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IIW: Developing Global Best Practices for the Fatigue Assessment of Welded Structures

Abstract: The International Institute of Welding (IIW) acts as the global network of knowledge exchange concerning the joining of materials. One of the working teams, i.e. Committee XIII, is dedicated to new research results and the implementation of innovative technologies in order to avoid fatigue failures in welded structures. Presently, the Committee is developing several new guidelines aimed to increase the fatigue service life of welded structures. One of the guidelines concerned with the frequent use of mechanical treatment is a method of increasing the fatigue strength of welded structures. The article discusses aspects of the above-named guidelines and the unique international IIW collaboration enabling the development of these guidelines.

Keywords: International Institute of Welding, IIW, welded structures, fatigue assesment, Comittee XIII guidelines

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Introduction

The IIW was founded in 1948 by 13 countries as a means of advancing scientific and technical progress in the rapidly expanding field of welding. Since then the organisation has grown to include 59 member countries in all regions of the globe.

The IIW provides a unique platform to enhance excellence in the fields of welding and joining sciences and technologies, and their uptake and implementation through education, training, qualification and certification worldwide. It also contributes to the global awareness of environmental and workplace health and safety imperatives, and plays an important role in global standardisation. Small, medium and large scale enterprises, as well as governments and academic organisations, jointly benefit through enhanced weld quality, design and performance structures while reducing the cost of the fabrication, improving safety and ensuring sustainability.

The primary aim of the IIW is to improve the global quality of life through the optimum use and innovation of welding and joining technologies. This aim is implemented via two main avenues. The actions of training, qualification and certification are supervised by the International Authorization Board whereas technical and scientific advancement is supported

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and coordinated by the Technical Management Board (TMB).

Via its 23 technical working units, the TMB is pursuing four main objectives:

- organize the exchange of scientific and technical information and provide an environment to encourage and sustain knowledge transfer
- initiate and develop global best practices
- oversee all technical aspects of IIW standardization activities
- encourage and support a safe, healthy and environment-friendly world

All of the Working Units serve as global centres of information exchange in their respective disciplines. Each unit comprises experts and professionals from industry, research institutes and world-leading universities. University students and young professionals also make outstanding contributions to the Working Units and the participation of these future leaders in IIW activities is being encouraged.

The IIW acts and is recognized as an ISO standardization body. In many cases draft standards are submitted to the relevant Commissions for comment or discussion. Other Working Units have specialist groups or subunits which work closely with ISO to develop and draft new standards.

One IIW Working Unit considers solely the direct and imminent effects of welding and joining on workers' health, as well as their impact on the environment. However, all Working Units contribute to the realization of a safe, healthy and environment-friendly world through their work. This may take the form of decreasing the failure rates of welded joints through better weld inspection and assessment or by reducing the use of raw materials by more efficient fabrication processes.

Global best practices in the IIW

In IIW technical working units, ambitious working programmes are being pursued to develop IIW Best Practice Guidelines. These documents are in great demand to industries who view the IIW logo as a symbol of quality and scientific and engineering excellence. These documents also serve as an important starting point for new international standards and for new fields of research.

The Example of Commission XIII: Fatigue of Welded Components and Structures

The experts that contribute to Commission XIII: Fatigue of Welded Components and Structures come from world-leading companies and universities. The Commission typically meets twice per year to present and discuss new scientific results and the application of new technologies to avoid fatigue failures in welded structures. The objective is to develop expertise and provide science-based guidelines that can be applied to challenging design and life extension cases for fatigue-loaded structures. Industries that benefit from Commission XIII publications include ship building, automotive, transportation, bridge and infrastructure, offshore, mechanical engineering and process equipment.

In recent years, Commission XIII has developed and published four best practice recommendations relating to fatigue assessment, fatigue design and fatigue life improvement for welded structures [1-4]. In addition, one ISO technical report on fatigue testing of welded structures has been developed [5].

