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TECHNICAL ARTICLE

# Corrosion Effect on the Efficiency of High-Frequency Mechanical Impact Treatment in Enhancing Fatigue Strength of Welded Steel Structures

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**Fatigue and corrosion are two material degradation phenomena that occur in welded steel structures. High-frequency mechanical impact (HFMI) treatment is a post-weld treatment method that aims to increase the fatigue strength of welded details. This paper investigates the effect of steel corrosion on the efficiency of this method in enhancing fatigue resistance. More than 150 fatigue test results on corroded and HFMI-treated welded details are collected from several research articles and analyzed for both transverse welded attachment and butt-welded details. The efficiency of HFMI treatment decreases in corroded details as the corrosion level increases. However, HFMI treatment is found to have a high potential in prolonging the fatigue life, even in circumstances of an extremely corrosive environment.**

**Keywords** corrosion, fatigue, high-frequency mechanical impact, offshore, seawater, steel

## 1. Introduction

Welding is a widely used fabrication process in different types of metallic structures such as bridges, aircraft, ships, vehicles and offshore structures. Welds are characterized by their satisfactory strength and robustness against static loading. However, cyclic loading is more critical for welded structures as it causes a progressive localized damage at the weld toe which is known as 'fatigue.' Therefore, fatigue should be considered when designing cyclically loaded structures. For instance, it constitutes the most governing state in the design of welded steel bridges (Ref 1).

Corrosion is another degradation phenomenon that poses a threat to the durability of welded structures. The severity of corrosion depends on both the corrosive environment that influences the rate of corrosion and the time of exposure. Corrosion also depends on other factors such as steel quality and material strength. Therefore, corrosion protection is usually applied to protect the structure in the form of spraying, painting or coating, and inspection intervals are assigned to check the adequacy of the protection as it may fail due to inappropriate application (Ref 2). Besides, inspection is not always practically possible in all parts of the structure because of the limited accessibility. Moreover, pitting corrosion causes a remarkable reduction in fatigue resistance of the welded details because of its localization at the weld vicinity (Ref 3). Examples of corrosion localization at the weld toe in different welded details

are shown in Figure 1. Therefore, the International Institute of Welding (IIW) recommends reducing the fatigue strength of the welded details existing in corrosive environments by 30%. Moreover, the S-N curve's knee point, and the threshold stress intensity are disregarded for offshore structures that are built in such environments (Ref 4).

In fatigue testing, corrosion can be introduced and modeled using two different methods. Either by conducting the fatigue test on treated specimens in a corrosive environment (i.e., simultaneous fatigue-corrosion), or by soaking the treated specimens in a corrosive media for a specific time before fatigue testing (i.e., pre-corrosion) and then fatigue testing is conducted in air conditions. The former case resembles the situation in new structures (i.e., with no preexisting damage), while the latter case resembles the existing structure that has already undergone some corrosion damage.

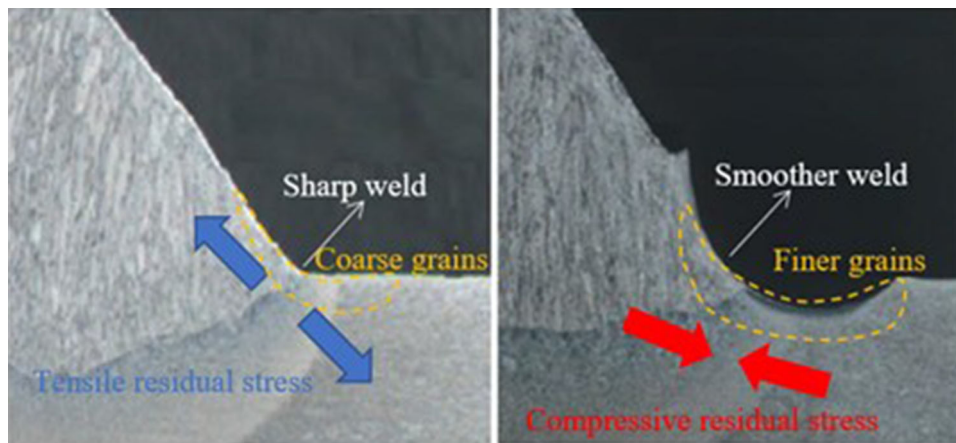
High-frequency mechanical impact (HFMI) treatment is a post-weld treatment method that aims to increase fatigue strength by inducing a permanent deformation locally. Three beneficial effects can be remarked after treating the welds: the induced compressive residual stress, the reduction in the stress concentration and the local material hardening (Ref 6), see Figure 2. The method shows significant capabilities in enhancing fatigue resistance which led to its inclusion in several international specifications and recommendations (Ref 7-9). Nevertheless, there is a believed risk of elimination or reduction of HFMI-induced effects (i.e., compressive residual stress and surface hardening) due to surface layers removal. The rate of removal varies depending on the corrosive environment and the time of exposure. Nonetheless, the corrosion rate becomes slower after HFMI treatment when compared to as-welded details (Ref 10). It is noteworthy that in the case of pitting corrosion, the layer removal will not be uniform but concentrated in specific spots.

