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## Possibilities of Increasing the Fatigue Strength of Welded Joints in Steel S700MC through High Frequency Impact Treatment (HiFIT)

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**Abstract:** The article presents today's possibilities of modifying the fatigue strength of welded joints made in steel S700MC using the high frequency impact treatment (HiFIT). Research-related fatigue tests involved MAG-welded butt joints, T-joints with two-sided fillet welds as well as joints with a longitudinal rib and a girth fillet weld. The tests required the adjustment of appropriate parameters of the HiFIT and the performance of the above-named treatment in relation to the half of previously made joints. The article presents results of fatigue tests of joints after welding and after the HiFIT. The research also included the development of fatigue characteristics and the calculation of fatigue categories FAT, constituting the basis for the design of structures exposed to fatigue (in accordance with European standards). The results obtained in the tests unequivocally demonstrated the possibility of increasing the fatigue strength of welded joints made in steel S700MC by applying the HiFIT, with the level of fatigue strength modification depending on the type of a joint.

**Keywords:** modification of fatigue strength, fatigue strength of welded joints, FAT S700MC, peening, HiFIT

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### Introduction

Most structures exposed to changing loads during operation are at risk of fatigue failure. The fatigue strength of notch-free materials depends primarily on their mechanical properties, surface quality, surrounding environment and the level of imposed stresses. Once the fatigue crack has been initiated, its propagation depends, among other things, on the material

microstructure. The initiation of the crack and its propagation can be avoided or delayed by the generation of compressive stresses in the subsurface area of an element near the notch.

Techniques enabling the generation of high compressive stresses are varied and many. They can be divided into mechanical treatment methods (shot blasting, peening, surface burishing, overstraining etc.) and heat treatment

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methods (carbonising, nitriding, flame hardening, induction hardening etc.). The process of welding is accompanied by the generation of tensile stresses reducing fatigue service life of the joint. Available techniques, such as surface impact treatment (e.g. peening), make it possible to reduce tensile stresses or change the stress condition in welded joints.

In most cases, the fatigue strength of entire structures can be increased through the modification of the fatigue strength of crucial elements (e.g. welded joints exposed to high loads). In the above-named cases, the use of local methods aimed to increase the fatigue strength of welded joints proves effective. Plastic strains of interfaces between the weld face and weld root and the base material lead to the generation of internal compressive stresses in the near-weld layer and an increase in the hardness of surface. A local increase in hardness is tantamount to a local increase in tensile strength and delayed crack initiation. Introduced compressive stresses interact with service load-induced stresses, resulting in delayed crack initiation and increased strength [1-5].

Welded joints of high-strength steels (e.g. TMCP steels or toughened steels), more sensitive to the notch phenomenon than conventional structural steels, are often subjected to treatment extending fatigue service life (e.g. shot blasting, TIG method-based remelting of weld edges, impact treatment or grinding). Recent years have seen the significant development of impact techniques, including the high-frequency mechanical impact (HFMI). The above-named technique was originally developed by the Northern Scientific and Technological Foundation in Severodvinsk in Russia in conjunction with the E.O. Paton Electric Welding Institute in Kiev. Presently, this technique is the subject of research in many other countries as well. The recent decade has seen a steady increase in the number of producers offering HFMI equipment as well as a growing number of related service providers. There are many

systems enabling high-frequency impact generation, e.g. ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements or elements involving the use of high-pressure compressed air.

The principle of high-frequency impact treatment has evolved from the conventional peening technique and involves the local high-frequency burnishing of a crucial joint area using specifically designed tips made of very hard materials. In cases of welded joints, the above-named cold high-frequency strains improve the joint profile, introduce favourable compressive strains and increase hardness. All of the above-named factors lead to the increased fatigue strength of welded joints.

The HFMI treatment is more user-friendly and characterised by very short intervals between successive impacts affecting the workpiece. As a result, the surface finish is smoother than that obtained through conventional peening.

