Analysis of the residual stress stability of high frequency mechanical impact (HFMI)-treated transverse stiffeners of mild steel (S355) and high strength steels (S700) under p (1/3) and straight-line shaped spectrum loading

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ABSTRACT

The effectiveness of high-frequency mechanical impact treatments (HFMI) and the associated increase in fatigue resistance is still being discussed, because it is generally assumed that the generated residual compressive stresses probably may be reduced by variable amplitude loading (VAL) and may therefore lose their beneficial effect. This study analyses further results for the sequence effect of VAL of a p (1/3) and straight-line shaped spectrum loading on the fatigue strength as well as the residual stress behavior of HFMI-treated transverse stiffeners (TS) of mild steel (S355) and high strength steels (S700). Fatigue test results with Random and High-Low loading for the two states as-welded (AW) and HFMI-treated joints together with in-situ residual stress measurements will be presented. The effect of VA loading on the residual stress behavior of as-welded (AW) and HFMI-treated joints and on the resulting fatigue improvement will be discussed.

Keywords: High strength steel, Welded joints, spectrum loading strength, residual stresses

1. Introduction

Hammer peening of welds is a well known simple technique to improve the fatigue strength of welds. Improved air driven or ultrasonic excited tools use higher hammer frequencies to enable a localized high treatment intensity. The target is to combine a simple tool-handling even under rough service conditions with an improved near surface material condition which enables a high benefit in applicable stress levels or endurance. The improvement of the fatigue strength is related to the generated compressive residual stresses, the plastic strain induced hardening of thin surface layers and a smoothening of the weld toe radii depending on the shape of the used tool. Within the scope of the common design rules [2,12] the effectiveness of such treatments is mainly related to the generated residual stresses. Since the effect of residual stresses on the resulting fatigue strength generally depends on their stability during the load history it is often argued that under service conditions, e.g under loading with variable amplitudes (VAL) in the lifetime of a component several overloads must occur which may reduce the initial residual stresses due to local or entire plastifications almost completely. Then it must be expected that the benefit of such treatments, which is well proved by comprehensive investigations under constant amplitude loading (CAL), dissolves thoroughly due to the residual stress relaxation.

2. Influence of the HFMI-treatment on the fatigue performance

For the fatigue strength of welded steel structures, the local loading of the fatigue critical locations is of decisive importance. The fatigue strength and thus the durability can be increased by different postweld treatment methods. Numerous studies [1,3-10] using high-frequency mechanical impact (HFMI) called hammer peening methods have proven to be an effective method for increasing the fatigue strength of welded details. Results of these studies have been commonly accepted and incorporated into recommendations and guidelines [11, 12]. However, the effectiveness of HFMI treatments under real service loading is currently still questioned because initial residual stresses induced by the HFMI can relax due to cyclic loading and high peak stresses as part of the service load [13–15]. Then it is expected that the benefit of the initial residual stresses dissolves in practice [16.20]. However, the beneficial effect of the strain-hardened surface layer, as well as the reduction of notch stresses due to the HFMI treatment is not necessarily affected. These studies focus mostly on the additional influence of high mean stresses, high peak stresses as single incidents or the influence of randomly distributed VAL on the fatigue strength of HFMI-treated notch details. For untreated welded joints, first studies on the sequence effect were carried out in [21].

Recent works [21] reveal that the fatigue life obviously depends on the type of VAL-test and that means if the tests are performed once with blocked and once with random loading sequence. These results are in accordance with the literature [22], showing that due to random loading, lower fatigue life is to be expected compared to blocked loading sequence. However, there are no studies available for HFMI-treated welds that focus on sequence effects for discrete load spectra. Previous studies have focused on the sequence effect of individual overloads within a constant amplitude load or the influence of random service loading on the fatigue strength of HFMI-treated welds. For this purpose, tests and HFMI-treated welded T-joints of the steels S355 N and S700M with transverse stiffeners were carried out under different loading conditions. The welds were investigated in the as-welded condition and after a HFMI-treatment performed at the critical weld toes (Fig 1). The applied load spectra are schematically shown in Fig.2. The stress ratio was set uniformly to R=-1. Each spectrum included $2 \cdot 10^6$ load cycles and was repeated continuously during the lifetime. Details of the test programme and the evaluation of the damage calculation using the palmgren-miner rule are summarized in [22].