Corrosion usually contributes to increasing the surface roughness, which leads to earlier fatigue crack initiation. Moreover, corrosion pits form stress raisers where stresses become significantly larger than the surrounding region. When

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**Fig. 1** Examples on corrosion at butt-welds and transverse attachment



**Fig. 2** The beneficial effects of HFMI treatment (Left: Before treatment Right: After treatment)

crack initiates, the corrosive medium penetrates into crack surfaces and leads to embrittlement and ductility reduction of the material in the crack tip's vicinity (Ref 3). Thereby, crack propagation occurs at a faster rate. Therefore, the constant  $C$  shall be magnified to take corrosion into account in fracture mechanics calculations using Paris law. Besides, no threshold stress intensity value shall be considered for details existing in severely corrosive environments as mentioned earlier (Ref 4). However, it is found that HFMI treatment increases the corrosion resistance due to both grains refinement and tensile residual stress reduction. Therefore, it is concluded that HFMI causes an increase in fatigue strength, even in a corrosive environment, providing that there is no significant thickness loss due to corrosion (Ref 5). Nevertheless, it is still vague whether the increase of fatigue strength in corroded welded details by HFMI treatment is attributed to the delay in crack initiation, or to the reduction in propagation rate or due to both (Ref 3).

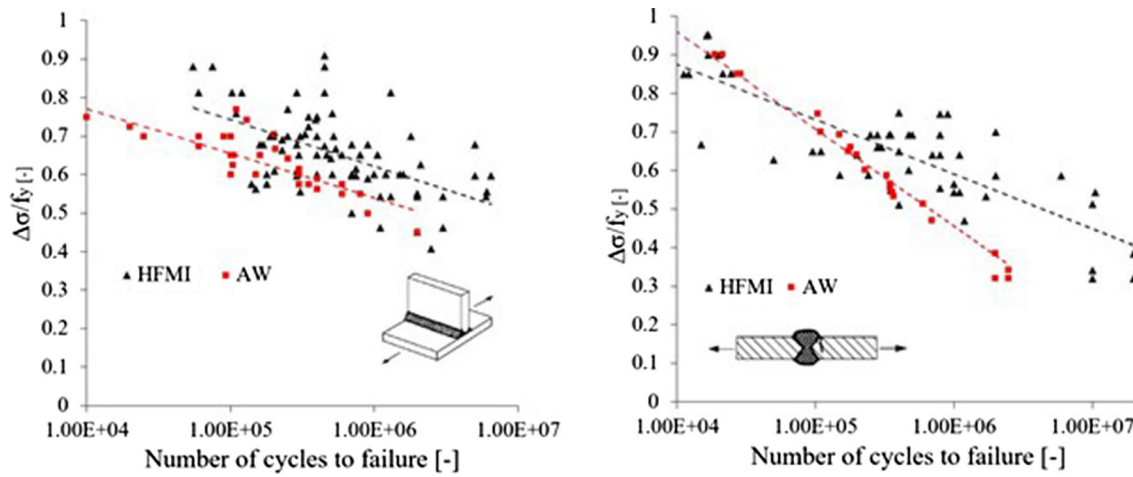
Corrosion's effect on fatigue resistance of HFMI-treated details is studied in several research articles (Ref 3, 10-16). Different conclusions were drawn about the degree of potential improvement in HFMI treatment in a corrosive environment. Moreover, is still ambiguous whether HFMI is recommended to treat corroded structures, and what level of corrosion can be tolerated before treatment. In addition to that, the recommendation regarding using HFMI treatment is still restricted to the