Presently, the market offer includes HFMI treatment devices available under various names, e.g.:

- devices for ultrasonic impact treatment (UIT) [6],
- devices for ultrasonic peening (UP) [7],
- devices for ultrasonic peening treatment (UPT) [8-9],
- devices for high-frequency impact treatment (HiFiT) [5],
- devices for pneumatic impact treatment (PIT) [10],
- devices for ultrasonic needle peening (UNP) [11-12].

Regardless of names of devices used by producers and differences, if any, in terms of the design and power supply, all of the above-named devices are related to techniques composing the general high-frequency mechanical impact technique (HFMI).

The article presents the results of experimental fatigue tests, where the modification of the fatigue strength of welded joints was performed using a high-frequency impact treatment

(HiFIT) device. In the above-named system, the element affecting the surface is a cylindrical pin having (usually) a diameter of 3 mm (but also 5 mm and 10 mm) and a tip rounding radius of 1.5 mm. During peening, the steel pin is moved along the interface between the face and root of excess weld metal and the base material, resulting in the generation of plastic strains and the unification of the interface geometry. The surface subjected to treatment becomes harder and provided with compressive stresses at a depth restricted within the range of 1 mm to 1.5 mm. The interface is smooth and strained at a depth restricted within the range of 0.1 mm to 0.3 mm. All of the above-named factors lead to the increased fatigue strength of the joints.

The use of the HFMI technique enables the obtainment of significantly greater (in comparison with that obtained using classical peening) improvement in fatigue strength combined with an increase in the strength of workpieces (the higher the strength of the material, the higher the obtainable fatigue strength of the material).

## Tests and testing methodology

### Test materials

The tests involved the use of 10 mm thick welded joints made of fine-grained TMCP steel S700MC. The chemical composition of steel S700MC is presented in Table 1, whereas the most important mechanical properties of the steel are presented in Table 2.

Table 1. Chemical composition of steel S700MC (in accordance with the inspection certificate), in %

Steel grade	C	Si	Mn	P	S	N	Al
	0.07	0.18	2.0	0.012	0.001	0.005	0.049
S700MC	Ti	Cr	Ni	Mo	Nb	V	B
	0.06	0.06	0.16	0.12	0.08	0.08	0.0001

Table 2. Mechanical properties of steel S700MC (in accordance with the inspection certificate)

Steel grade	Yield point $R_{e_s}$ MPa	Tensile strength $R_m$ MPa	Minimum elongation at rupture $A_5$ , %	Impact energy KV <sub>2</sub> in -40°C, J
S700MC	686	762	21	107

### Test joints

Joints used in the tests included butt joints, T-joints with fillet welds and joints with the longitudinal rib and the girth fillet weld. The aforesaid joints were made at the Welding Technologies department of Instytut Spawalnictwa using the MAG method and a KEMPPi PROMIG 500 welding machine. The filler metal used in the tests was the BÖHLER X 70-IG solid electrode wire having a diameter of 1.2 mm, whereas the shielding gas was mixture M21 (82% Ar +18% CO<sub>2</sub>).

The fatigue tests involved 3 series of welded joints referred to in Table 3. Each series was sampled for 12 test specimens in the as-welded state and 12 specimens after the HiFIT. Table 4 presents information concerning welding process technological parameters.

### High-frequency impact treatment of test joints

The high-frequency impact treatment (HiFIT) process was performed using a HiFIT station provided with a pin having a diameter of 3 mm, a flexible air duct and a filter equipped with a manometer enabling the adjustment of required supply pressure (Fig. 1). The test joints subjected to the treatment were fixed to the table using conventional joinery clamps (Fig. 2).