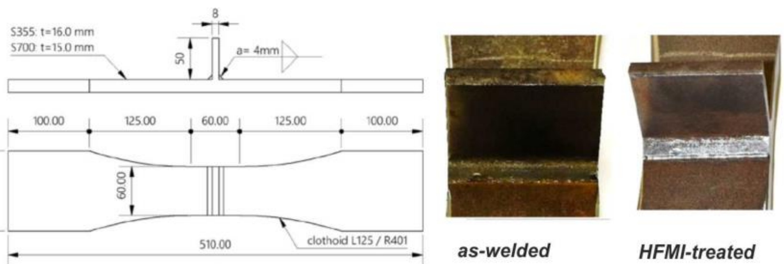

Figure 1: Shape of the test samples

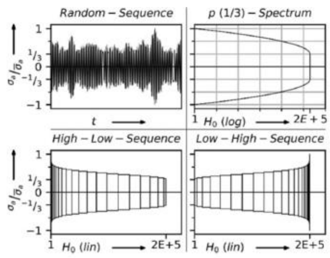

Figure 2: applied load spectra

The results of the comparative tests under CAL show the expected beneficial effect of the HFMI treatment (Fig.3). Both steels show a strong increase of the fatigue strength due to the

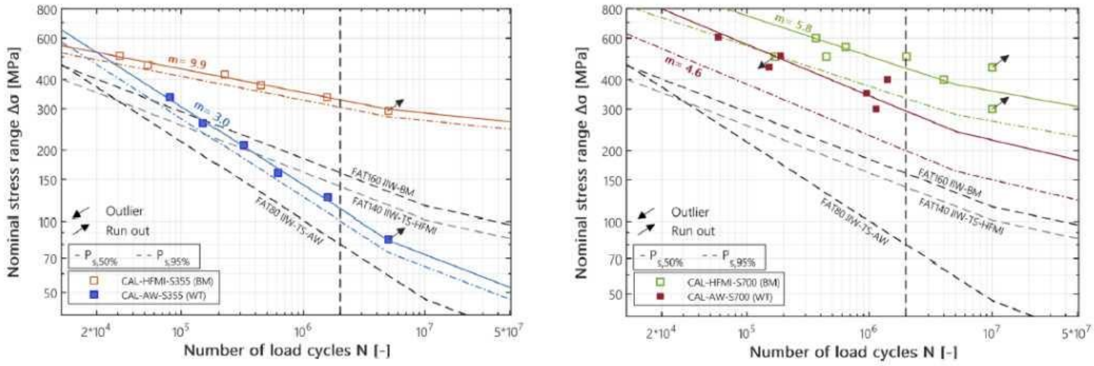

Figure 3: Test results of the CAL-as-welded and HFMI-treated series, S355N (left hand side), S700M (right and side).

treatment while the improvement is obviously higher in the high strength S700M. Noticeable is the different slope of the SN-curves. This effect is usually explained with the lower residual stress effectiveness in lower strength steels due to their stronger relaxation at higher stress levels. Therefore the fatigue strength improvement is expected to be higher at higher lifteimes. The same behavior is present under random-VAL (Fig.4) and under blocked VAL (Fig.5).

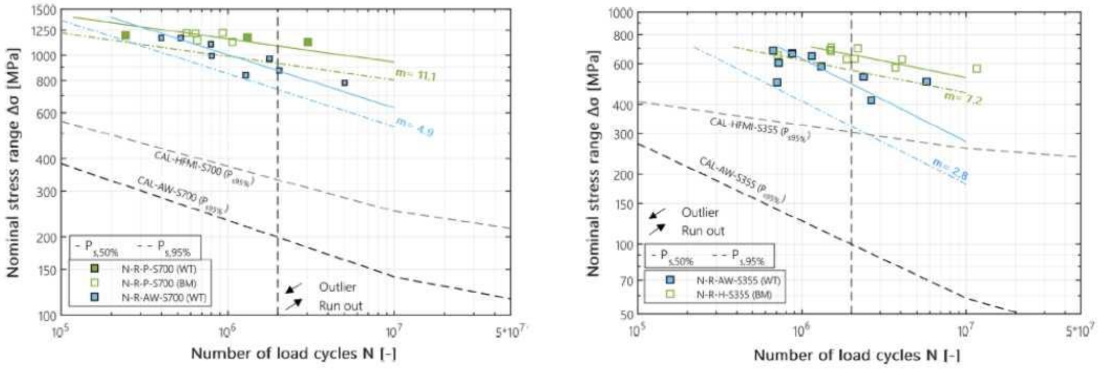

Figure 4: Results of the random VAL-tests. S355N (left hand side), S700M (right hand side)

