The efficiency of HFMI treatment and TIG remelting for extending the fatigue life of existing welded structures

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Different post-weld treatment methods have been developed to enhance the fatigue strength of welded steel structures and extend the service lives of their components. High-frequency mechanical impact (HFMI) treatment and tungsten inert gas (TIG) remelting are two methods that have attracted considerable interest in recent decades. This paper presents the results of a study of fatigue life extension for pre-fatigued welded steel details which can be achieved using HFMI treatment and TIG remelting. More than 250 fatigue test results were collected – including different details such as butt welds, longitudinal attachments, transverse attachments and cover plate attachments. HFMI treatment was found to extend the life considerably when the specimens treated were free from cracks or when existing cracks were < 2.25 mm deep. TIG remelting could extend fatigue lives even with cracks > 4 mm deep. In comparison to TIG remelting, HFMI treatment results in a longer fatigue life extension for pre-fatigued details, provided existing cracks are < 2.25 mm deep. Regarding TIG remelting, the depth of possible remaining cracks was found to be a substantial parameter when assessing the degree of life extension.

Keywords high-frequency mechanical impact; fatigue life extension; TIG remelting; allowable crack size; pre-fatigue

1 Introduction

Increasing traffic loads combined with the ageing of materials make fatigue of steel joints a major concern for transportation authorities in Europe, which currently manage a large stock of metallic bridge infrastructures. Fatigue is often the main cause of cracks detected in steel bridge members and connections. In the 20th century (when welds were first introduced into the bridge industry) the limited knowledge about the fatigue phenomenon and the behaviour of fatigue-prone details in welded structures have been among the main causes of fractures and failures. As the awareness of fatigue in welds increased, so bridge engineers started to take fatigue into consideration when designing new steel bridges [1]. However, more than two-thirds of the bridges in Europe were constructed more than 50 years ago [2]. This means that these bridges require either replacement or retrofitting.

Different post-weld treatment methods have been developed for both extending the fatigue life of existing welded components and repairing details with existing fatigue cracks. These methods can be divided into two main groups according to their effecting mechanisms: residual stress and local geometry improvement methods. High-frequency mechanical impact (HFMI) treatment and tungsten inert gas (TIG) remelting are examples of the former and latter groups respectively. HFMI treatment induces a compressive residual stress at the weld toe and places possible existing cracks in compression, whereas TIG remelting enhances the local geometry at the weld toe and removes – fully or partially – any existing cracks through remelting and fusion. Fig. 1 shows the weld toe profiles of as-welded weld and welds treated by means of TIG arc and HFMI indenter.

High-frequency mechanical impact (HFMI) is a relatively new post-weld treatment method. The main beneficial effect of HFMI treatment is to replace the tensile welding residual stresses -dominant in the weld toe region – by compressive residual stresses. In addition, it decreases the notch effect and increases the local hardness. Extensive research efforts have been made to study the effect of HFMI treatment on the fatigue performance of new and in-service welded structures [3]–[13]. In some studies, HFMI treatment efficiency decreased as a function of fatigue life before treatment [12]. Moreover, some other studies suggested an inverse correlation between the sizes of existing cracks before treatment and the degree of fatigue life extension achieved via this treatment method [3]. However, the conclusions regarding the crack depth after which HFMI treatment loses its efficiency differ considerably in different studies, with values ranging from 0.5 to 3 mm [14].

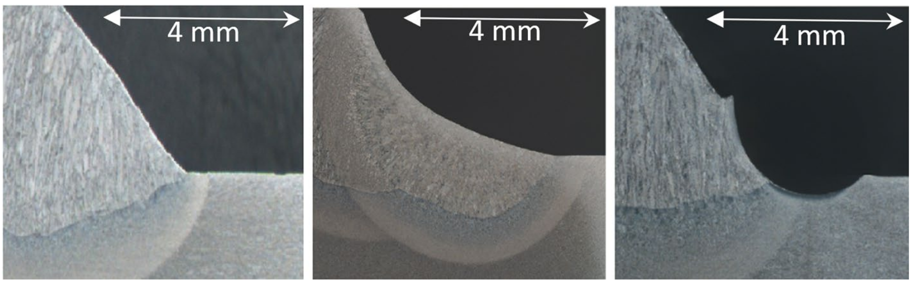

Fig. 1 Micrographs of welded structures in (left to right) as-welded, TIG and HFMI conditions

TIG remelting removes any existing cracks or flaws by fusing the material in the vicinity of the weld toe. It also reduces the sharpness of the weld toe, thus increasing the toe's smoothness [15]. Furthermore, TIG remelting might change the status of residual stresses and the local hardness in the toe region [16]. Yildirim found a step-wise increase in the fatigue strength of different virgin (i.e. non-pre-fatigued) welded details when using TIG remelting, with a proposed fatigue strength curve slope equal to 4 [17]. Moreover, several research papers ([4], [16], [18]) stated that the life extension achieved by TIG remelting depends on the fusion depth in relation to the depth of possible existing cracks. The fusion depth is a function of TIG arc parameters such as voltage and heat input [18].

The use of HFMI treatment and TIG remelting for extending fatigue life has attracted a good deal of interest from engineers and researchers. However, an integrated framework for the validity and efficiency of these methods for treating different pre-fatigued welded details is still lacking. Therefore, this paper aims to draw firm conclusions regarding the allowable maximum number of cycles (i.e. pre-fatigue cycles) or the allowable maximum crack size at which the treatment can still achieve a considerable fatigue life extension. The efficiency of HFMI treatment and TIG remelting in extending the fatigue life of existing structures was studied for the first time using more than 250 data points published in different articles. Moreover, the effect of combined TIG-HFMI treatment on fatigue life extension has also been examined.

2 Methodology

2.1 Fatigue dataset

More than 250 fatigue test results were extracted from research papers dealing with fatigue testing on pre-fatigued welded steel joints and treated with either HFMI treatment or TIG remelting. The results extracted were either tabulated or presented in fatigue strength curves in the papers and are plotted for each type of detail individually in Figs. 2, 3, 4 and 5. In the figures, *Nf* is the number of cycles to failure. The references of the pre-fatigued specimens test results (i.e. denoted in the figures by the red, green and blue dots) are presented in Tab. 1 and Tab. 2. Moreover, test results of treated virgin specimens were extracted from [4], [6], [9], [12], [17] and [19]–[25] and included in the same figures (denoted by the black and orange data points).

In the figures, no distinction is made based on the failure position, mean stress, stress ratio, pre-fatigue cycles, crack size, steel quality or plate thickness. The characteristic S-N curves of the as-welded details obtained from EN 1993-1-9 [26] are indicated by the black solid curves in the figures. For transverse and longitudinal attachments, the pre-fatigued treated specimens given by the red, green and blue dots lay within the scatter band of the virgin ones. The resistance of the longitudinal attachments was found to be more scattered because of its dependency on the attachment length. The only one pre-fatigued HFMI data point lying below the as-welded characteristic curve for a longitudinal attachment corresponds to a specimen containing a long visible surface crack.

Fewer test results were available for butt welds and cover plate details. For butt welds, the pre-fatigued treated specimens are remarkably stronger than the virgin ones. A few data points of pre-fatigued HFMI-treated cover plate attachments lie below the characteristic curves as they contain relatively deep cracks (i.e. > 2 mm deep). To the best of the authors' knowledge, there are no tests results available for pre-fatigued TIG-treated butt-welded details. Furthermore, the use of combined TIG-HFMI treatment is still limited to transverse and longitudinal attachments.

