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### 3rd International Conference on Material and Component Performance under Variable Amplitude Loading, VAL2015

## Lightweight Potential of Welded High-Strength Steel Joints from S700 under Constant and Variable Amplitude Loading by High-Frequency Mechanical Impact (HFMI) Treatment

Halid Can Yıldırım<sup>a</sup>, Gary Marquis<sup>a,b</sup>, Cetin Morris Sonsino<sup>c,\*</sup>

<sup>a</sup> Department of Applied Mechanics, Aalto University, P.O. Box 14300, FI-00076 Aalto / Finland <sup>b</sup>KTH – Royal Institute of Technology, Division of Lightweight Structures, 100 44 Stockholm / Sweden <sup>c</sup>Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt / Germany

#### Abstract

Investigations with longitudinal stiffeners of the steel grade S700 under fully-reversed, constant amplitude loading and under variable amplitude loading with a straight-line spectrum show impressive fatigue strength improvement by high-frequency mechanical impact (HFMI) treatment. However, the degree of improvement was for variable amplitude loading lower when compared to constant amplitude loading due to local plasticity which occurs during larger load levels and consequently reduces the beneficial compressive residual stresses. Apart from the HFMI-treatment, the exceedance of constant amplitude loading (Woehler-lines) by variable amplitude loading (Gassner-lines) offers further lightweight potential, despite the lower degree of improvement by HFMI under spectrum loading.

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Keywords: High-frequency mechanical impact treatment; longitudinal stiffeners; high-strength steel; constant and variable amplitude loading; lightweight design

\* Corresponding author. Tel.: +49 6151 / 705-268 *E-mail address:* c.m.sonsino@lbf.fraunhofer.de

#### 1. Introduction

Welding technology offers innovative design solutions and manufacturing possibilities for complex heavy-duty structures. However, in spite of the great advantages offered by welding, there always remains the challenge of overcoming strength limits imposed by the local deterioration of the microstructure, the local stress concentrators like weld toes and roots, and unfavourable tensile residual stresses. Fatigue strength limits are encountered especially when lightweight designs are required. Good design practice on both the global- and local scales can be employed for the reduction of local stresses and thereby increase the structural durability. However, this alone does not ensure that the potential for lightweight design will be fully exploited. Additional fatigue strength benefit can be realised using various thermal and mechanical post-weld treatment processes. These include thermal stress relieving, TIG-dressing, grinding, hammering, shot peening and different high-frequency peening techniques which were developed in the late 20th century [1 - 9] and have been more recently incorporated into fatigue design regulations and guidelines [10 - 12]. During the past twenty years, in particular, high-frequency-based methods have gained significant interest and importance [13-23].

This paper will focus on recent results obtained by the high-frequency mechanical impact (HFMI) treatment of longitudinal stiffeners. Significant fatigue strength improvement has been observed for constant amplitude loading and also for variable amplitude (spectrum) loading. These results are assessed with respect to the further potential for lightweight structural design rendered by these types of loading [24, 25].

Nomenclature								
D	damage sum	K <sub>t</sub>	theoretical stress concentration factor					
Ls	sequence length	t	thickness					
Ν	number of cycles	$T_{\sigma}$	scatter of fatigue strength					
Ps	probability of survival	Δ	range					
R	load or stress ratio, $R = F_{min}/F_{max}$ or $\sigma_{min}/\sigma_{max}$	Subscri	pts					
k	slope of the Woehler- or Gassner-line	а	amplitude					
k*	slope of the Woehler-line after the knee point	al	allowable					
	for constant amplitude loading	an	nominal amplitude					
k'	slope of the Woehler-line after the knee point	k	knee point of the Woehler-line					
	for cumulative damage calculation	f	failure					
ρ	notch radius	th	theoretical					

#### 2. High-frequency mechanical impact treatment of investigated joints

#### 2.1. Principles of HFMI – treatment

There has been a steady increase in the number of HFMI peening equipment manufacturers and service providers during the past decade. Manufacturers have customised the effectiveness of their own tools by using indenters with different diameters, tip geometries, or multiple indenter configurations. Alternate power sources are also employed, for example, ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements, or compressed air [19- 21]. In all cases, however, the working principle is identical: Cylindrical indenters are accelerated against a component or structure with high frequency (> 90 s<sup>-1</sup>). Consequently, Commission XIII of the International Institute of Welding (IIW) introduced the term high frequency mechanical impact (HFMI) as a generic term to describe numerous related technologies [21]. Fig. 1 shows typical weld profiles in the as-welded condition and after HFMI-treatment. The impacted material after HFMI is highly plastically-deformed. This causes changes to the material microstructure and the local geometry, as well as to the residual stress state in the region of impact.