non-corrosive environment or under conditions of applying corrosion protection (Ref 4).

In fatigue-prone structures, there is a persistent risk of failure or deficiency of the corrosion protection. Moreover, there is a need of improving the fatigue strength of structures existing in a corrosive environment (e.g., offshore structures, bridges, ships). Therefore, this paper contributes to studying the effect of surface corrosion on fatigue resistance of welded joints enhanced by HFMI treatment via data collection and subsequent statistical evaluation of fatigue strength. Other forms of corrosion such as pitting are not covered in this article.

## 2. Methods

In this paper, more than 150 fatigue test results are collected from nine research articles dealing with fatigue strength enhancement via HFMI in a corrosive medium. The extracted test results are either presented in fatigue strength curves (S-N curves) or tabulated in the source articles. All tests are performed in a room temperature (around 25 °C), and NaCl is used as a salt solution to resemble seawater. Two-third of the collected tests are conducted on transverse attachment and the rest are conducted on butt-welded details. The collected test results are plotted for transverse and butt welds in Figure 3



**Fig. 3** Collection of fatigue test results of HFMI-treated and corroded and untreated and uncorroded transverse and butt-welded details, respectively

**Table 1** Information about the collected fatigue test results of corroded and HFMI-treated details

Ref	Testing sequence	Test type	Solution %	Thickness (Ref mm)	Detail type	Number of specimens	Steel type	Fy (Ref MPa)
18	HFMI, Simultaneous fatigue-corrosion testing	Immersion	10	6.5	Butt weld	6	A106-B	361
11	HFMI, corrosion, then fatigue testing	Salt spray	5	12	Cruciform	11	15KhSND	400
10	HFMI, corrosion, then fatigue testing	Salt spray	3	12	Cruciform	12	15KhSND	400
10	Preloading, HFMI, corrosion, fatigue testing	Salt spray	3	12	Cruciform	10	15KhSND	400
3	HFMI, corrosion, fatigue testing	Immersion	5	15	Butt weld	24	S355	469
3	HFMI, corrosion, simultaneous fatigue-corrosion	Salt spray	4.2	15	Butt weld	5	S355	469
12	HFMI, corrosion, then fatigue testing	Immersion	3.5	—*	Butt weld	12	AISI 316	496
5	HFMI, corrosion, then fatigue testing	Immersion	5	15	Transverse	23	S355	369
5	HFMI, corrosion, simultaneous fatigue-corrosion	Salt spray	4.2	15	Transverse	13	S355	369
13	HFMI, corrosion, the fatigue testing	Immersion	10	10	Butt weld	6	U75V	510
15	HFMI, corrosion, then fatigue testing	Salt spray	5	—*	Transverse	9	AISI 316	586
16	HFMI, Simultaneous fatigue-corrosion testing	Immersion	3	12	Butt weld	5	15KhSND	400
16	HFMI, Simultaneous fatigue-corrosion testing	Immersion	3	12	Transverse	12	15KhSND	400

\* Not described in the source articles

together with collected results of uncorroded and untreated details (i.e., as-welded) from the same source articles. More information about the data pool including the steel type, the concentration of the salt solution and the type of welded details is given in Table 1. Moreover, the type of test (immersion or salt spray) and the testing sequence are also given in the table.