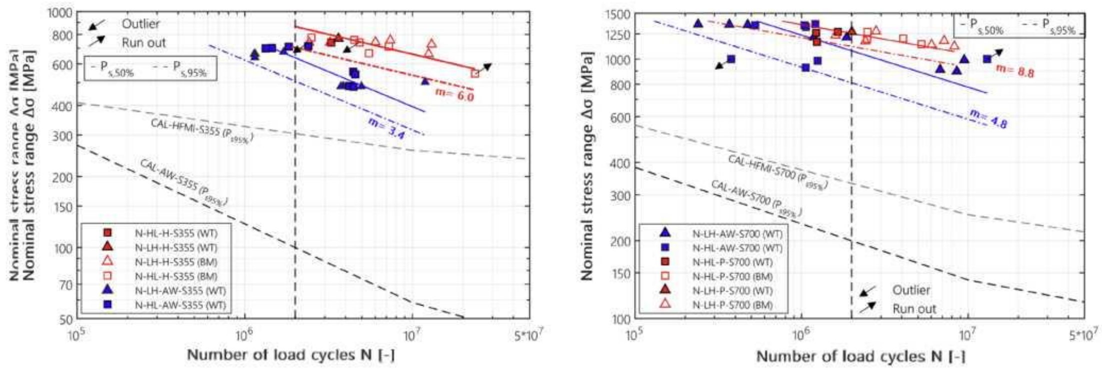

Figure 5: Results of the blocked VAL-tests. S355N (left hand side), S700M (right hand side)

The comparison of the VAL-test results obviously show that under VAL the fatigue life is obviously almost independent from the shape of the load spectrum. Stress peaks and overloads occurring during the first load cycles or at the end of the block as well as randomly do not lead to a significantly different lifetime or fatigue strength (e.g. the gassner-line). Assuming that the fatigue behavior is influenced by the initial residual stresses two conclusions are possible. Either the residual stresses are stable during the lifetime and not relaxed due to to single overloads or, if a relaxation is present the fatigue performance is not affected mainly by the residual stress condition.

3. Residual stress stability under different load conditions

3.1. Initial residual stresses

The initial residual stress condition after the local HFMI-treatment of both steels is presented in Fig.6. The residual stress profiles at the surface show the typical shape with maximum compressive residual stresses in the bottom of the peening track. In load direction ($\sigma^{RS}_{trans)}$ the level of the compressive residual stresses is at approximately -300 MPa (S355N) and -450 MPa (S700M) while in longitudinal direction the residual stresses are uniformly at -450 MPa which is also typical for this kind of treatment. The integral widths of the related diffraction lines which are influenced by the local microstructure indicate that in the treated zone a strain hardening which is higher in the high strength S700M must be effective.

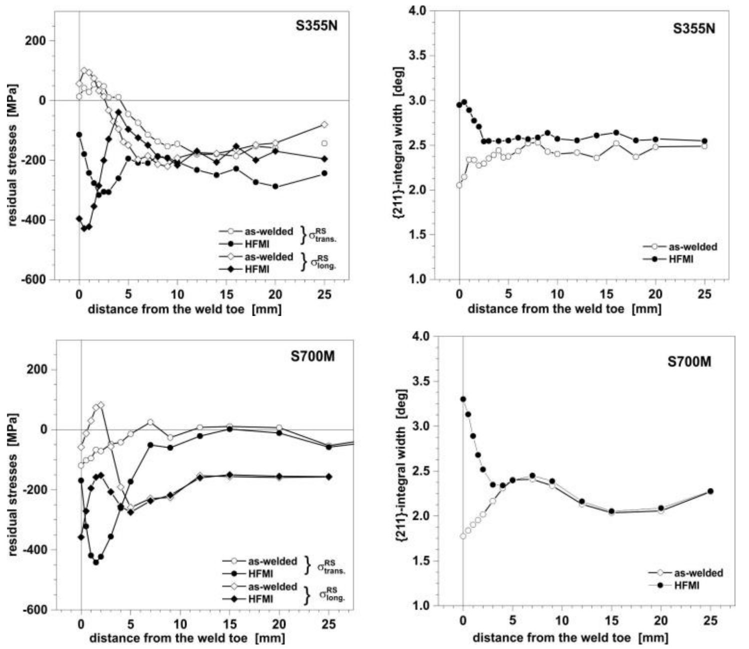

Figure 6: Initial residual stresses in the weld toe area at the surface before and after the HFMI-treatment

In depth direction both steels show a slight decrease of the compressive residual stresses without a steep gradient up to a depth of 0.5mm (Fig.7).