The HiFIT proper requires the adjustment of appropriate process parameters. The process parameters are identified experimentally by:

- adjustment of appropriate operating pressure,

Table 3. Test joints


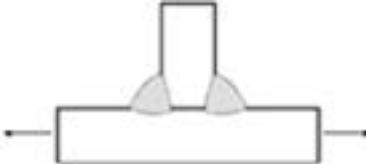
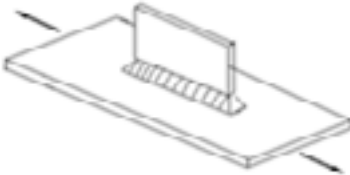
Type of joint (series)	Schematic diagram	Joint in the as-welded state	Number of specimens	Joint after HiFIT	Number of specimens
Butt joint		YES	12	YES	12
T-joint with fillet weld		YES	12	YES	12
Joint with longitudinal rib with girth fillet weld		YES	12	YES	12

Table 4. Welded joints and technological parameters

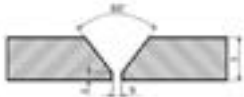

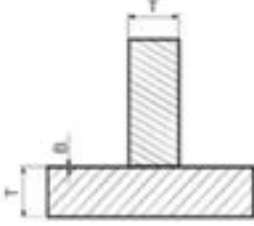


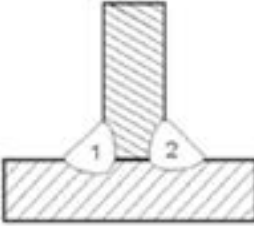
Type of joint	Butt joint	T-joint with fillet weld	Joint with longitudinal rib and fillet weld
Schematic diagram and welding sequence	 $t = 10 \text{ mm}; b = 2-3 \text{ mm}; c = 1-2 \text{ mm};$	 $t = 10 \text{ mm}; b = 0-1 \text{ mm};$	 $t = 10 \text{ mm}; b = 0-1 \text{ mm};$
			
Welding method	135	135	135
Filler metal wire diameter	$\varnothing 1.2 \text{ mm}$	$\varnothing 1.2 \text{ mm}$	$\varnothing 1.2 \text{ mm}$
Current	112-121 A (run 1) 240-254 A (run 2-5)	230-244 A	248 A
Arc voltage	16 V (run 1) 26 V (run 2-5)	26-25.5 V	26.8 V
Welding rate	138 mm/min (run 1) 350 mm/min (run 2-3) 400 mm/min (run 4-5)	380 mm/min	380 mm/min
Filler metal wire feeding rate	6.5 m/min	6.5 m/min	6.5 m/min



Fig. 1. Main view of elements used in the HiFIT



Fig. 2. Fixing of joints subjected to the HiFIT

- adjustment of peening intensity by changing a piston stroke in order to:
  - obtain smooth surface in the area subjected to the treatment (without jagged area/edges),
  - obtain the depth of treatment restricted within the range of 0.2 mm to 0.35 mm.

The quality of the surface in the area subjected to the HiFIT was assessed visually, whereas the depth of treatment (strain) was measured using a special gauge (an element of the HiFIT system).

### **Methodology of fatigue tests**

The fatigue tests were performed using an MTS 810 testing machine provided with a hydraulic drive (Fig. 3). The tests involved the axial exposure of the welded joints to force triggering changeable tensile stresses in the specimens; stress ratio  $R$  amounted to 0.2. Each series of the test welded joints was tested in two states, i.e. in the as-welded state and after the HiFIT.



Fig. 3. Test rig used in the fatigue tests (MTS 810 testing machine)

The fatigue tests of each series, i.e. the butt joints, the joints with the fillet welds and the joints with the longitudinal rib and the fillet weld involved 12 specimens, where statistical analysis involved representative test results in relation to 10 specimens. The assumptions adopted in all of the tests were the following:

- tests involving several ranges of stress level  $\Delta\sigma$ ,
- stress ratio  $R=0.2$  ( $R=\sigma_{\min}/\sigma_{\max}$ ),
- frequency of load changes: 20 Hz,
- ultimate number of cycles  $N=2\cdot 10^6$ ,
- tests performed until the rupture or the

obtainment of the ultimate number of cycles.