The tests are conducted on different steel types ( $586 \text{ MPa} \geq f_y \geq 361 \text{ MPa}$ ) and under different stress ratios ( $0.1 \geq R \geq 0$ ). The thickness of the studied steel's base metal ranges from 6.5mm to 15mm. Failures occur from the weld toe in most of the cases, while only two specimens fail from the base metal. In few cases, the specimens do not fail after two million cycles of loading (i.e., run-out). Fatigue test results are also published on A. corroded and As-welded, B. uncorroded and As-welded, and C. uncorroded and HFMI-treated specimens in some papers.

The characteristic reference fatigue strength  $\Delta\sigma_c$  of the specimens in the collection is determined using the prediction interval method (Ref 17). The slope of the S-N curve 'm' and the intercept with the x-axis 'a' are not fixed to specific values but evaluated statistically using regression analysis. The

characteristic value indicates a 95% survival probability. It is worth mentioning that the run-out specimens (i.e., those which do not fail after 2 million cycles of loading) are not taken into account when evaluating  $\Delta\sigma_c$ . The interested readers are referred to (Ref 17) for more information about the statistical evaluation of  $\Delta\sigma_c$ .

### 3. Results

To quantify the effect of corrosion level on the efficiency of HFMI treatment, a dimensionless gain factor, G1 in fatigue life is introduced. G1 gives the ratio between the fatigue life of the corroded and HFMI-treated detail  $N_{\text{HFMI,Corroded}}$  to the fatigue life of the uncorroded and HFMI-treated detail  $N_{\text{HFMI,New}}$ , see Eq 1. Both  $N_{\text{HFMI,Corroded}}$  and  $N_{\text{HFMI,New}}$  are determined experimentally through fatigue testing. This gain factor is plotted against the corrosion level in Figure 4. The corrosion level is calculated as the product of the time of immersing the specimens in the corrosive medium in hours multiplied by the

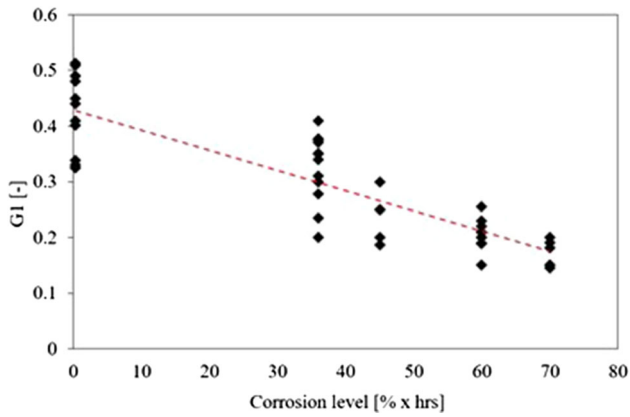


Fig. 4 Corrosion level effect on the efficiency of HFMI treatment

salt concentration of the medium. It is worth mentioning that only the pre-corrosion tests where the specimens are immersed in a salt spray chamber before testing are considered in Figure 4.

$$\left( G1 = \frac{N_{HFMI,Corroded}}{N_{HFMI,new}} \right) \quad (\text{Eq 1})$$

An inverse correlation between the corrosion level and the gain factor G1 is found. This is attributed to the progressive weight loss and layer removal from the surface of the treated detail where HFMI-induced compressive residual stress dominates. Besides, the layer removal due to corrosion has a proven effect on reducing the ultimate strength of the corroded steel; which leads to fatigue strength reduction (Ref 19). This indicates that the severity of the corrosive environment and the period of exposure are vital aspects to be considered when assessing the expected improvement in fatigue life by HFMI treatment. However, it is not practically possible to correlate the results of the salt spray hours to the real-life duration (Ref 20).

Pre-corrosion in the sequence given in Table 1 (i.e., HFMI treatment, corrosion followed by fatigue testing) is a suitable representation for cases where it is of interest to increase the applied load levels. In this case, the structure would have undergone corrosion damage even before increasing the load level as corrosion depends mainly on the environment and not on the applied load. On the other hand, the simultaneous fatigue-corrosion test is more suitable to symbolize the use of HFMI in enhancing new manufactured structures built in a corrosive environment.