Post-weld Fatigue Strength Improvement of Welds

Post-weld improvement is frequently specified during the repair of existing structures and, more recently, for new structures. In 2007 the IIW Commission XIII on Fatigue of Welded Components and Structures approved a best practice guideline concerning post-weld treatment methods for steel and aluminium structures [4]. This guideline covers four commonly applied post weld treatment methods, burr-grinding, TIG re-melting (or TIG dressing), hammer peening and needle peening. Burr-grinding and TIG re-melting are generally classified as geometry improvement techniques for which the primary aim is to remove or reduce the size of the weld toe flaws and to reduce the local stress concentration due to the weld profile by achieving a smooth blend at the transition between the plate and the weld face. Hammer peening and needle peening are classified as residual stress modification techniques which eliminate the high tensile residual stress in the weld toe region and induce compressive residual stresses at the weld toe. These methods also result in a reduced stress concentration at the weld toe. The guideline also gives practical information on how to implement the four improvement technologies including good work practices, training, safety, and quality assurance.

The IIW guideline for post-weld improvement applies to plate thickness 6 to 50 mm for steel and 4 to 20 mm for aluminium. The improvement methods are only relevant to fatigue failures initiating from the weld toe. Thus, in some situations the analyst may also need to consider alternate failure modes. For welds improved by burr grinding or TIG re-melting or for hammer peening or needle peening of low strength steel ($f_y < 355$ MPa), the fatigue strength benefit corresponds to an increase in allowable stress range by a factor of 1.3, corresponding to a factor of 2.2 on life for S-N slope $m = 3$. However, the maximum class which can be claimed is the closest category below the FAT (FAT is the stress range corresponding to 95% survival probability at $N = 2\times10^6$ cycles) value obtained when the as-welded FAT value is multiplied by 1.3. For ease of computation, this corresponds to a two (2) fatigue class increase based on the IIW Fatigue Design Recommendations [1]. For aluminium and high strength steel ($f_y > 355$ MPa) welds improved by hammer peening or needle peening, the fatigue strength benefit consists of an upgrade by a factor of 1.5 applied to the stress range, with a change in S-N slope $m = 3$ to $m = 5$ at $N = 1\times10^7$ cycles. However, the maximum class which can be claimed is the closest category below the FAT value obtained when the as-welded FAT value is multiplied by 1.5. For ease of computation, this corresponds to a three (3) fatigue class increase. For example, when a weld detail which, in the as-welded condition, would be classified as FAT 63 is hammer peened, the new FAT value is FAT 90. The highest detail class for which an improvement can be claimed is FAT 90, and the highest S-N curve that can be claimed following improvement is FAT 125. The slopes of the S-N curves follow the IIW Fatigue Design Recommendations [1].

An important practical limitation on the use of improvement techniques that rely on the presence of compressive residual stresses is that the fatigue lives are strongly dependent on the applied mean stress of the subsequent fatigue loading. In particular, the beneficial affect decreases as the maximum applied stress approaches tensile yield. Thus, in general, the techniques are not suitable for structures operating at applied stress ratios $R > 0.5$ or maximum applied stresses above around 80% yield. The guideline gives special limitations for high stress ratio situations. Even occasional application of high stresses in tension or compression can also be detrimental in terms of relaxing the compressive residual stress but systematic guidelines are not yet available. Special limitations also exist for improved large-scale structures. It is recommended that for steel structures with plate thickness greater than 20 mm the benefit for hammer peening is assumed to be the same as for burr grinding and TIG dressing. Burr grinding and TIG re-melting can be applied only to conditions where the nominal stress range is less than twice the material yield strength, $\Delta\sigma<2f_y$

New Developments for High Strength Steels and High Frequency Mechanical Impact (HFMI) Treatment Methods

As previously mentioned, the existing IIW guideline allows the same degree of fatigue improvement for all steels with $f_y > 355$ MPa. Numerous researchers have observed that the degree of improvement increases with material strength, see e.g., Maddox [6] and Bignonnet [7]. There has been a desire to develop an IIW guideline covering high strength steel (HSS) and in 2003 a new round robin exercise was initiated within IIW Commission XIII. Typical relationships between fatigue strength and material strength are shown in Fig. 1. For base materials and notched components there is aclear increase in fatigue strength with material strength. In the as-welded state, the fatigue strength of a welded joint is essentially independent of material strength. However, for improved welds, there is increased fatigue strength with material strength. This is of major importance when high strength steels are used in the design of fatigue loaded structures and offers tremendous potential for new lightweight and energy efficient structures.