The test results in the form of the number of cycles preceding the rupture were recorded using the Multi Purpose Test Ware software

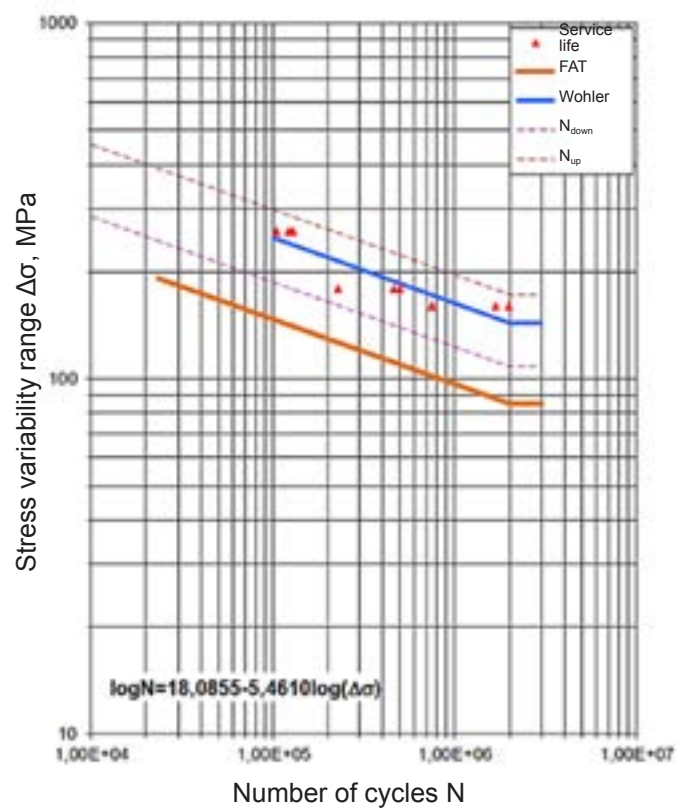
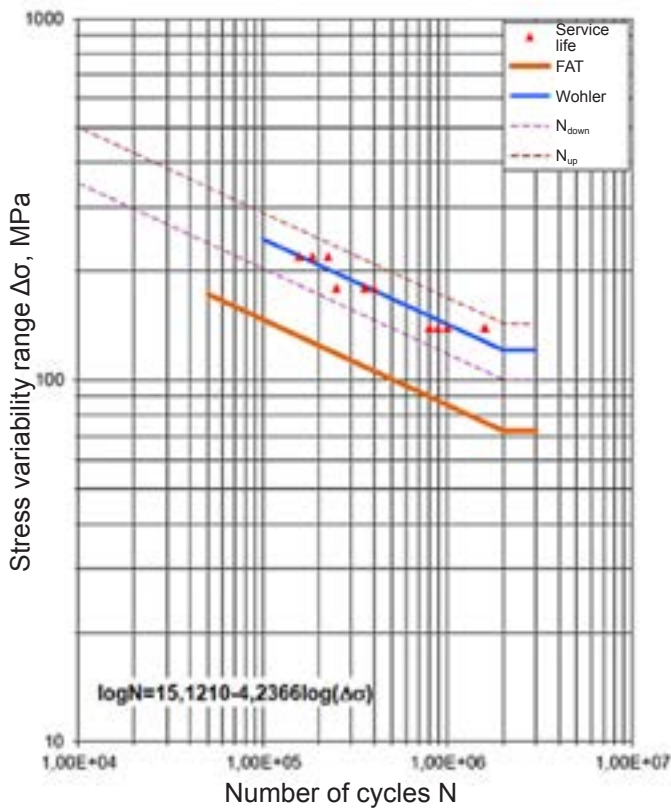


Fig. 4. Fatigue curves in relation to the butt joints made of steel S700MC; a) without HiFIT; b) after HiFIT [14]