As seen in Fig. 1, the HFMI-treatment influences the weld toe geometry by increasing the weld toe radius and consequently reducing the stress concentration. Further, the local hardness is increased due to the local cold forming and beneficial local compressive residual stresses [3] are induced, as illustrated in the following section.

Table 1. Typical treatment parameters [8]	
Frequency of the ultrasonic transducer	27 kHz
Impact frequency under loaded conditions	100-120 Hz
Ultrasonic oscillation amplitude during treatment	10-40 μm
Depth of plastic deformation	up to 1.5 mm
Indenter: Hardness	HRC 6264
Radius (varies depending on treatment parameters)	2 and 5 mm
Power of the tool	600-1200 W
Range of tool oscillation angle during treatment relative to the initial position of 45°	35-55°
Number of pins	1 or 4
Typical treatment rate (not less than 0.2 m/min)	0.3 – 1.5 m/min

a. As-welded local geometry



Fig. 1. Macrographs of the fatigue-critical locations of longitudinal stiffeners before and after the HFMI-treatment

b. A typical local geometry after HFMI

#### 2.2. Joint geometry and material states

Investigations were carried out on welded specimens containing longitudinal stiffeners, as shown in Fig. 2. Details of the specimens and welding procedures have been described previously [17, 22]. The experimental observation that this specimen geometry demonstrates low fatigue strength, even for fully-reversed loading, is attributed to relatively high tensile residual stresses [1], as compared to butt-welded specimens, or specimens with transverse stiffeners. These high residual stresses justify the use of a post-weld treatment process which promises significant fatigue strength improvement. Joints in the current study were fabricated from the high-strength steel, S700. The chemical composition and conventional material properties are detailed in Tab. 2. The welding parameters are presented in Tab. 3. Fig. 3a shows the hardness distributions in the as-welded and HFMI-treated states as HV10- and HV0.2-values. Increased hardness for the HFMI-treated joints is observed.

Significant variations in the measured surface residual stress distributions at the fatigue-critical locations before and after HFMI-treatment are observed in Fig. 3b. Residual stress measurements were carried out non-destructively using X-ray diffraction. Measurements for the HFMI-treated specimens were performed at the bottom of the HFMI groove at the end of the stiffener. For the as-welded specimens, measurements were taken as close was possible to the weld toe. Measured stresses were perpendicular to the weld toe, i.e., longitudinal with respect to the axis of the specimen. The dashed lines in Fig. 3b represent the 10% and 90% scatter limits of the measured data. It can be clearly seen that the surface residual stresses were transformed from tensile residual stresses in the aswelded state into beneficial compressive residual stresses by the HFMI-treatment [3]. Even in the absence of the reduced stress concentration factors mentioned previously, the change in residual stress state would be expected to result in longer fatigue life as compared to the as-welded condition.



Fig. 2. Geometry of longitudinal stiffeners

Table 2. Conventional material data

a. Chemical composition

Steel type	С	Si	Mn	Р	S	В	Cr	Cu	Мо	Al	Nb	Reference
S700	0.15	0.44	1.32	0.012	0.002	-	1.50	0.50	0.70	0.099	0.06	Marquis (2010)
S700	0.20	0.80	1.70	0.020	0.010	0.005	1.50	0.50	0.70	-	-	Yıldırım and
												Marquis (2013)

[%] ladle analysis, maximum values

b. Mechanical properties (reported minimum values)

Steel type	R <sub>p0.2</sub> in MPa	R <sub>m</sub> in MPa	Elongation in %	Impact strength J at -40 °C	Reference
S700	700	850	14	-	Marquis (2010)
S700	690	770-940	14	30	Yıldırım and Marquis (2013)