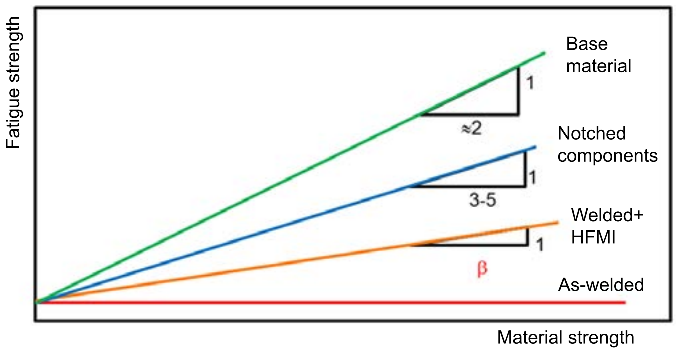

Fig. 1. Schematic of relationship between fatigue strength (e.g. stress amplitude at 1×10^6 cycles to failure) and material strength.

The initial technology for high frequency mechanical impact (HFMI) treatment was developed at the Northern Scientific and Technological Foundation in Severodvinsk, Russia in association with Paton Welding Institute in Kiev, Ukraine [8]. The past decade has seen steady increase in the number of HFMI technology developers and service providers. Numerous systems are employed to generate high frequency impacts, e.g., ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements or high pressure compressed air. In all cases, however, the working principal is identical: cylindrical indenters are accelerated against a work piece, e.g., the weld toe region, with high frequency. The impacted material is plastically deformed causing both a change in the local geometry and residual stress state in the region of impact. Figure 2 shows typical weld profiles in the as-welded condition and following HFMI treatment. In comparison to more traditional hammer peening, HFMI is more user-friendly and the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish. The indenters are high strength steel cylinders, and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations. Devices are known by the names: ultrasonic impact treatment (UIT) [9], ultrasonic peening (UP) [10], ultrasonic peening treatment (UPT) [11-14], high frequency impact treatment (HiFIT) [15-16], pneumatic impact treatment (PIT) [17], and ultrasonic needle peening (UNP) [18-19].

Development of Guidelines

The choice of $m = 3$ for the S-N curve slope in the current IIW post-weld improvement guideline [4] results in conservative design curves in the high cycle fatigue regime but less

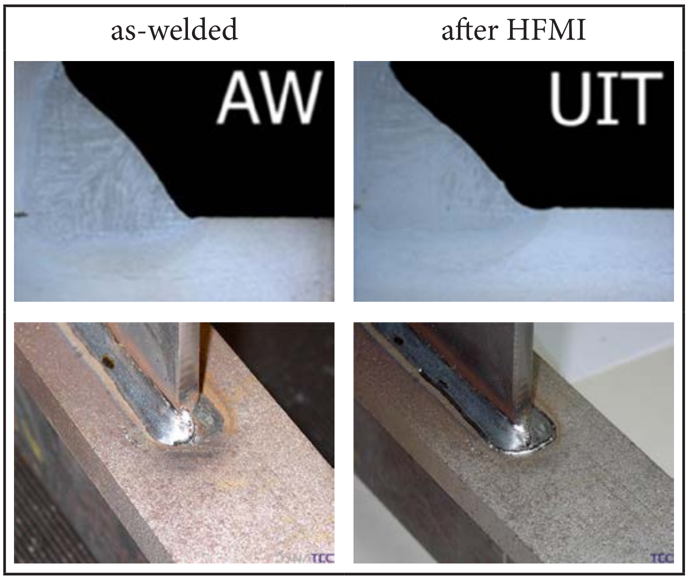

Fig. 2. Typical weld toe profile in the as-welded condition and following HFMI treatment [16]