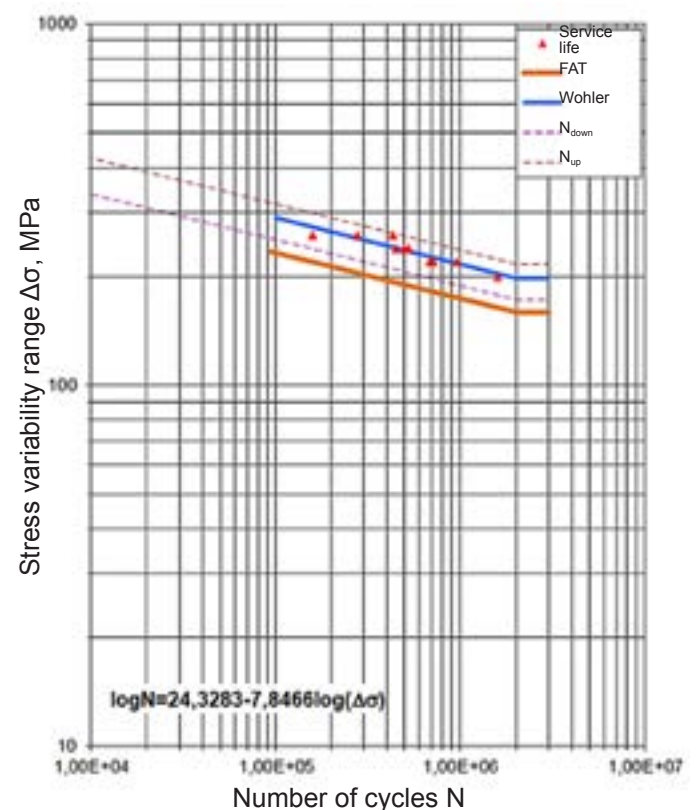
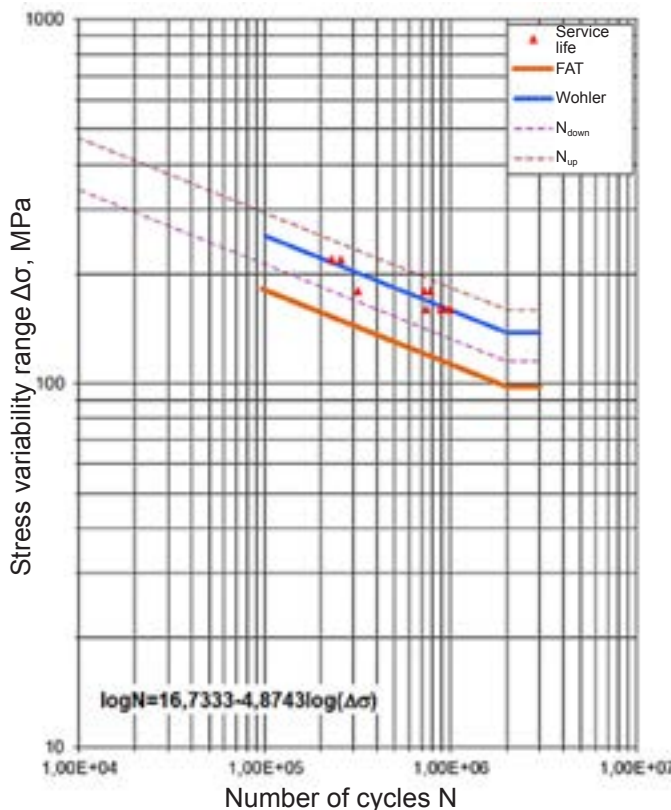


Fig. 5. Fatigue curves in relation to the T-joints with the fillet welds made of steel S700MC; a) without HiFIT; b) after HiFIT [14]