In fatigue-corrosion tests, the corrosion level could not be represented as before because there is no pre-corrosion period. Therefore, the gain factor is plotted against only the salt concentration. However, the fatigue lives of the uncorroded and HFMI-treated specimens are not reported in many of the source articles. Therefore, another gain factor, G2 is defined which gives the ratio between the corroded fatigue lives of the treated detail  $N_{HFMI,Corroded}$  to the as-welded detail  $N_{AW,Corroded}$ , see Eq. 2. In other words, G2 indicates the potential benefit of using HFMI treatment in enhancing fatigue-corrosion resistance.

$$\left( G2 = \frac{N_{HFMI,Corroded}}{N_{AW,Corroded}} \right) \quad (\text{Eq 2})$$

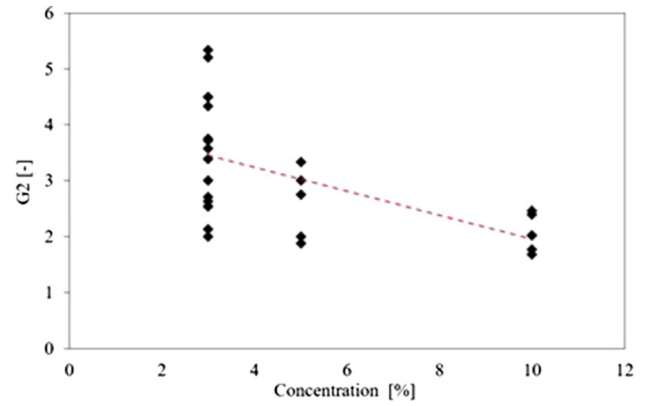


Fig. 5 Characteristic fatigue strength curves of the butt-welded detail

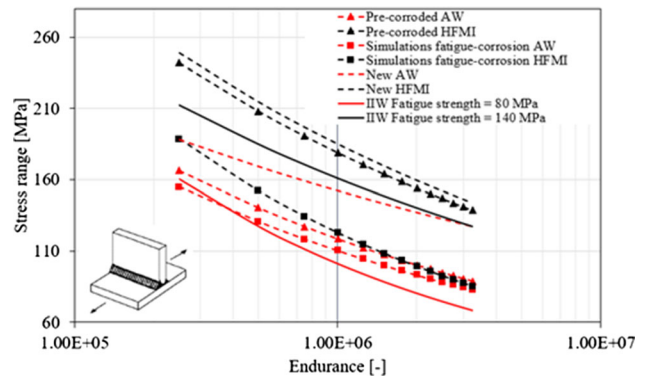


Fig. 6 Characteristic fatigue strength curves of the transverse attachment welded detail

Unlike G1, G2 is expected to always be larger than 1.0 as shown in Figure 5. The figure indicates that as the salt concentration increases, the potential improvement due to HFMI treatment decreases. This is because the salt concentration represents the severity of exposure to the corrosive medium. The salt concentration in natural and artificial seawater is around 3.5-4.2% according to the standard practice for the preparation of substitute ocean water (Ref 3). G2 is found to be significantly larger than 1.0 for these percentage as shown in Figure 5. In fact, G2 is larger than 1.0 even when the salt concentration reaches 10% as the figure indicates.

The important question is whether HFMI can be used to treat structures that are either subjected to corrosion before fatigue loading (i.e., Pre-corroded), or exposed to a corrosive environment and subjected to fatigue loading simultaneously. Therefore, the available fatigue test results are analyzed using the prediction interval method described in Section 2. The analysis results for pre-corrosion, simultaneous fatigue-corrosion and corrosion-free details are compared to the characteristic fatigue strength obtained from the IIW recommendations for both butt-welds and transverse attachments in Figure 6 and 7, respectively. Table 2 includes more information about the analysis results. The fatigue strength ( $\Delta\sigma_c$  value) and the corresponding S-N curve slope (m) are estimated based on the prediction interval method calculations. The knee points are not considered in the plotted S-N curves because it is assumed to be

reduced significantly depending on the spectrum of fatigue loading and the time of exposure to fatigue load (Ref 4).