Using the S-N curves to evaluate the efficiency of the treatment methods studied for fatigue life extension in existing structures is partially ineffective for several reasons. Firstly, it does not take into account different fac-

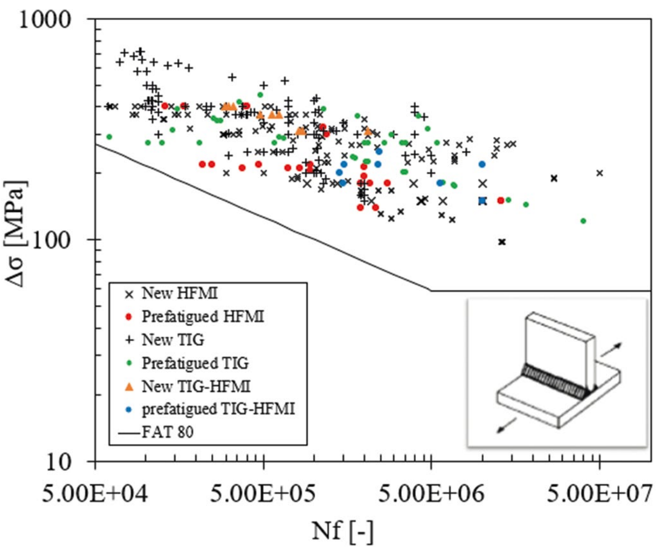

Fig. 2 Fatigue test results for treated transverse attachment

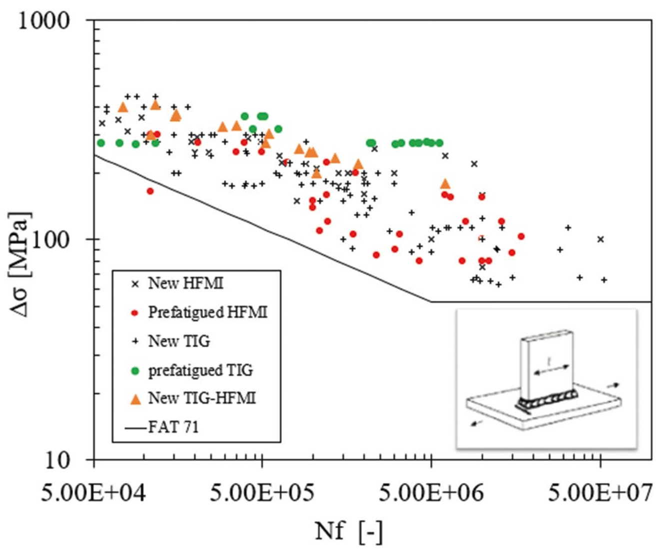

Fig. 3 Fatigue test results for treated longitudinal attachment

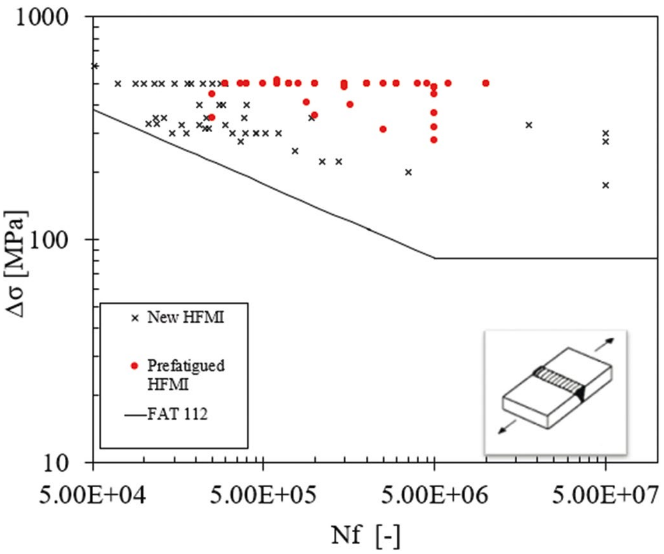

Fig. 4 Fatigue test results for treated butt-welded attachment

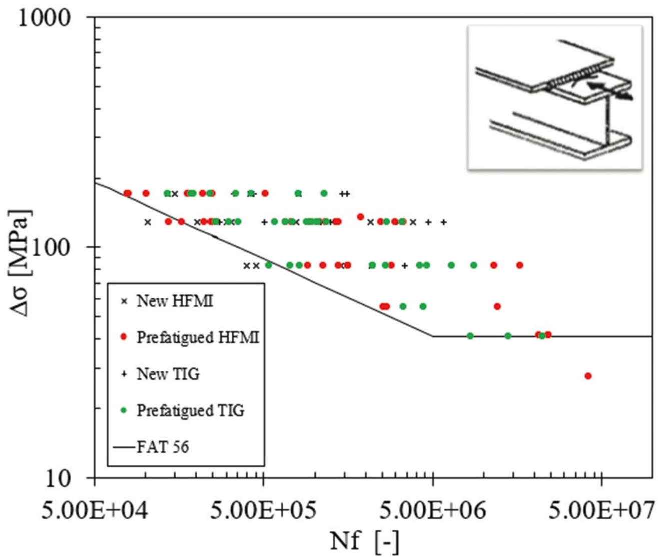

Fig. 5 Fatigue test results for treated cover plate attachment

tors such as R-ratio, steel quality and plate thickness, which have a proven effect on the efficiency of HFMI treatment [27]. Moreover, no conclusion about the effect of loading history (i.e. pre-fatigue cycles or crack size) can be made using this evaluation approach. In fact, the only conclusion that can be drawn is that the use of these treatment methods can restore at least the characteristic life of the detail. Based on these reasons and in order to incorporate the aforementioned effects, the efficiency of the treatment methods is studied in this paper using the gain factors in fatigue life.

2.1.1 Extracted HFMI treatment fatigue data

About 130 data points extracted from 13 datasets were collected and reviewed, see Tab. 1, which includes the references for the collected data. The dataset consists of fatigue tests on different types of specimen with different steel qualities, and tests were conducted with different stress ratios. The data includes details with long transverse welds (transverse attachments, butt welds and cover plate details) and weld ends (longitudinal attachments). The data pool was divided into two main categories depending on the determination of crack size before HFMI treatment. The first category comprises all tests on specimens that contained fatigue cracks of known depth prior to HFMI treatment. Two sub-groups are distinguished in this category. In the first one (group 1.1), the fatigue cracks were authentic (i.e. generated through fatigue testing), with crack sizes estimated by one or more crack detection methods. In the second subgroup (group 1.2), cracks were generated artificially by electrical discharge machining and no fatigue tests were conducted before treatment.

Specimens in the second category (group 2), were all pre-fatigued up to a given number of cycles, but no information on existing cracks was provided, either because the

Tab. 1 Experimental fatigue data for pre-fatigued welded joints improved by HFMI treatment

Ref	Group	Crack detection	Thickness (mm)	Detail type	*a* (mm)	f_y (–)
[9,10]	1.2	Artificial crack	5	Butt weld	1.0–1.5	307
[9,11]	1.2	Artificial crack	20	Butt weld	0.4–1.6	371
[28]	1.2	Artificial crack	14	Longitudinal	0.4	321
[3]	1.1	Strain gauge	12.5	Transverse	1.3–6.1	410
[13]	1.1	ACPD	30	Longitudinal	0.5–1.5	390
[6]	1.1	Strain gauge	305	Longitudinal	1.0	355
[4]	1.1	Ultrasonic testing	14	Cover plate	1.5–3.0	252
[29]	1.1	Strain gauge	16	Transverse	0.6–1.2	355
[8]	2.1	Dye penetrant	20	T-joint	Not known	460
[12]	2.1	–	15	Butt weld	Not known	790
[30]	2.1	Dye penetrant	31	Cover plate	Not known	398
[7]	2.1	–	20	Transverse	Not known	260
[4]	2.2	Dye penetrant	14	Cover plate	Not known	252

