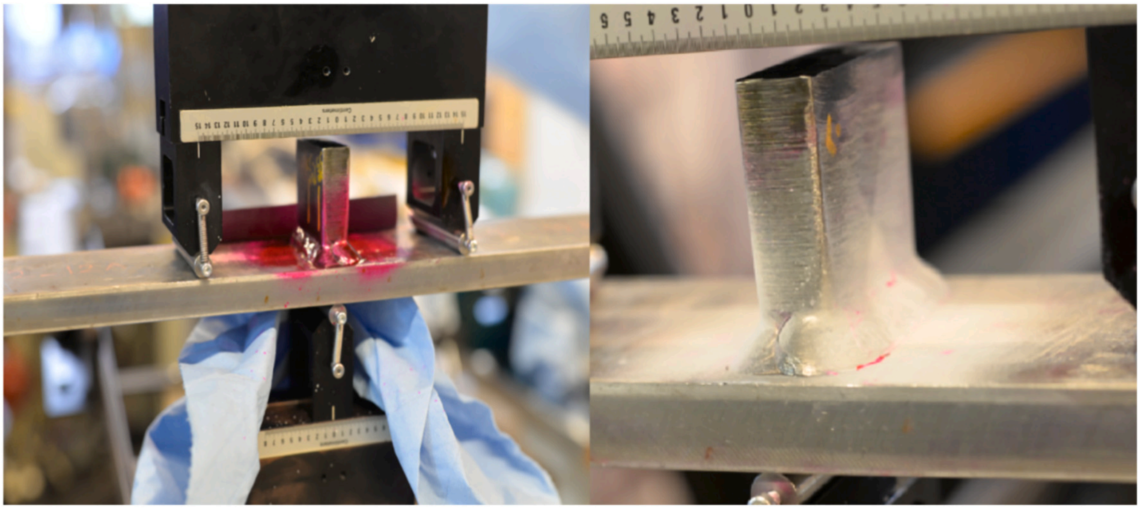

Fig. 21. Cracks revealed by applying red dye penetrant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

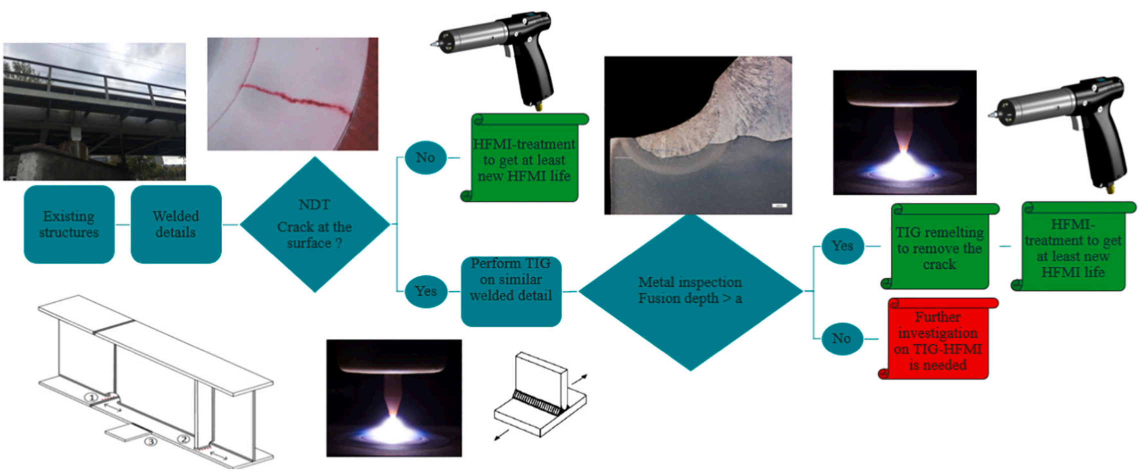

Fig. 22. Flowchart for the studied post-weld treatment of existing structures.

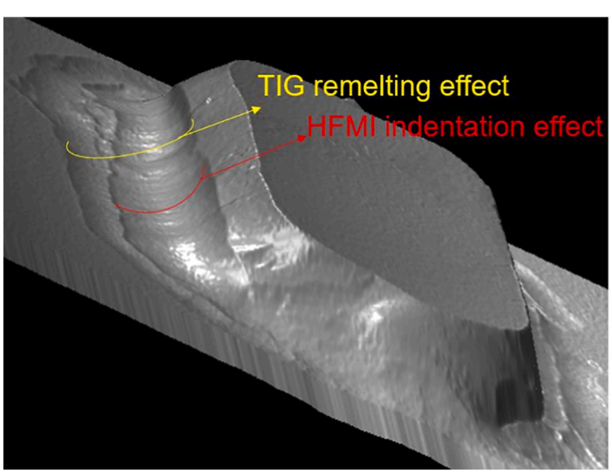

Fig. 23. Large HFMI indenter preserves the improvement in toe radius.

crack-free. However, this practice causes material flow toward the remaining crack, if any remains, and contributes to crack closure.

- The depth of indentation should be large enough to cause crack closure, see Fig. 26. The IIW recommends that it should not be <0.2 mm [2]. However, the required depth might be larger to cause full crack closure [24]. Moreover, the TIG fusion depth should be large enough to remove the whole crack.