Table 3. Welding materials and conditions

Welding material	Wire diameter in mm	Current in A	Voltage in V	Speed in cm/min	Shielding gas flow in l/min	Shielding gas	Reference
Union X96	1	260	30.2	42-60	18	Ar + 10% CO2	Marquis 2010
ESAB: OK	1	150	28	23	15	Ar + 8% CO2	Yıldırım and
AutRod 13.29							Marquis (2013)



Fig. 3. Hardness and residual stress distributions of longitudinal stiffeners before and after HFMI-treatment

#### 3. Fatigue tests under constant and variable amplitude loading

The fatigue test results re-evaluated in the present paper originate from previous investigations carried out with the same material, S700, and joint type, i.e., a longitudinal stiffener [17, 22], Tab. 2 and Fig. 2. The fact that two different specimen batches are compiled in this study may be questioned with regard to their joint evaluation; but the similarity of the base materials, welding conditions and, above all, of the local geometries and the acceptable scatter of obtained fatigue strengths below  $T_{\sigma} = 1:(N_{Ps=10\%} / N_{Ps=90\%}) \leq 1:1.50$  [11], justifies this approach. Previous evaluations of the data did not consider the Woehler-lines obtained under constant amplitude loading (CAL, rectangular spectrum) and the Gassner-lines determined under variable amplitude loading (VAL, straight-line spectrum) for the two investigated material states, i.e., as-welded and HFMI-treated. In addition to the computed fatigue strength improvement obtained via HFMI-treatment, the degree to which the Woehler-lines exceeds the Gassner-lines offers a more complete picture concerning the potential for lightweight design for HFMI treated joints subjected to spectrum loading [24, 25].

#### 3.1. Testing conditions

Constant amplitude tests were carried out using 8 as-welded and 10 HFMI-treated specimens, while the variable amplitude tests were performed with 6 as-welded and 24 HFMI-treated joints. Stress ranges were selected such that the resulting fatigues lives tests were in the range of  $10^5$  to  $10^7$  cycles to failure under fully-reversed loading, R = -1. Depending on the load range, frequencies of specific cycles varied from 3 to  $10 \text{ s}^{-1}$ . The failure criterion was total rupture. In the case of constant amplitude loading, the results are presented according to the stress amplitude; for variable amplitude loading, the results are shown in relation to the maximum amplitude of the spectrum [24, 25].

The applied spectrum was a cumulative, straight-line distribution with a sequence length of  $L_s = 2x10^5$  and an irregularity factor of I = 0.99, as shown in Fig. 4. The spectrum was obtained from a straight-line distribution with a sequence length of  $L_s = 2x10^7$  by imposing a 19% omission of small amplitude cycles. This omission level reduced the testing time by an estimated factor of 10. Previous investigations show that this omission level is not expected to significantly influence the number of repetitions of the sequence to failure [24].





#### 3.2. Results

Figure 5 shows the computed Woehler- and Gassner-lines for both weld conditions. The knee-points of the Woehler-lines at  $N = 1 \times 10^7$  cycles and the assumed slope below the knee-point,  $k^{*=} 22$ , were deduced based on previous studies [11, 26]. The slopes of the Woehler- and Gassner-lines above the knee-points were determined by linear regression. The shallower slopes of the HFMI-treated joints result from the fact that, at higher stress levels, the beneficial compressive residual stresses near the weld toe are more reduced due to localised reversed plasticity than at lower stress levels [3].



Fig. 5. Woehler- and Gassner-lines obtained by constant and variable amplitude loading of longitudinal stiffeners of S700 in as-welded and HFMI-treated states

#### 4. Discussion of results with regard to lightweight design

#### 4.1. Effect of the HFMI – treatment

Generally, the HFMI-treatment improves the fatigue strength due to induced compressive residual stresses and owing to the reduced stress concentration factor. However, the increase in fatigue strength under constant amplitude loading by HFMI, factor 3.3 at e.g.  $1 \times 10^7$  cycles, is significantly higher than for spectrum loading, factor 1.4 respectively, as seen in Fig. 5. The reason for this is that under spectrum loading, higher load levels lead to a more severe reduction of compressive residual stresses than under constant amplitude loading. Even under constant amplitude loading at higher load levels, the increase in fatigue strength is less than at lower load levels for the aforementioned reasons [3].