Tab. 2 Experimental fatigue data for pre-fatigued welded joints improved by TIG remelting

Ref	Group	Crack detection	Thickness (mm)	Detail type	Remaining crack	f_y (–)
[18]	3.1	Ultrasonic testing	15	Longitudinal	Yes	590
[18]	3.1	Ultrasonic testing	15	Transverse	Yes	590
[18]	3.2	Ultrasonic testing	15	Transverse	No	590
[31]	3.2	Ultrasonic testing	15	Transverse	No	590
[16]	3.2	Strain gauge	16	T-joint	No	355
[18]	3.2	Strain gauge	30	Longitudinal	No	390
[4]	3.3	Ultrasonic testing	14	Cover plate	Not known	252
[4]	4.1	Dye penetrant	14	Cover plate	Not known	252
[16]	4.1	Dye penetrant	15	Longitudinal	Not known	590
[18]	4.1	Dye penetrant	15	Transverse	Not known	590
[32]	4.1	Dye penetrant	31	Transverse	Not known	360
[30]	4.1	Dye penetrant	31	Cover plate	Not known	398

pre-fatigued phase was terminated before crack initiation or because no crack measurements were conducted (or reported) at the end of this phase. Also here, the second category was divided into two subgroups. Group 2.1 contains tests for which the fatigue lives or strengths of the as-welded details were known from fatigue testing of similar specimens, whereas no fatigue tests were conducted on as-welded specimens in group 2.2. In some studies, dye penetrant was applied to check the crack length before HFMI treatment in group 2. However, no information about the presence of cracks or the crack length was reported. An overview of all tests used in the evaluation of HFMI treatment is given in Tab. 1. The number of fatigue tests in each subgroup is given in Fig. 6.

2.1.2 Extracted TIG remelting fatigue data

In total, about 130 fatigue tests on welded specimens treated by TIG remelting were collected from several publications. The data pool includes three detail types: transverse attachment, longitudinal attachment and cover plate details. The steel qualities of the details studied range from 250 to 590 MPa. Similarly to the HFMI dataset, the TIG data were divided into two main groups depending on the determination of crack size before remelting. The first group was divided into three subgroups depending on the presence of cracks remaining after TIG remelting. In the first subgroup (group 3.1), the existing fatigue cracks were not completely removed after TIG treatment and the remaining crack size was measured. Contrasting with this, the cracks were completely removed in the second subgroup (group 3.2) and this was assured by crack detection or metallurgical analysis. In the third subgroup (group 3.3), no crack detection was performed after TIG remelting. Group 4.1 includes tests in which no crack detection was conducted after or even before TIG remelting (see Fig. 7). Tab. 2 presents some information on the extracted datasets with respect to the detail types, crack sizes, pre-fatigue lives and steel qualities.

2.2 Evaluation of the efficiency of the treatment methods studied

In order to quantify the benefit of HFMI treatment or TIG remelting for extending the fatigue life of pre-fatigued

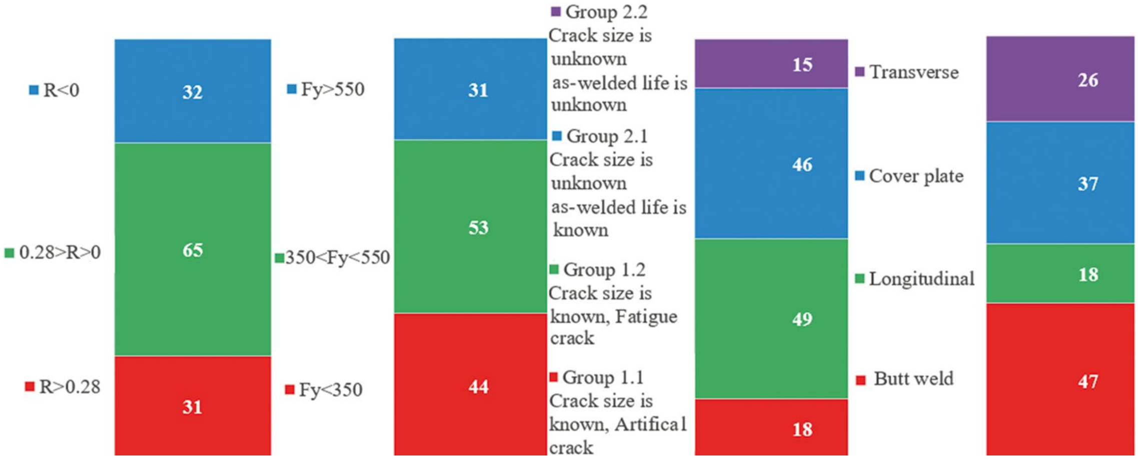

Fig. 6 The distribution of the R-ratios, steel qualities, different subgroups and detail types in the extracted HFMI data points

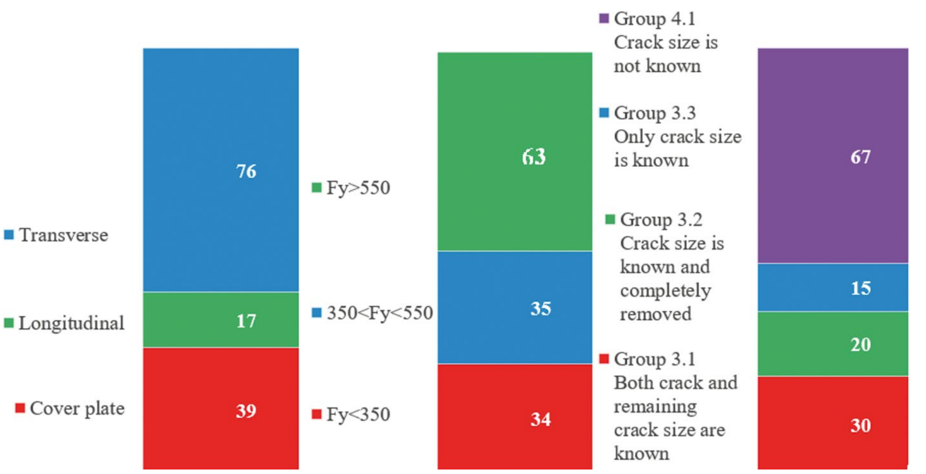

Fig. 7 Distribution of the details, steel qualities and subgroups studied for the TIG data points extracted

welded structures, two gain factors were introduced for fatigue life. The first gain factor ($G1$) is the ratio between the fatigue life of the repaired specimen obtained from testing $N_{Ext,HFMI}$ or $N_{Ext,TIG}$ divided by the experimental pre-fatigue life before treatment N_{pre} normalized to the ratio of the characteristic life of the treated detail $N_{IIW,HFMI}$ or $N_{IIW,TIG}$ to the characteristic life of the as-welded detail $N_{IIW,AW}$ (see Eqs. (1) and (2)). Factor $G1$ was used to evaluate tests results in groups where N_{pre} figures were available.