4. Conclusions

The paper in hand presents a numerical investigation on an innovative combination of two post-weld treatment methods which are HFMI-treatment and TIG-remelting. A Coupled thermo-mechanical analysis is used to model the TIG process and a mechanical analysis is conducted to simulate the HFMI-treatment. The fatigue life is then estimated using a strain-based approach and successive deletion of the damaged elements. Different factors are considered in the analysis to include the post-weld treatment effects such as residual stress relaxation, topography improvement and local hardness change. The analysis enables drawing the following conclusions:

- The analysis shows that the combined treatment results in longer fatigue life than any of the individual treatments. Moreover, fewer

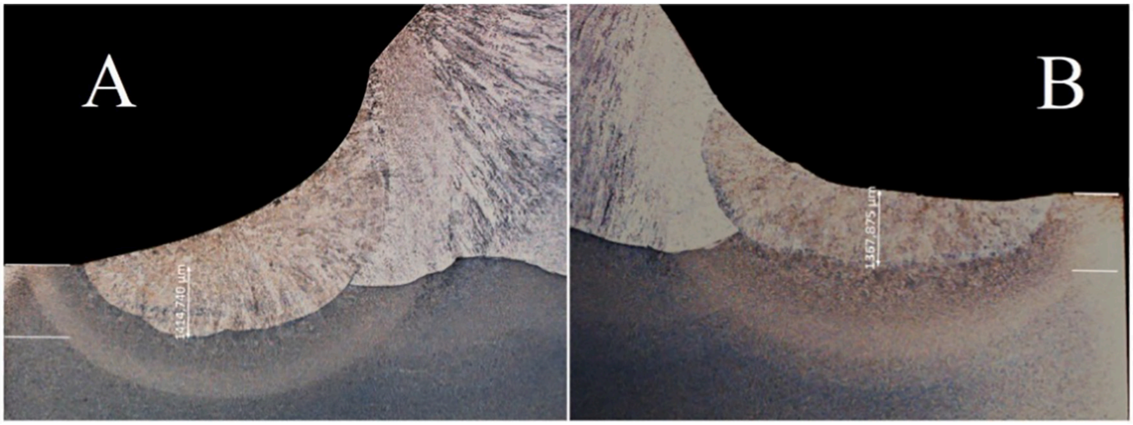

Fig. 24. Fusion depth when the TIG electrode is placed A: Directly at the weld toe B: according to the IIW recommendations [5].

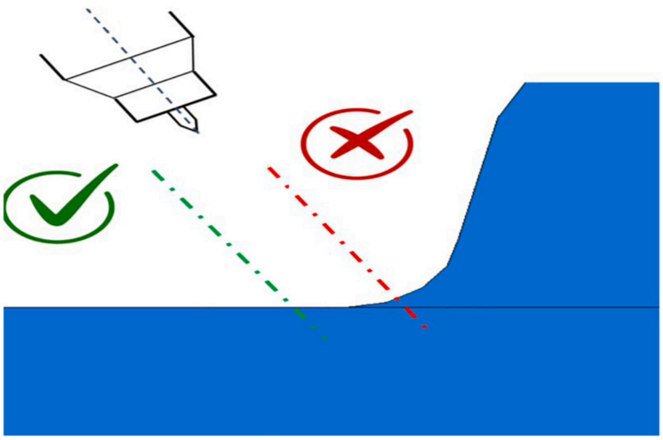

Fig. 25. HFMI indenter optimum positioning.

finite elements are found to be damaged after propagation when both treatments are applied.

- The obtained fatigue lives are found to be 1.33, 3.67 and 5.23 million cycles after TIG-remelting, HFMI-treatment, and the combination of both respectively. The maximum compressive residual stresses at the weld toe before relaxation are found to be 172, 257 and 277, MPa respectively.
- The combined treatment can be used for either increasing the fatigue life of new details or extend the life of existing details. For the latter case, non-destructive testing is required to check the capability of TIG-remelting in removing the whole crack.
- The analysis shows that the remaining crack has detrimental effects on the enhanced detail by TIG-remelting. On the contrary, the TIG-HFMI combination gives a significantly long fatigue life even with remaining crack up to 2.25 mm deep.
- When applied to cracked details, TIG arc should be positioned right at the weld toe to achieve deep fusion, while HFMI indenter should be inclined to the base plate to cause material flow toward the crack. Besides, the depth of indentation should be larger than 0.2 mm to induce enough compression.
- More investigations are needed to approve the use of the combined treatment in enhancing both new and in-service welded steel details. Furthermore, the accuracy of the numerical investigation can be improved by including the welding residual stress, steel phases transformation and more realistic crack shape in fatigue life estimation.

Author statement

There is only one author for this manuscript who is responsible for everything in it.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

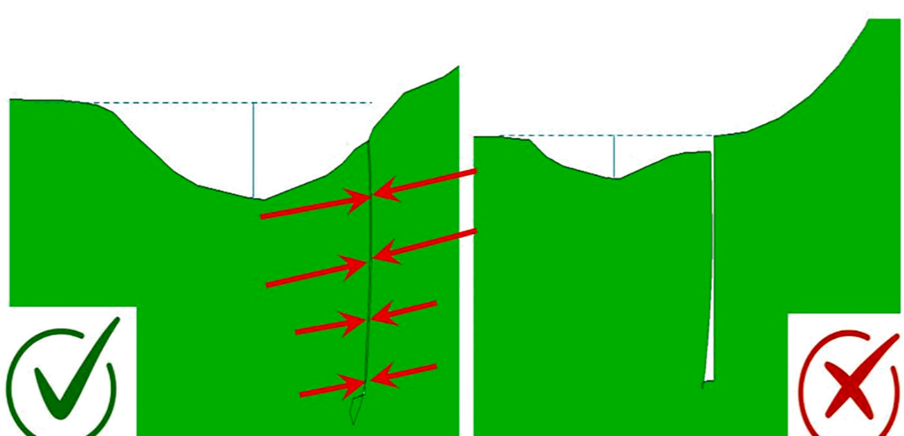

Fig. 26. L: Enough indentation depth to cause crack closure R: Insufficient indentation depth leaves the crack open.

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