It is noteworthy that the difference in steel quality is not a problem when analyzing all data for as-welded details because fatigue strength is independent on the steel quality (Ref 4). Nonetheless, the level of increase in fatigue strength is dependent on the steel quality after HFMI treatment. Therefore, only steels with a yield strength of ( $550 \text{ MPa} \geq f_y \geq 355 \text{ MPa}$ ) are used in the analysis. The maximum possible number of fatigue classes improvement for this strength interval is equal to four (Ref 9).

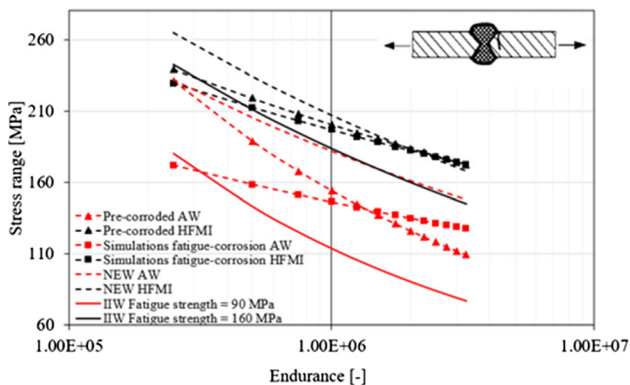


Fig. 7 Characteristic fatigue strength curves of the butt-welded detail

## 4. Discussion

By comparing the obtained fatigue strength of as-welded and HFMI-treated details shown in Table 2, it can be concluded that the treatment causes improvement for both of the test types (i.e., pre-corrosion and simultaneous fatigue-corrosion), and for both of the studied details (transverse attachment and butt-welded details). However, the improvement level is still less than this the one corresponding to the uncorroded detail, which is in line with the results presented in Figure 4. Nonetheless, the obtained fatigue strengths are greater than the design values assigned for HFMI-treated details according to the IIW recommendations (Ref 9). This is not surprising as the standards tend to be conservative and on the safe side. The only exception corresponds to the simultaneous corrosion-fatigue test for transverse HFMI-treated detail which has a fatigue strength 30% smaller than the design value (i.e., 99 MPa compared to 140 MPa). This necessitates looking closer at the collected data to determine how considerable the risk of obtaining fatigue strength less than the design values would be.

Hence, the normal distributions of the obtained fatigue live  $Nf_{\text{Corroded}}$  normalized to the mean recommended values by the IIW,  $Nf_{\text{IIW}}$  is plotted in Figure 8. The mean values for the ratios are equal to 1.4 and 2.4 for as-welded and HFMI treatment, respectively, as shown in the figure. This indicates that the welds—in general—become less affected by the corrosion damage after HFMI treatment. Moreover, the risk of having fatigue strength less than the mean recommended value decreases after treatment, as shown in the shaded areas in the figure. It is noteworthy that the mean value of  $Nf_{\text{IIW}}$  used for

Table 2 Characteristic fatigue strength curves of the transverse attachment welded detail 6 and 7

	Pre-corrosion			Fatigue-corrosion			Without corrosion			IIW	
	m	$\Delta\sigma_c$	n	m	$\Delta\sigma_c$	n	m	$\Delta\sigma_c$	n	m	$\Delta\sigma_c$
Butt-AW	3.43	126	18	8.60	135	5	5.69	161	41	3	90
Butt-HFMI	7.81	183	42	8.98	182	16	5.63	183	18	5	160
Transverse-AW	4.08	100	27	4.08	93	12	6.56	137	40	3	80
Transverse-HFMI	4.61	154	66	3.23	99	27	4.69	160	24	5	140

m: slope of the S-N curve  
 $\Delta\sigma_c$ : fatigue strength  
n: number of specimens