In order to make the evaluation more generic even in the absence of N_{pre}, another gain factor ($G2$) was introduced. Factor $G2$ is the ratio of the life of the repaired specimen to the characteristic as-welded life $N_{IIW,AW}$ normalized to the ratio of the characteristic life of the treated detail $N_{IIW,HFMI}$ or $N_{IIW,TIG}$ to the as-welded detail $N_{IIW,AW}$ (see Eqs. (3) and (4)). Alternatively, $G2$ expresses the ratio of the life of the repaired detail to the characteristic life of the treated detail. All characteristic design lives in $G1$ and $G2$ formulae ($N_{IIW,AW}$, $N_{IIW,HFMI}$ and $N_{IIW,TIG}$) were obtained from the fatigue strength curves of different details given in the International Institute of Welding IIW recommendations ([15], [27], [33]). When calculating the characteristic life, the reduction in fatigue strength due to plate thickness, steel quality and stress ratio effects was taken into account in accordance with the recommendations [27].

$$G1_{HFMI} = \frac{N_{Ext,HFMI}/N_{pre}}{N_{IIW,HFMI}/N_{IIW,AW}} \quad (1)$$

$$G1_{TIG} = \frac{N_{Ext,TIG}/N_{pre}}{N_{IIW,TIG}/N_{IIW,AW}} \quad (2)$$

$$G2_{HFMI} = \frac{N_{Ext,HFMI}/N_{IIW,AW}}{N_{IIW,HFMI}/N_{IIW,AW}} \quad (3)$$

$$G2_{TIG} = \frac{N_{Ext,TIG}/N_{IIW,AW}}{N_{IIW,TIG}/N_{IIW,AW}} \quad (4)$$

3 Results

The location of fatigue failure after treating pre-fatigued specimens varied across the dataset (see Fig. 8). More than 30 % of the data collected for both treatment methods did not show toe failure. Failures of the weld root were reported for both treatment methods. In some cases, failures in the base metal close to the locations

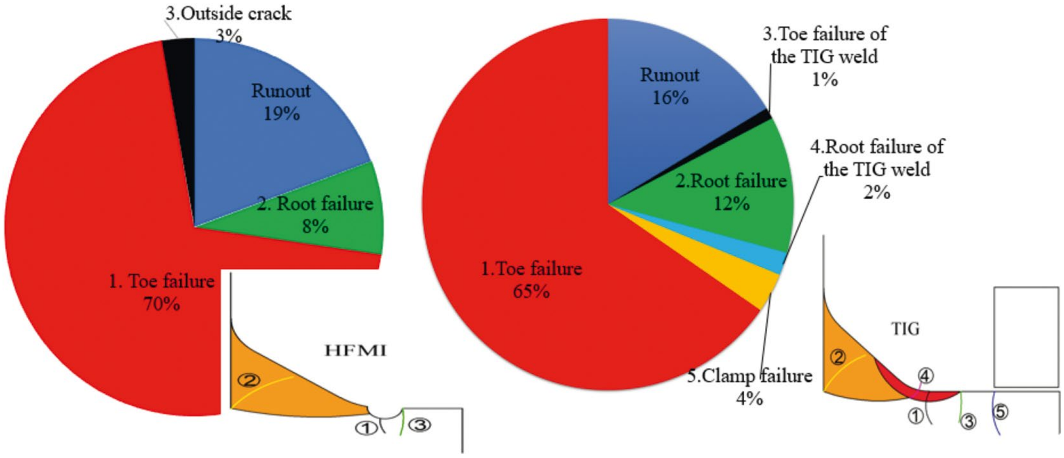

Fig. 8 Different failure locations in HFMI-treated and TIG-remelted welds

where the specimens were clamped in the testing machine were reported after TIG remelting. In other cases, fatigue tests were aborted without reaching failure; such tests are referred to as "Runout" in the figure, and they indicate the high efficiency of the treatment methods studied. These failure locations could be found in [6], [13] and [31].

3.1 HFMI treatment

The efficiency of HFMI treatment can be expected to decrease, or totally diminish, if the details already contain fatigue cracks prior to treatment. Test specimens for which the sizes of existing cracks before treatment were reported (groups 1.1 and 1.2) can be used to study this dependency. In Fig. 9, test results expressed in terms of gain factor $G1_{HFMI}$ are plotted against the depth of fatigue crack before HFMI treatment. A gain factor > 1.0 indicates that the treatment was so successful that not only the fatigue life of the as-welded detail was restored, but a fatigue life extension equivalent to a virgin HFMI-treated detail could be reached. The figure indicates that this situation is possible if the depth of the existing crack is < 2.25 mm. The few data points falling within the framed area are runouts. The same data is plotted again in Fig. 10 along with results for specimens with artificial cracks (i.e. group 1.2). As there was no pre-fatigued period for this group, the evaluation was based on the second gain factor $G2$. The same conclusion can be drawn regarding the allowable crack size.

Fig. 10 shows that the scatter in gain factors is wide, even when the crack size was precisely determined (i.e. artificially made crack). This indicates that the scatter observed in these tests cannot be entirely attributed to the uncertainties in determining the crack size, but it is also due to the variability in the HFMI-induced parameters such as compressive residual stress. However, the gain factors obtained when the cracks were created artificially were generally larger than those corresponding to authentic fatigue cracks. This can be traced back to the plasticity created around the authentic fatigue crack, which does not exist around artificially made cracks.

Another way of evaluating the efficiency of HFMI treatment is to relate the gain factors to the "degree of pre-fatigue" expressed as the ratio of the number of cycles in the pre-fatigued phase N_{pre} to the fatigue life of the detail in the as-welded condition. For groups 1.1 and 2.1, the experimental as-welded fatigue $N_{Exp,IIW}$ life is known from fatigue tests on the same specimens, and the mean fatigue life from tests was used as a reference. For group 2.2, the experimental fatigue life was not reported for the details tested. Therefore, the characteristic as-welded life $N_{AW,IIW}$ according to the IIW was used as a reference.

Figs. 11 and 12 show the gain factors plotted against the pre-fatigue life of HFMI-treated details normalized to as-welded life obtained from testing $N_{Exp,IIW}$. It can be concluded that HFMI has the capability to treat welded structures pre-fatigued to < 100 % of their mean lives if an inspection reveals no cracks > 2.25 mm deep.

Evaluating the gain factor considering the mean fatigue life of the details in as-welded conditions is conservative. Subsequently, the characteristic value of fatigue strength can be used to assess the remaining fatigue life. Figs. 13 and 14 again show the gain factors $G1_{HFMI}$ and $G2_{HFMI}$, but here as a function of the degree of pre-fatigue expressed by the ratio of number of cycles in the pre-fatigued phase N_{pre} to the characteristic fatigue life $N_{AW,IIW}$. This approach enables groups for which the as-welded fatigue lives were not determined experimentally (i.e. group 2.2) to be included too.

Figs. 13 and 14 clearly show that when the evaluation is carried out based on the characteristic fatigue life, a new HFMI life can be obtained even with cracks > 2.25 mm deep. In addition, the evaluation did not take into account the partial factors in fatigue strength which will be applied depending on the fatigue assessment method and the consequence of failure [26]. It is worth mentioning

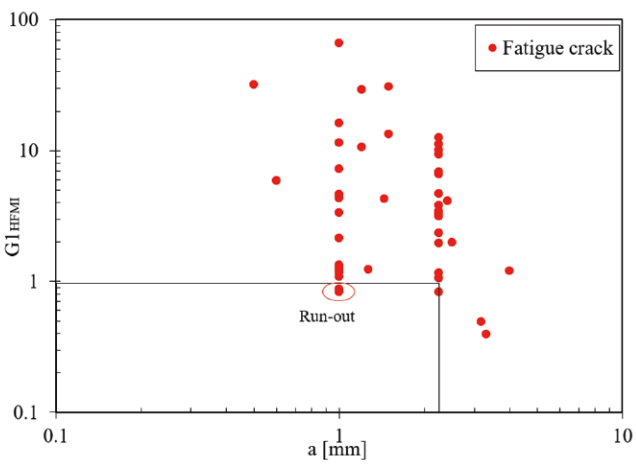

Fig. 9 Factor $G1$ plotted against depth of fatigue crack repaired by HFMI treatment for group 1.2

