Fatigue Investigation of Ultrasonic Impact Treatment on Welded Structures

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ABSTRACT

The present paper describes the technology of Ultrasonic Impact Treatment (UIT) to improve the mechanical properties of engineering components focusing on welds. It shows its current successful application to thick welded components and proposes research activities to extend the applicability of UIT to thin welded structures. In addition, metallurgical, surface and fatigue investigations are proposed within the framework of the research programme. A calculation procedure according to the IIW guideline is brought into discussion to assess the fatigue behaviour of UI treated thin welded structures based on hot spot and/or effective stresses.

KEYWORDS

Ultrasonic impact treatment, welds, fatigue, finite element modelling, analytical concepts

INTRODUCTION

Ultrasonic Impact Treatment (UIT) is an after-treatment surface technology developed to improve quality, carrying capacity and life of metallic components and welded structures with long service life [1]. Positive results of fatigue testing [2, 3] and UIT applications [4] are well known. IIW UIT Specification was issued [5] and a guideline was created [6]. In the last two decades UIT has been further developed and additional data on UIT efficiency have been obtained [7, 8]. Algorithms of UIT operational procedures have been developed for fabrication, maintenance, and repair of welded joints with considerations for metal properties and welded joint types. The design and technical parameters of UIT equipment are continuously improved with the aim to increase the fatigue strength of welded structures. Until today, the engineering application of UIT refers to thick components or welded structures. The proposed research activities aim at the
- optimization of the UIT technology and specification of the technological parameters for its application to thin welded structures (thicknesses \(2 \leq t \leq 5\) mm) made of ductile steels in order to improve their surface properties and fatigue life
- development of an accurate theoretical model calculating the mechanical response and fatigue life of thin welded structures subjected to operational fatigue loading taking into account the UIT.

UIT TECHNOLOGY

The Ultrasonic Impact Treatment (UIT) method belongs to the class of residual stress improvement methods. Especially the UIT method, as a promising post-weld surface treatment technique to improve the fatigue resistance of welded joints, was first invented and patented in the 1970s [9]. The working principle of the UIT method is based on the transmission of high frequency impacts (approximately 27 kHz) into the welded joint material. The main tool of the UIT equipment that is excited by ultrasonic harmonic vibrations is illustrated in figure 1. This occurs under the action of the impulse of force, which is generated by ultrasonic transducer vibrations at the rear end of a freely axially moving needle indenter (III) with a normalized wave length directly contacting the transducer tip (II) and the impact welded surface (IV). The core (I) of the ultrasonic transducer is from magnetostrictive material and is oscillated at ultrasonic vibrations due to the magnetic field induced by the transducer coil that is supplied by high frequency alternating current.

![Fig. 1: Post Weld UIT working principle](image)

The applied impact force (lower wavelength) on the weld toe material, as well as the resulted impact displacement of the indenter (upper wavelength) is shown in Figure 2.
The UIT results on the treated surface are schematically demonstrating in Figure 3. In this scheme in a cross-sectional view of surface layer of treated metal all affected zones of the welded joint due to the Ultrasonic impact treatment are shown as well as its physical action [1].

The main technological factors of the UIT method that are significant for the weld toe treatment are the impact frequency, the impact force and the indenter geometry. Former studies curried out [7, 10, 11] demonstrated the successful implementation of UIT method on welded joints by minimization of the thermal residual stresses, optimization of the microstructure and smoothing of the geometry in the welding area. Moreover, the above treatment has as outcome the restriction or obstruction of the shape distortion of the
structure. This positive effect of the treatment is depicted characteristically in the scanning electron microscopy photos of Figure 4.

Fig. 4: Microstructure modification and surface smoothing of the weld toe due to UIT

In addition, the plastic deformation caused by the ultrasonic impact treatment in the substrate of the welded joint region is combined with the development of compressive stresses, which prevent both the appearance and propagation of cracks and thereby with significantly improvement of the fatigue strength of the welding structure, as shown in the Wöhler diagram of Figure 5.

Fig. 5: Impact of after welding treatments on the fatigue strength of welded joints

The following Table shows the qualitative and the quantitative assessment of the UIT method based on its implementation in thick welded joint structures [12].
### Physical Zones

<table>
<thead>
<tr>
<th>Physical Zones</th>
<th>Ultrasonic Impact Treatment Results</th>
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<tbody>
<tr>
<td>“White layer”</td>
<td>Enhancement of wear-resistance, corrosion resistance and surface quality</td>
</tr>
<tr>
<td>Plastic deformation</td>
<td>Improvement of cyclic endurance, corrosion-fatigue strength and compensation of structure deformation</td>
</tr>
<tr>
<td>Impulse relaxation</td>
<td>Reduction in residual welding stress and strain of up to 70% of the initial state</td>
</tr>
<tr>
<td>Ultrasonic relaxation</td>
<td>Reduction in residual welding stress and strain of up to 50% of the initial state</td>
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</table>

Table 1: Qualitative and quantitative review of the UIT method in thick wall welded structures

The advantages of the UIT utilization on welded joint material properties and condition are widespread a lot and of partial interest to improve the fatigue life of welded structures. To sum up, the UIT method as a post-weld treatment technique reduces unfavorable residual tensile stresses, creates beneficial compressive stresses in the weld and at the weld toe region, reduces stress concentrations and improves the corrosion and corrosion fatigue resistance of UIT treated areas of welded joints. Thus, the innovative UIT method is capable to provide new opportunities for manufacturers, engineers to meet the requirements for lightweight but safe constructions (e.g. use of high strength steel in combination with reducing of the construction elements thickness, etc.).