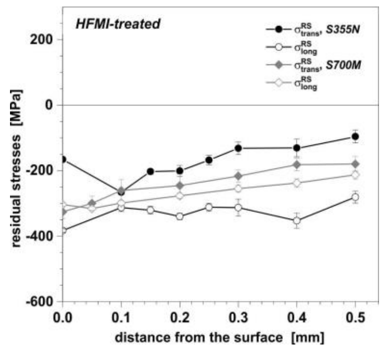

Figure 7: Initial residual stress depth profiles in the centre of the HFMI-zone

3.2. Residual stress relaxation due to static overloads

Figures 8 and 9 illustrate the effect of a static overload ocurring due to a single sress peak in the load history. In the S355N steel the loads were adjusted close to the nominal yield strength of the base material while in the S700M steel the load was varied from 55% R_e to 100% R_e. As Fig 8 shows the initial compressive residual stresses at the weld toe are released by a single load close to the yield strength almost completely. A slight increase of the load up to 377 MPa, which represents the yield strength of the related base material leads obviously to an overall plastic deformation in the near weld zone and the adjacent material. The shape of the residual stress profile changes completely and low tensile residual stresses are generated in the HFMI-treated zone. Nevertheless the constant amount of the integral widths indicates a stable hardening condition.

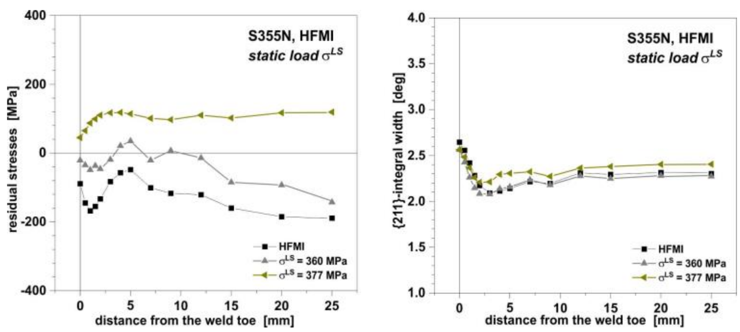

Figure 8: Residual stress surface distributions after single overloads, S355N

The high strength S700M shows a more sophisticated behaviour. The residual stress relaxation increases continuously with the maximum load but the plastic deformations are limited on the HFMI-treated zone. Even after the highest load representing the yield strength of the base material compressive residual stresses of 300 Pa remain in the treated zone as well as the shape of the profile is not changed remarkable. A slight decrease of the integral widths can be observed but the general shape of the strengthening condition seems to be not affected significantly (Fig.9).

It can be concluded in accordance with recent investigations [22] that the stability of the residual stresses is generally connected with the amount of single overloads. As expected the relaxation is the more pronounced the lower the yield strength of the material is. In low strength material probably an overall plastification is responsible for a general change of the entire residual stresses while in high strength materials the plastifications are more focused on the local residual stress peak at the notch due to the notch stress condition. However the strain hardening condition rarely affected in cases where the load stress does not exceed the yield strength significantly which seems also reasonable considering the particular stress-strain behaviour of the material.

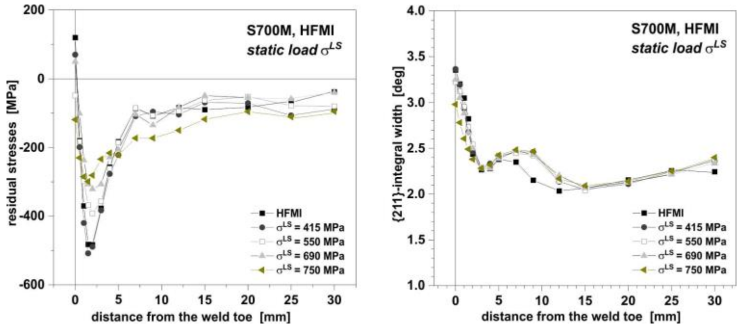

Figure 9: Residual stress surface distributions after single overloads, S700M.