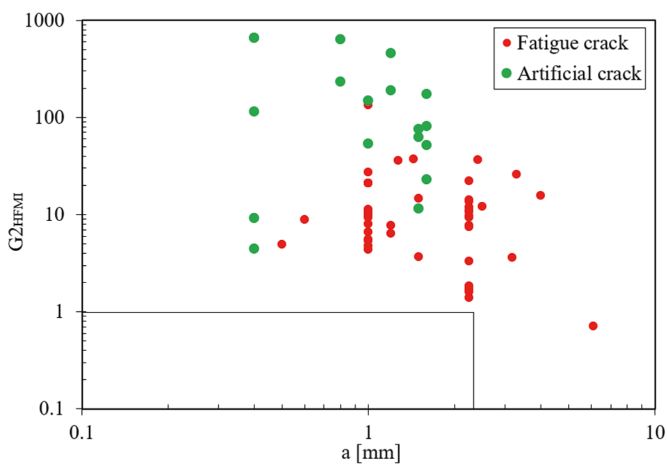

Fig. 10 Factor $G2$ plotted against depth of fatigue crack repaired by HFMI treatment for groups 1.1 and 1.2

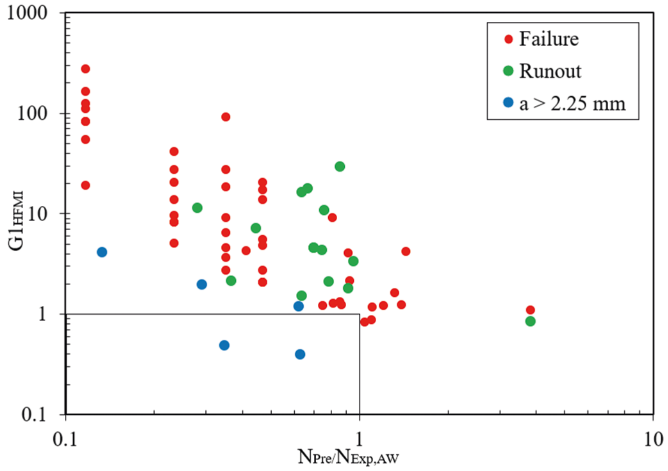

Fig. 11 Factor $G1$ plotted against the pre-fatigue cycles before HFMI treatment normalized to the experimental mean as-welded life for groups 1.1 and 2.1

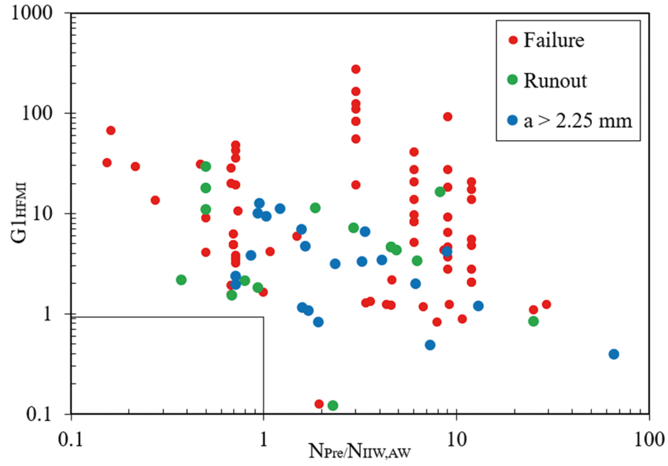

Fig. 13 Factor $G1$ plotted against the pre-fatigue cycles before HFMI treatment normalized to the characteristic as-welded life for groups 1.1, 2.1 and 2.2

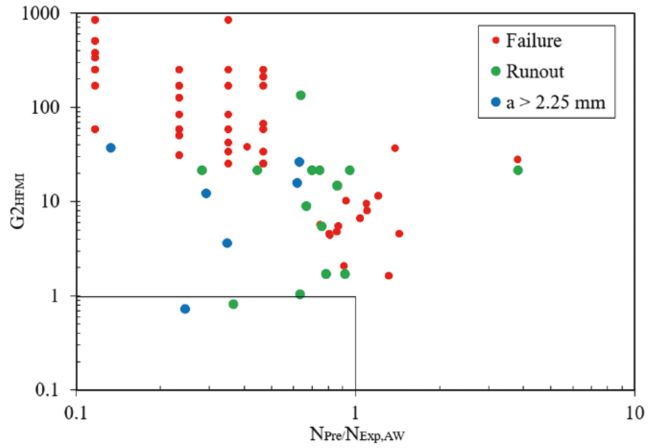

Fig. 12 Factor $G2$ plotted against the pre-fatigue cycles before HFMI treatment normalized to the experimental mean as-welded life for groups 1.1 & 2.1

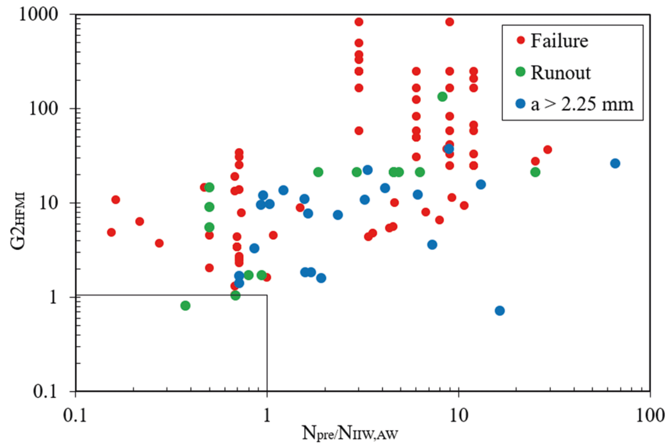

Fig. 14 Factor $G2$ plotted against the pre-fatigue cycles before HFMI treatment normalized to the characteristic as-welded life for groups 1.1, 2.1 and 2.2

that root failure data points also lay outside the "safe region", which indicates that there is no need to consider root failure when making a decision about life extension using HFMI treatment.

3.2 TIG remelting

As mentioned earlier, extending fatigue life by way of TIG remelting relies on crack removal and geometry improvement. Deep fusion is significant with reference to the first point, whereas a large radius is important for the second. Both can be optimized if the welding parameters are well controlled. When dealing with structures that may contain cracks, deep fusion should be prioritized over a large radius in order to minimize the risk of incomplete crack fusion – if any exists –. Similarly to HFMI-treated joints, the efficiency of TIG remelting can be evaluated using gain factors $G1_{TIG}$ and $G2_{TIG}$. In Figs. 15 and 16, these gain factors are plotted against the remaining crack depth after TIG remelting. Thus, only tests from groups 3.1 and 3.2 (i.e. where information about the remaining crack size was available) are included in these figures.

The weld toes of TIG-treated specimens with full crack removal have a relatively high fatigue strength, as no toe failure was reported. All specimens with no remaining crack failed outside the toe region or ran out after many millions of cycles (see Figs. 15 and 16). The figures show that the lives of the treated specimens were longer than both the pre-fatigue lives N_{pre} and the characteristic design lives of the virgin TIG-treated details $N_{IIW,TIG}$, as both gain factors, $G1_{TIG}$ and $G2_{TIG}$, are > 1.0. In fact, the characteristic fatigue lives of virgin TIG-treated specimens could be reached even for specimens with remaining cracks < 2 mm deep, as shown in Fig. 16. For group 3.3, no crack detection or metallurgical analysis to check the depth of fusion were conducted after TIG remelting. Therefore, both gain factors were plotted against the crack size before treatment for groups 3.1, 3.2 and 3.3 in Figs. 17 and 18. In this instance, the safe region could be extended to > 4 mm instead of 2.25 mm, which corresponds to HFMI treatment.