#### 4.2. Effect of spectrum loading

With respect to proper design procedures for lightweight structures, and after the consideration of HFMI on fatigue strength, the benefit of considering spectrum loading for dimensioning components and structures should also be reviewed [24 - 28]. Figure 5 shows that the Gassner-lines for as-welded as well as HFMI-treated states lie significantly above the respective Woehler-lines, at e.g.  $1 \times 10^7$  cycles factor 6.0 versus 2.6.

The significance of these exceedance factors is that, for a given spectrum and a required fatigue life, much higher fatigue strengths are allowed for a component subjected to spectrum loading than for one under constant amplitude loading [24 - 27]. Thus, the dimensions of a component can be further optimised with respect to reduced weight, based on the spectrum shape-dependent exceedances.

The possibility to make use of higher computed fatigue strengths for components subjected to spectrum loading, as opposed to constant amplitude loading, contributes very significantly to the realisation of lightweight designs. The practical use of this observation in engineering design practice was one of Gassner's many innovations [29]. Therefore, in the context of lightweight design, it must be underscored that the benefit by the HFMI-treatment is further amplified when the advantage of spectrum loading is also considered. However, there are also limitations regarding the reduction of plate thickness by stability requirements like avoidance of buckling or not allowed global plasticity.

#### 5. Conclusions and prospects for lightweight designs

The disadvantages of the welding process, i.e., the coarsening of a good microstructure, the introduction of defects and stress concentrators (weld toe) and the unfavourable tensile residual stresses, can all be overcome, as indicated by the exceedance and improvement factors in Fig. 5. Indeed, they are quite impressive and pave the way for a wide range of opportunities for lightweight design. Notwithstanding, these factors were obtained for longitudinal stiffeners under spectrum loading with a straight-line distribution, and under fully-reversed loading (R = -1) only, i.e., under stress ratios of R > -1. However, fuller distributions and lower stress concentrations would not be expected to result in such high strength levels.

This is demonstrated in Fig. 6 by the comparison of Gassner-lines obtained under different spectra with longitudinal stiffeners in the as-welded state. The base metals are not the same, but since their Woehler-lines do not differ significantly from each other, it can be assumed that the Gassner-line for S700 under a Gaussian spectrum will not differ significantly from that obtained with the St52 steel (corresponds to S355). The Gassner-line for the Gaussian distribution [3, 30] is, as expected, below the line for the straight-line distribution; the exceedance factor at e.g.  $1 \times 10^7$  cycles is lower, 4.8 versus 5.8. The inferior position for the Gaussian spectrum results from the fact that under a fuller spectrum, compressive residual stresses are decreased more than under a less full spectrum. The slopes of the Gassner-lines depend not only on the spectrum shape, but also on the different yield stress levels of the materials. An HFMI-treatment would probably result under a Gaussian spectrum-less improvement, compared to a

straight-line spectrum, because of the more pronounced decrease of the compressive residual stresses due to the spectrum fullness.



Fig. 6. Woehler – and Gassner –lines of as-welded longitudinal stiffeners of the steels S700 and St52-3 (corresponds to S355) under different loading spectra.

The result of this short discussion is that the improvement factors presented in this paper cannot be overgeneralised. Improvement factors result from the interaction between joint geometry, local stress concentration and residual stress state, spectrum shape and finally, loading mode. Further, for reasons associated with stability, high improvement factors cannot be fully exploited because impact or elasto-plastic overloads [27, 28] may limit the reduction of material thickness.

The current state of knowledge reveals that for a wider application of the HFMI-treatment, more data about the influence of weld geometry, spectrum shape, loading mode and residual stress state would be beneficial to lightweight design considerations, due to the interaction of these parameters which determine the grade of improvement related to the as-welded state. However, particularly in the case of safety components, experimental verifications are strongly recommended.

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