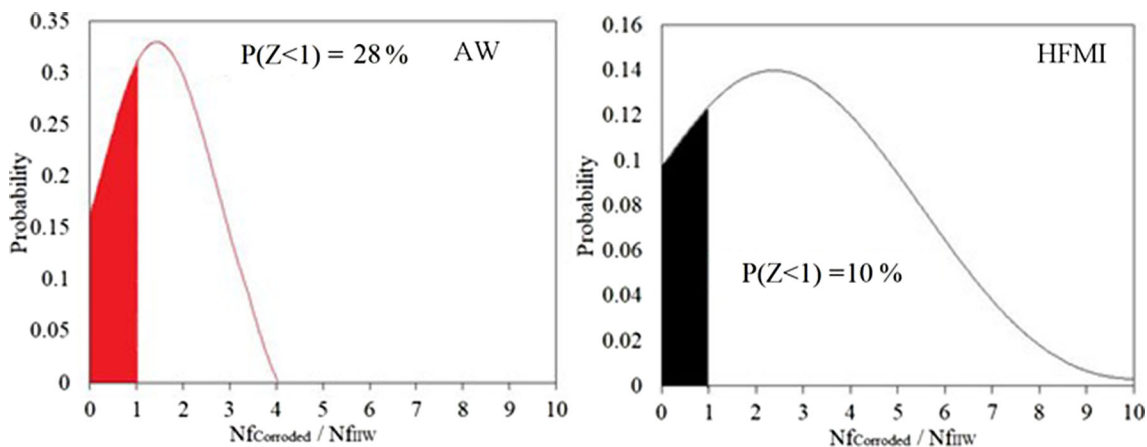


Fig. 8 Probability density functions of the corrosion fatigue life normalized to the mean recommended fatigue life

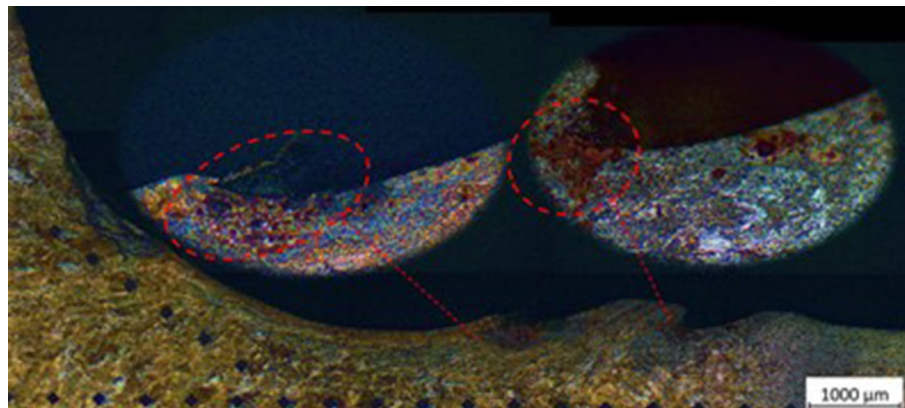
the normalization is not the value used in the design. The value used by designers which is the characteristic fatigue strength (i.e., 95% probability of survival) is significantly smaller than the mean value  $N_{f_{IIW}}$  given in the figure, which indicates that the presented risk in the figure is overestimated. In fact, the risk of having a shorter fatigue life due to corrosion than the design life does not exceed 4% for HFMI-treated details.

The analysis conducted in this paper is limited to steels with a specific yield strength ( $550 \text{ MPa} \geq f_y \geq 355 \text{ MPa}$ ), which makes any drawn conclusion regarding the potential improvement in fatigue life due to HFMI treatment in corrosive medium exclusive to these steel qualities. However, one of the main objectives of applying HFMI treatment is to reduce the material consumption by using high strength steel. Therefore, more light should be shed on fatigue-corrosion effect on HFMI-treated high strength steels. Besides, the study does not include other types of welded details such as cope-hole attachment which are widely used in steel bridges. This type of detail is of interest because of the difficulty in performing HFMI treatment and applying the corrosion protection due to the limited accessibility, see Figure 9.