Similarly to the HFMI-treated joints, in Figs. 19 and 20 gain factors $G1_{TIG}$ and $G2_{TIG}$ were plotted against the pre-fatigue lives N_{pre} normalized to the as-welded mean

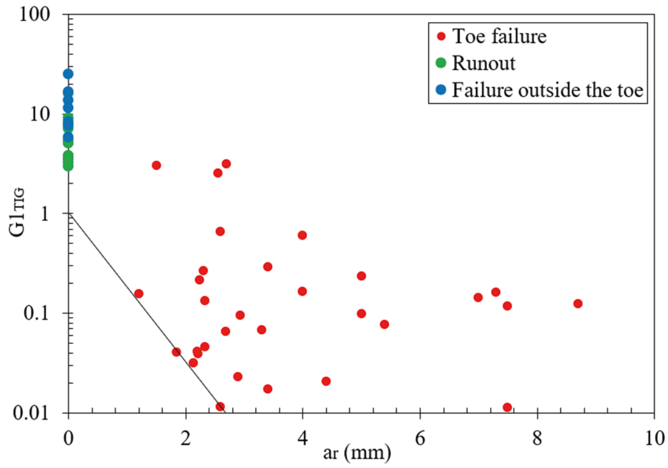

Fig. 15 Factor *G*1 plotted against remaining crack depth after TIG remelting for groups 3.1 and 3.2

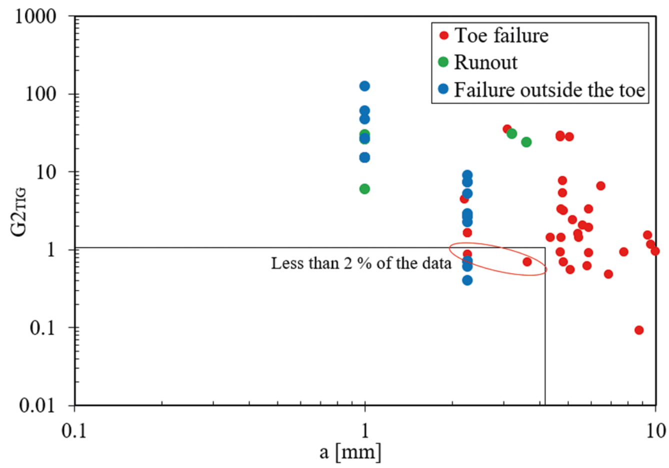

Fig. 18 Factor *G*2 plotted against fatigue crack depth after by TIG remelting for groups 3.1, 3.2 and 3.3

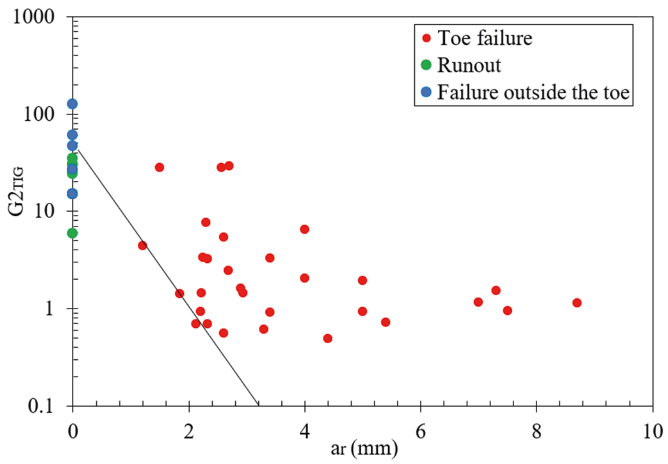

Fig. 16 Factor *G*2 plotted against remaining crack depth after TIG remelting for groups 3.1 and 3.2

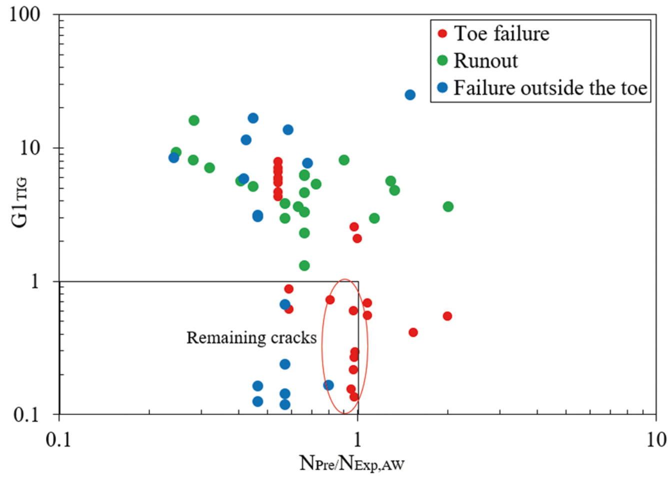

Fig. 19 Factor *G*1 plotted against the pre-fatigue cycles before TIG remelting normalized to the experimental mean as-welded life for groups 3.1, 3.2, 3.3 and 4.1

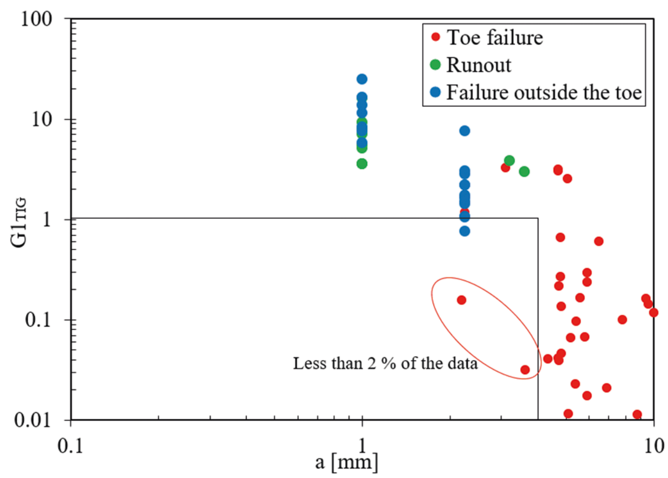

Fig. 17 Factor *G*1 plotted against fatigue crack depth after by TIG remelting for groups 3.1, 3.2 and 3.3

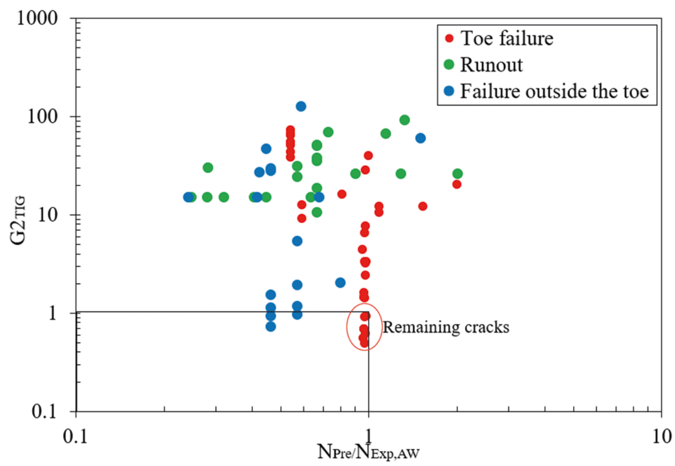

Fig. 20 Factor *G*2 plotted against the pre-fatigue cycles before TIG remelting normalized to the experimental mean as-welded life for groups 3.1, 3.2, 3.3 and 4.1

lives obtained from fatigue testing $N_{Exp,IIW}$ for all TIG groups. Several data points showed gain factors < 1.0 even when the specimens were pre-fatigued to less than their corresponding mean lives. Half of these specimens failed outside the toe region, while the other half still had cracks after TIG remelting. However, it should be emphasized that this is not remarkable, because using the mean fatigue life as a reference is conservative (i.e. 50 % of the specimens have failed), as mentioned earlier. A more reasonable evaluation should be made with reference to the