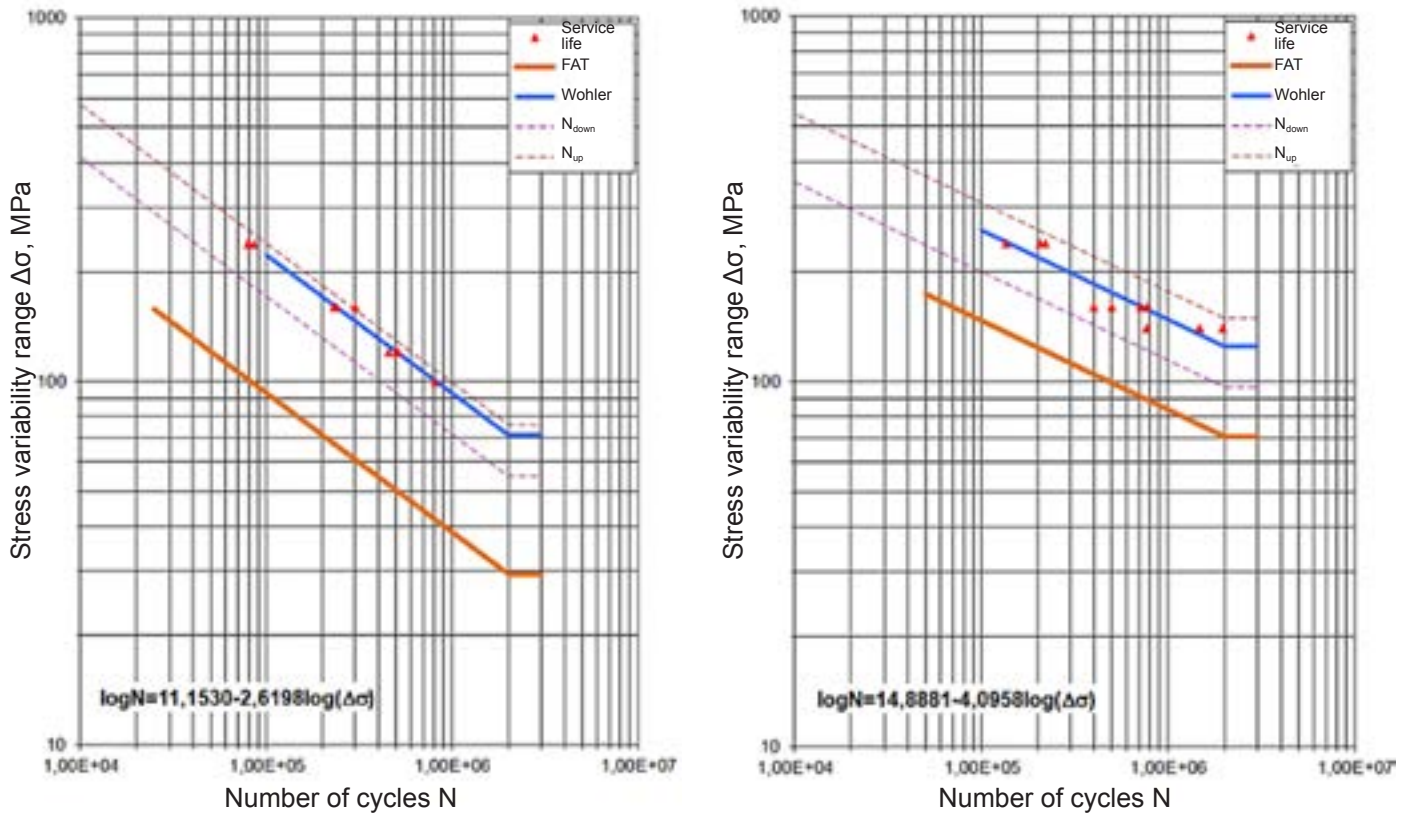


Fig. 6. Fatigue curves in relation to the welded joints with the longitudinal rib and the girth fillet weld made of steel S700MC; a) without HiFIT; b) after HiFIT [14]

programme (MTS). The results are presented in the form of Wöhler fatigue curves. Fatigue categories FAT were calculated in accordance with guidelines specified by the International Institute of Welding [13].