The paper in hand focuses on the influence of corrosion on the efficiency of HFMI treatment. This is clearly emphasized in Table 1 which shows that the treatment is always conducted before the corrosion. However, there are possible scenarios in which the effect of HFMI treatment on corrosion severity can be of interest, for instance applying HFMI treatment on in-



**Fig. 9** Examples on cope holes in a welded steel bridge



**Fig. 10** Sharp edges after HFMI treatment leads to corrosion

service corroded structures. It is reported in some articles that the corrosion rates in HFMI-treated welds are less than these for as-welded details which might be attributed to the local steel hardening as mentioned in Section 1. However, it is still unclear if the material hardening due to HFMI treatment can be claimed even if the detail is weakened due to corrosion. Another important aspect that is not covered in this paper is the effect of pitting corrosion where the layer removal rate is not uniform due to the corrosion localization.

When HFMI is to be used for treating welds that exists in a corrosive medium (e.g., coastal, marine, farm or industrial environment), some practical aspects should be taken into consideration:

- Despite the promising results which show that corrosion poses marginal risk of HFMI deficiency to reach the design life (i.e., less than 4%), corrosion protection application is still recommended to reduce the exposure and to utilize the treatment efficiently.
- The welds should be visually inspected after HFMI treatment to check the smoothness of the surface, especially at the groove edges. These edges can be critical because condensed moisture and dirt can be trapped there which lead to accelerating corrosion, see Figure 10. Moreover, the risk of corrosion protection failure is larger at sharp edges and corners. If such edges exist, they should be removed by light grinding. However, grinding should be performed under HFMI-operator supervision to avoid over-removal which might lead to compressive residual stress reduction (Ref 9).
- If HFMI treatment is to be applied on an existing structure—which has been already subjected to fatigue loading—nondestructive testing (e.g., dye penetrant or magnetic particle) can be useful to check if fatigue crack already exists. Similarly to groove edges, cracks are also potential locations for dirt and condensed moisture accumulation which leads to embrittlement and ductility reduction in the crack vicinity as mentioned in Section 1.

## 5. Conclusions

This paper investigates the efficiency of HFMI treatment in fatigue strength improvement in transverse and butt-welded details existing in a corrosive environment (e.g., bridges,

offshore structures or ships). More than 150 fatigue test results are collected from several publications and analyzed. The following conclusions can be drawn:

- An inverse correlation between the corrosion level (i.e., pre-corrosion period and concentration of corrosion medium) and the efficiency of HFMI treatment is found. However, the obtained fatigue life after the treatment is greater than the as-welded fatigue life under exposure to seawater environment.
- The prediction interval method is used to evaluate the fatigue strength of the specimens in the collected data. It is found that the fatigue strength for pre-corroded butt-welds and transverse attachments enhanced by HFMI treatment is equal to 183 and 154 MPa, respectively, in comparison with 126 and 100 MPa, respectively, for untreated detail.
- The obtained fatigue strength under simultaneous fatigue-corrosion tests for treated butt-welds and transverse attachments is equal to 182 and 99 MPa, respectively, these values are smaller than those corresponding to pre-corroded specimens. The obtained fatigue strengths are only limited to steels with a specific yield strength ( $550 \text{ MPa} \geq f_y \geq 355 \text{ MPa}$ ).
- The recommended design fatigue strength for HFMI-treated details can be extended for details existing in a corrosive medium. In fact, the risk of obtaining lesser fatigue strength is marginal and does not exceed 4%.
- Despite the proven efficiency of HFMI in treating corroded details, corrosion protection is still recommended. In addition to that, fine grinding is suggested to remove HFMI-induced sharp groove edges—if exists—under the supervision of the HFMI-operator. Besides, nondestructive testing is also advised to verify that the detail is crack-free after treatment.
- More research is needed to study the potential of reducing the corrosion severity by HFMI treatment in existing in-service structures. Besides, a light should be shed on the pitting corrosion effect on HFMI treatment.

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## Conflict of interest

The authors declare no financial or commercial conflict of interest.

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