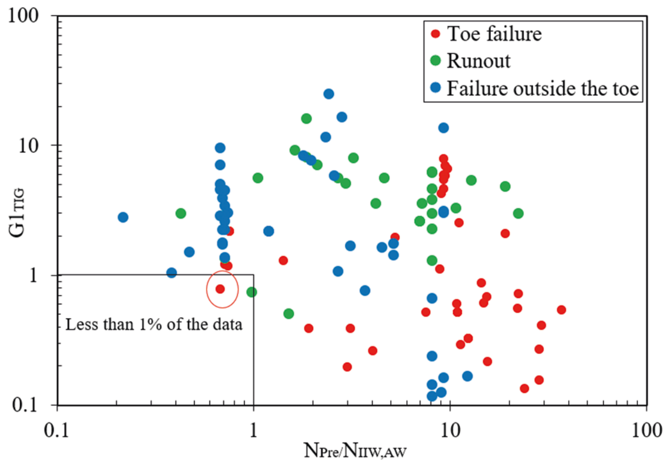

Fig. 21 Factor $G1$ plotted against the pre-fatigue cycles before TIG remelting normalized to the characteristic as-welded life for groups 3.1, 3.2, 3.3 and 4.1

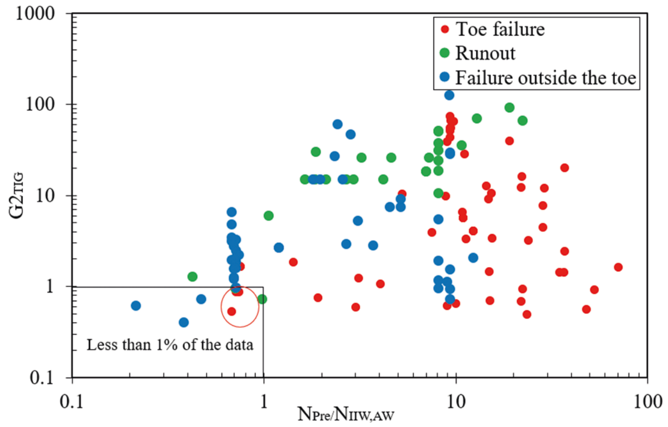

Fig. 22 Factor $G2$ plotted against the pre-fatigue cycles before TIG remelting normalized to the characteristic as-welded life for groups 3.1, 3.2, 3.3 and 4.1

characteristic fatigue life $N_{AW,IIW}$ instead. The results of such an evaluation are shown in Figs. 21 and 22. Both gain factors were > 1.0 for more than 99 % of the data points in the groups considered.

4 Discussion

For new structures, the fatigue strength enhancement via HFMI treatment is usually greater than that typically achieved using TIG remelting [20], [34], particularly in high-cycle fatigue regimes. This is also expected to be the case if these two methods are used on crack-free pre-fatigued structures. However, TIG remelting is capable of repairing deeper cracks. The gain factor $G1$ is plotted against crack size and pre-fatigue cycles for both treatment methods in Figs. 23 and 24 respectively. The data of both treatments are interlocked, but the scatter in gain factors for HFMI treatment is wider. The standard deviation for the HFMI treatment gain factor is more than five times greater than the corresponding value for TIG remelting in both Figs. 23 and 24. In addition to the variability in crack size, the larger scatter of the HFMI results

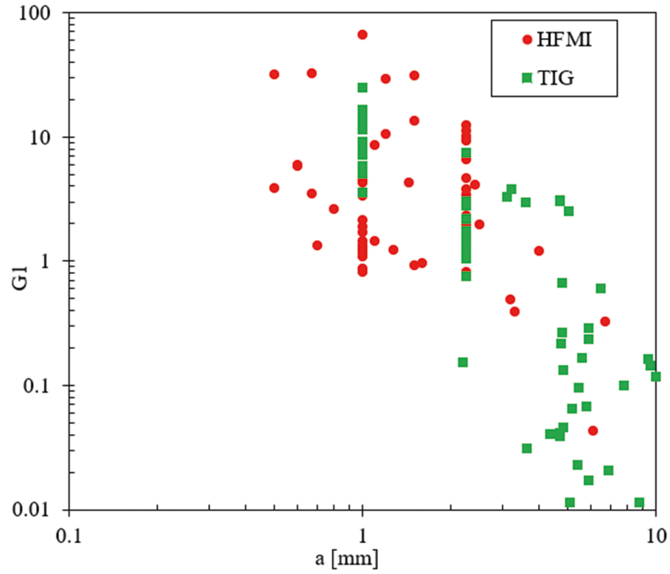

Fig. 23 Factor $G1$ plotted against crack size for both treatment methods

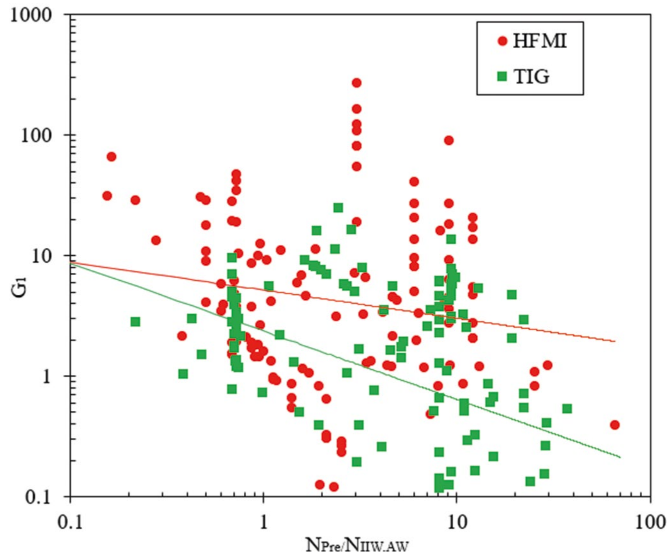

Fig. 24 Factor $G1$ plotted against pre-fatigue cycles for both treatment methods

can also be attributed to the variability in the HFMI-induced residual stress, which is the main mechanism behind fatigue life extension by HFMI treatment.

When the two post-weld treatment methods studied are applied to extend the fatigue lives of existing structures, there are some practical aspects that should be taken into account. Regarding HFMI treatment, a smaller inclination of the indenter with respect to the base plate results in improved crack closure. Furthermore, when treating cracked details, the indenter should be directed more towards the base metal than towards the welds in order to avoid unintentional crack widening. Regarding TIG remelting, the electrode should not be directed towards the base plate which is the case when treating new structures [33]. Instead, it should be positioned at the weld toe, which may create undercuts and increase the local stress concentration. However, this guarantees that the maximum fusion depth coincides with the crack

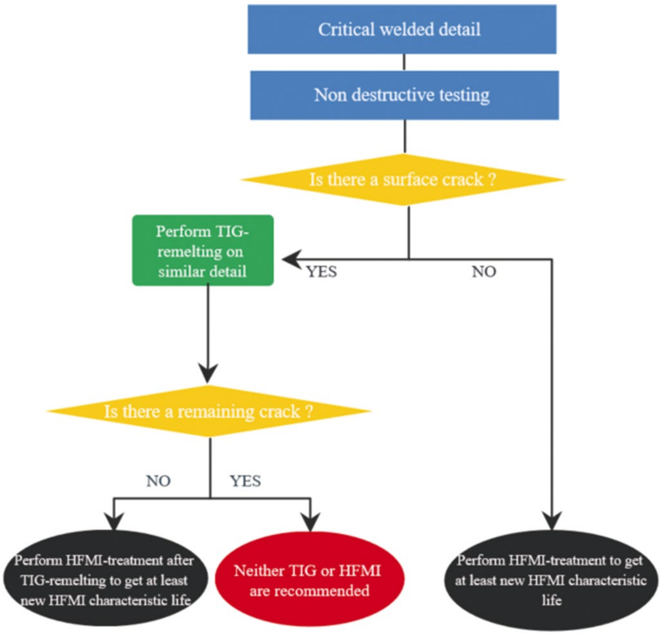

Fig. 25 Fatigue life extension flowchart

plane. Besides, the undercut possibly created would be less detrimental on fatigue life than a remaining crack.