3.2. Residual stress relaxation during variable amplitude loading

Figures 10 and 11 show the near weld residual stress profiles in different stages of a block loading programme with a North-Sea- representative load spectrum. The upper limit of the maximum load was set to 370 MPa for the S355N-steel and to 618 MPa for the S700M-steel. Blocks from 60% to 95% of the maximum load (200000 cycles each) were performed until the failure of the samples. Thus the number of block repetitions was 20 for the S355N and 6 for the S700M. The correlation between the amount of the observed relaxation of the residual stresses and the maximum load is less pronounced than determined under static overloads. However the relaxation takes place in the early stadium of the load history. After the first block almost stable residual stresses are present with neglectable remaining residual stresses in the low strength S355N and lowered compressive residual stresses in the S700M. Contrary to the static tests the S355N shows a slight cyclic softening with increasing number of load cycles while the strengthening condition of the S700M seems to be less affected. Similar results for the investigated weldments were found under a block sequence LowHigh with the same loading conditions and under random loading.

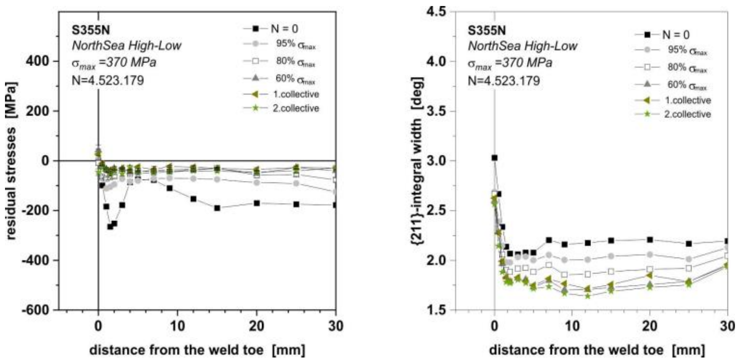

Figure 10: Residual stress surface distributions after spectrum loading (HighLow-Block programme), S355N.

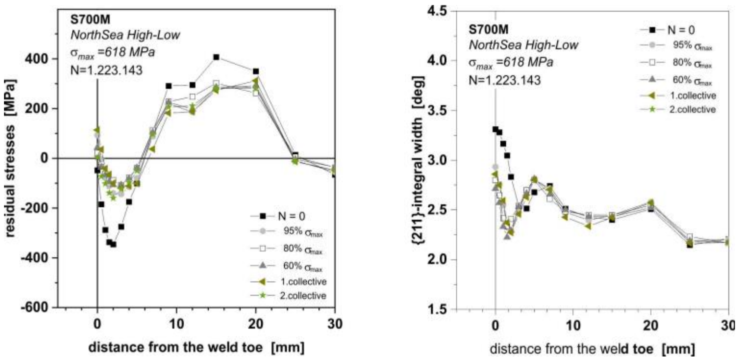

Figure 11: Residual stress surface distributions after spectrum loading (HighLow-Block programme), S355N.

4. Conclusions

The initial idea of the presented investigations was to clarify the use of a localized mechanical surface treatment on the fatigue performance under typical service conditions.

Since the benefit of such treatments is in practice primarily related to the influence of the generated compressive residual stresses the relaxation behaviour e.g. their stability in presence of single overloads was observed in order to evaluate the interaction of fatigue strength improvement and the changed local material condition at the crack initiation sites. As expected the residual stresses are affected significantly during fatigue loading whereas the most important factor is obviously the amount of the greatest load occuring in the load history. The strain hardening condition, which was evaluated by means of the integral width the measured diffraction lines, induced by the local plastic deformation is the more affected, the lower the yield strength of the material is. In high strength steels the strain hardening condition is more or less stable. Additionally it must be taken into account that the local HFMI-tretament affects also the shape of the local notch geometry because the sharp notch at the weld toe is smoothend by the strong plastic deformation resulting in a weld toe radius related to the tool diameter.

Both investigated steels showed a strong increase of the lifetime respectively the fatigue strength under all investigated load conditions. Concerning the observed complete residual stress relaxation and the slight softening the increased fatigue strength of the S355N-welds obviously is mainly related to the local notch shape smoothening. The higher stability of the generated residual stresses and the hardening condition in combination with the improved notch geometry is responsible for the improved fatigue strength of the higher strength S700M-steel.

Further investigation on other weld details and different steel grades should always take into account that the evaluation of the use of a mechanical post weld treatment requires necessarily the consideration of the change of the near surface conditions at the weld toe in combination with the notch geometry. Focusing only on the generated residual stresses may lead to misinterpretation of the use of such treatments and an underestimation of the potential benefit.

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