### EXPERIMENTAL AND THEORETICAL PROGRAMME

#### Specimen geometry and load configuration

Fig. 6 shows exemplary the specimen geometry and the load configuration to be applied within the research investigation.

Two hollow, thin-walled, horizontal beams are joined perpendicular to a vertical, hollow, thin-walled beam via fillet welds. Standardized beam profiles according to DIN 2395 will be used made of two different ductile steels, St44 and M22, which are often used, e.g. in bus frame constructions. At least 3 different beam thicknesses, t=2mm, t=3mm and t=5mm, are to be investigated. The horizontal beams will be fixed and side forces will be applied perpendicular to the vertical beam axis. Nominal stresses as well as the ones acting in the weld toe areas will be measured by means of strain gages at monotonic and fatigue loading. The results will be used to verify the accuracy of the theoretical model.
UIT Experiments and Analysis

Once checked the functionality of the UIT equipment with preliminary tests in weld specimens, it will be used for conducting surface treatments of welded joints. The testing parameters are the impact frequency, the impact force, the feed velocity of the UIT pin along the weld seam, as well as the indenter’s geometry.

The weld specimens after the ultrasonic impact treatment will undergo to metallographic examination of their microstructure. An extensive characterization of the material and mechanical properties of the weld will also take part. This investigation consists of micro-hardness measurements, residual stress measurements, x-ray tomography and micro-topomorphy inspection by three-dimensional scan in micro scale of the weld seam surface.

The above investigations aim at checking the existence of porosities and discontinuities in the welds. Further object of the above mentioned investigations is the assessment of the weld properties and condition after the treatment, in order to prove the effectiveness of the UIT with regard to the elimination of residual tensile stresses and enhancement of the weld fatigue life.

The experiments to improve the fatigue strength of the welded specimens using the UIT technique, as well as the conducted investigations concerning the weld microstructure and its mechanical properties will be held as follows:

- In three specimens of each preselected geometry for the purpose of the weld properties characterization, both inside the weld material and in the transition zones without UIT (as-welded condition). The results of these investigations will constitute the reference values (as-welded condition).
• In at least three specimens of each one of the three preselected welding geometry (a total of 2x3x3 = 18 specimens with UIT). For these specimens will be also conducted metallographic examination and weld properties characterization after the weld surface ultrasonic impact treatment.

The following issues will be investigated on the specimens:

(a) Welding quality
(b) Microstructure into the weld layers and the transition zone
(c) Distribution of micro-hardness from the surface towards the heart of the weld seam
(d) Micro-topomorphy of the weld surface
(e) Exact geometry of the transition area from weld material to the parental one
(f) Allocation of residual stresses from the weld surface to the kernel
(e) Weld toe geometry that occurs after the surface smoothing due to UIT.

**Fatigue tests**

A series of fatigue tests with constant and variable amplitudes on all types of fillet joined specimens is defined to
- determine new knowledge on the influence of UIT on mechanical properties and fatigue behavior of welds in thin-walled structures
- determine Wöhler curves for welds after-treated with the chosen UIT parameters. The Wöhler curves will be compared with corresponding ones of welds without after-treatment
- quantify and describe the influence of load sequence effects on damage and fatigue life.

The Wöhler curves will cover at least two stress ratios. The strains in the weld affected areas as well as in nominal areas will be measured by means of strain gages.

**Theoretical fatigue assessment methodology**

The theoretical programme consists of two parts: the numerical (FE modelling) and analytical one.

The numerical part deals with finite element calculations executed by means of both shell and solid elements. Modeling by means of shell elements should be given precedence from the practical point of view, since the required deal of effort is low. Research activities should be dedicated to investigate the opportunities to consider local geometry variations caused by UIT. In the case of solid elements, emphasis will be given to investigate the influence of weld toe modeling (especially toe radius, local geometry after UIT, and number of elements) on the calculation stress results. Modeling techniques and recommendations described in the IIW guideline [13] will be explicitly taken into consideration. Comparison of the calculated results with each other and with corresponding measured ones will reveal the level of accuracy and the usefulness for fatigue life assessment of the various modeling procedures.
The analytical part deals with the implementation of the developed modeling techniques within the framework of various fatigue life assessment concepts. Besides the Nominal Stress Concept, the Geometric Stress Concept and the Effective Stress Concept are the most favored ones. Detailed in-depth description of the various concepts is provided in [13-17].

The end-result of the theoretical programme will be a unified theoretical procedure referring to FE modelling of UIT-welds in thin structures for calculating accurate geometric and/or effective stresses for fatigue life assessment according to the above mentioned concepts.

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