Fig. 25 shows a flowchart with a suggested workflow that can be followed before TIG remelting or HFMI treatment on existing structures. The crack size is the most important parameter limiting the efficiency of both treatment methods studied. Therefore, it is always recommended to carry out non-destructive testing (NDT) prior to the treatment in order to determine the existing crack size – if any exists –. The NDT method used should be able to detect 2 mm deep cracks with a high probability of crack detection (i.e. > 95 %). However, there are inherent uncertainties in any crack detection method, which implies that the existing crack size might be larger than the estimated value. Therefore, HFMI is the preferred treatment method when the NDT is negative (i.e. shows that there is no crack at the weld toe). Even if NDT misses a small crack, HFMI can still achieve considerable fatigue life extension, as shown in Figs. 9 and 10. On the other hand, if the NDT used is positive, TIG remelting can be used instead, providing that the depth of fusion is greater than the crack size determined. TIG remelting still achieves a reasonable life extension with the presence of small cracks where the NDT estimations are not accurate, as shown in Figs. 15 and 16. If the crack size is greater than the fusion depth, none of the methods studied are recommended, and other crack repair methods must be used (e.g. drilling stop-holes).

In order to compare the three treatment methods (HFMI treatment, TIG remelting and combined TIG-HFMI treatment), the mechanisms behind fatigue life extension are compared in Fig. 26. These mechanisms are divided into three parts: the change in residual stress, the local increase in hardness and the topography change at the weld toe. The figure shows the results of several investigations of residual stress, local tensile strength and stress concentration factors at the weld toe of identical specimens treated by different methods. More details about the evaluation of the local hardness, the stress concentration factor and the residual stress can be found in [31].

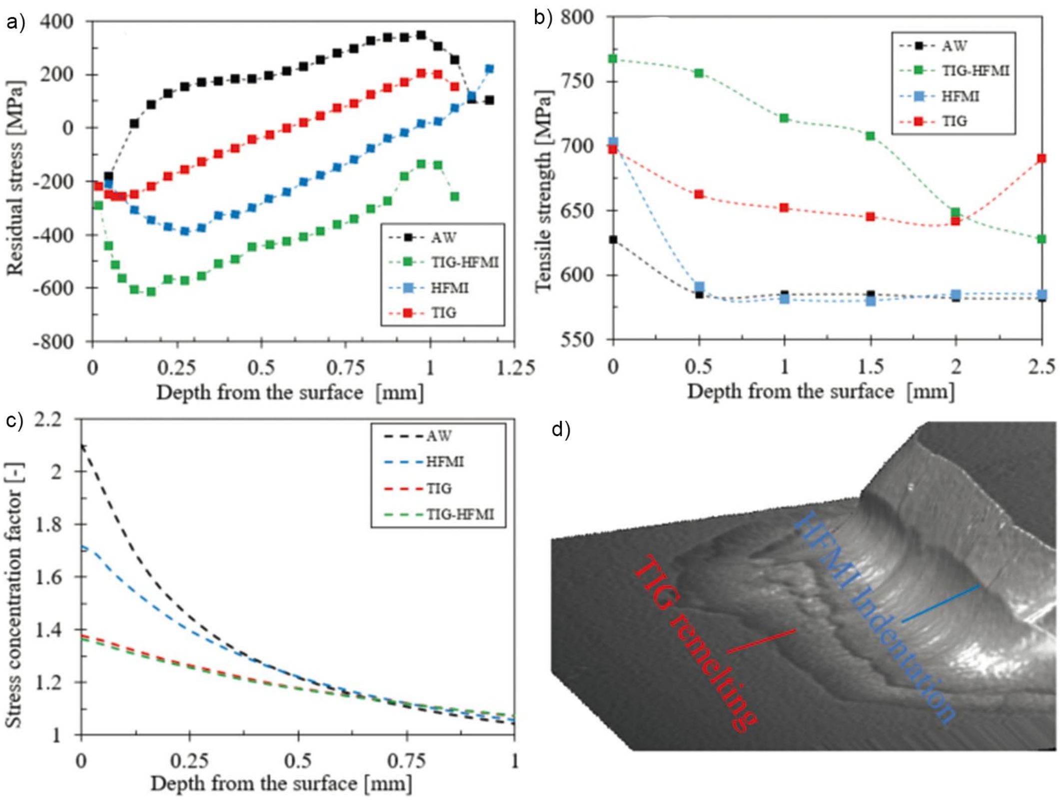

Fig. 26 a) Residual stress improvement, b) Local tensile strength increase, c) Decrease in stress concentration, d) Profile of weld after combined TIG-HFMI treatment

Combined TIG-HFMI treatment is obviously more useful than both HFMI treatment and TIG remelting alone in terms of the three mechanisms. Briefly, the combined treatment fuses the crack via TIG remelting, then puts the weld toe into compression via HFMI treatment. Furthermore, HFMI treatment removes any undercut that may occur after TIG remelting as mentioned above. This practice was used in several research articles ([21], [22], [31], [34]). In all of them, combined TIG-HFMI treatment resulted in a longer fatigue life extension than TIG remelting alone.

5 Conclusions

Available fatigue test data for pre-fatigued welded joints treated via HFMI treatment, TIG remelting or a combination of the two have been studied in this paper. Fatigue life gain factors were introduced and calculated for more than 250 test results. Analysing the fatigue test results collected led to the following conclusions:

- Using only the S-N curves to evaluate the fatigue life extension was found to be partially ineffective since it does not take into account several factors such as crack size, pre-fatigue cycles, R-ratio, steel quality and plate thickness in the remaining life assessment.
- Prior to the application of either of the two methods studied, NDT testing should be performed to verify that the structural detail is free from cracks, or, if cracks are detected, to get an insight into crack size. The NDT should be able to detect 2 mm deep cracks.
- HFMI treatment extends the fatigue life of welded structures in service even when the welded details contain fatigue cracks < 2.25 mm deep (i.e. through-thickness). For reasons related to uncertainties in crack size determination, it is recommended that HFMI treatment is only applied to crack-free welds. In such a case, a fatigue life extension equivalent to that obtained for virgin HFMI-treated details can be claimed.
- TIG remelting extends fatigue life even in the presence of fatigue cracks, provided these cracks can be fused by TIG remelting. In fact, testing has established a fatigue life extension even with subsurface cracks remaining after TIG remelting. However, TIG remelting is only recommended when NDT testing is negative after remelting.
- Combining TIG remelting with HFMI treatment delivers superior results for extending the fatigue life of welded structures in service. This combination is more favourable than TIG remelting alone.
- The scatter in the calculated gain factors is not only attributed to the uncertainty in crack size determination, but also due to the variability of the induced treatment effect (e.g. residual stress).

6 Future work

The work reported in this paper demonstrates the capabilities of the methods studied when it comes to extending the fatigue lives of existing structures. However, additional investigations are needed to assess the capabilities of different non-destructive testing (NDT) methods for crack detection and sizing. Moreover, additional attention should be paid to different quality assurance aspects (e.g. weld toe radius after treatment) to verify that the treatment is carried out correctly.

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