### Test results

The test results in the form of Wöhler fatigue curves (marked blue) are presented in Figures 4-6; lines corresponding to fatigue categories FAT are marked orange.

### Summary

The principal part of the research work involved experimental fatigue tests of welded joints made of steel S700MC. The tests aimed to determine the fatigue characteristics of the welded joints as well as to identify the possibility of increasing the fatigue strength of the welded joints using the HiFIT-based method. The fatigue tests involved three different types of welded joints in two states, i.e. in the as-welded state and after the HiFIT. The test results are presented in Table 5 for comparison. In addition, the Table

contains information concerning the percentage increase in the fatigue strength FAT of the joints subjected to the HiFIT.


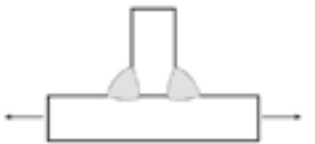
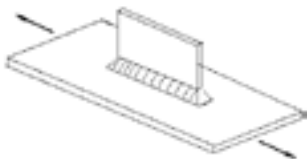
The analysis of the test results revealed an increase in fatigue strength in each type of joint made of steel S700MC and subjected to the HiFIT. In relation to the butt welded single-sided joints an increase in fatigue strength expressed in FAT amounted to 18% and represented the lowest value among the joints subjected to the tests.

In terms of the T-joints with the two-sided fillet welds in the as-welded state and after the HiFIT, the value of fatigue strength increased by 62%.

The highest increase in fatigue strength FAT obtained as a result of the HiFIT was observed in relation to the joints with the longitudinal rib with the girth fillet weld and stood at a massive 137% in comparison with the joints in the as-welded state.

The increase in fatigue strength, i.e. the increase in characteristic value FAT, proved high in relation to the T-joints and the joints with

Table 5. Fatigue test results and standard characteristic values [14]

Type of joint	Schematic diagram	Fatigue strength FAT, MPa		
		After welding	After HiFIT	Increase in FAT
Butt joint		72	85	18%
T-joint with fillet welds		98	159	62%
Joint with the longitudinal rib and the girth fillet weld		30	71	137%

the longitudinal rib. In the butt joints, the HiFIT effect was visibly lower, yet also considerable. The test results confirmed the principle that the greater the notch in the joint (i.e. the greater the effect of the notch), the higher the HiFIT-triggered increase in fatigue strength. Similarly, the smaller (or the more gentle) the notch, the less favourable the HiFIT effect. In relation to the subject of the research, the largest notch was the longitudinal rib and in relation to such joints the favourable effect of the HiFIT was the highest. In turn, because of the fact that the excess weld metal of the butt weld face and of the root constituted the gentlest notch, the effect of the HiFIT as regards an increase in fatigue strength was the lowest.

It should be stated that the HiFIT of welded joints made in steel S700MC leads to the higher fatigue strength of welded structures made of the aforesaid steel grade.

### Conclusions

The tests justified the formulation of the following conclusions:

1. It is possible to significantly modify the fatigue strength of welded joints made of TMCP steel S700MC using the high frequency impact treatment (HiFIT).
2. In relation to the steel grade subjected to the HiFIT, an increase in fatigue strength FAT

depended on the type of a joint and was related to the effect of the notch of a given welded joint.

3. The increase in the fatigue strength of the welded joints made in steel S700MC after the use of the HiFIT amounted to 18% in relation to the one-sided butt joints, 62% in relation to the T-joints with two-sided fillet welds and 137% in relation to the joints with the longitudinal rib and the girth fillet weld.

4. The HiFIT equipment is easy to use and offers the efficient modification of the fatigue strength of welded joints.

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