conservative or even non-conservative results for lower cycles to failure, i.e., $N = 1\times10^4$. Individual experimental studies for HFMI treatments also typically observe that the slope of the best-fit line through the S-N data is typically greater than the $m = 3.0$ used in the IIW guideline. The goal of the current study has been to collect and assess the available fatigue test data for a variety of HFMI treatments. Special attention is given to the S-N slope because the assumed S-N slope has a major impact on the measured degree of fatigue strength improvement and will eventually influence the improvement factors proposed for HSS. Virtually all the testing has been done using constant amplitude testing at $R = 0.1$, but some constant amplitude tests and other R ratios and variable amplitude tests are available and have been reported. From a mechanical point-of-view, the HFMI techniques are considered to most closely resemble hammer peening. For this reason a comparison is made between fatigue data following HFMI treatment and hammer peening.

In a review of published experimental data on the fatigue strength of welded joints improved by HFMI peening methods, Yildirim and Marquis [20] identified 19 publications containing fatigue data for welded steel joints improved by one of the HFMI methods mentioned in the previous section. Some of these studies contained multiple materials, improvement techniques, stress conditions or specimen types. Thus, a total of 45 data sets for four specimen types were reviewed. Figure 3 shows data for 122 longitudinal non-load carrying fillet weld components subjected to R=0.1 constant amplitude loading. Plate thickness was from 8 to 16 mm and the materials' yield strengths ranged from about 260 to almost 1000 MPa. Figure 3 also shows the as-welded design curve for this welded detail (FAT 71) based on IIW Recommendations [1]. The S-N slope m=5 provides a good fit for the experimental data and the mean minus two standard deviations line is FAT 142. This represents a 100% improvement in fatigue strength at $N_f = 2\times10^6$. Of course, because the slope of this line is different from the slope of the line for as-welded components, the degree of improvement changes depending on the life regime of interest. For example, at $N_f = 5\times10^4$ the improvement is only 22% while at $N_f = 5\times10^6$ the improvement is 225%. IIW Commission XIII is currently developing guidelines to include both high frequency mechanical treatment methods and high strength steels. More studies especially with variable amplitude loading are needed since it is observed that the type of loading can greatly influence the failure mode and the observed fatigue life [21].

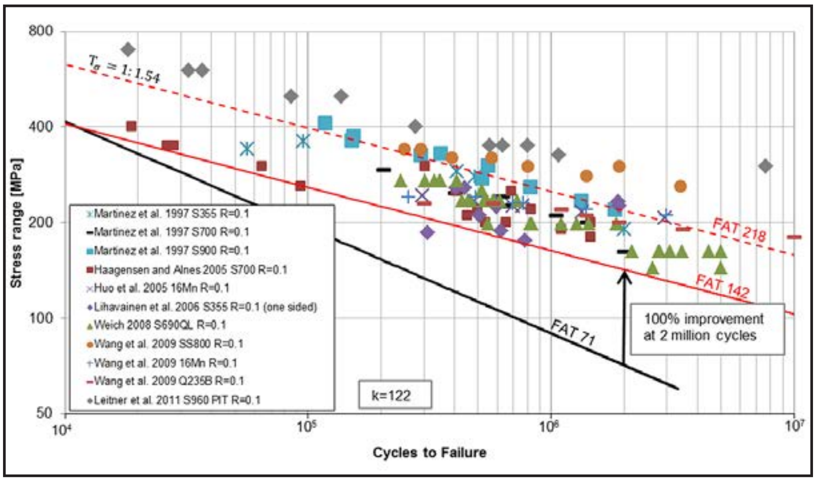

Fig. 3. Fatigue data collected from a number of studies where high frequency treatment methods were applied to longitudinal non-load carrying fillet weld components [20].

Several proposals concerning the degree of fatigue strength improvement as a function of material strength have been proposed. Yildirim and Marquis [22] studied these proposals and performed a comprehensive evaluation of published data for high frequency mechanical impact treated welds. In total, 228 experimental results for three weld geometries subject to R=0.1 axial loading have been reviewed. A design recommendation including one fatigue class increase in strength (about 12.5%) for every 200 MPa increase in static yield strength is proposed and are shown to be conservative with respect to all available data.

Figure 4 shows a proposed increase in the number of FAT classes as a function of yield strength. The solid line presents the proposed increase and the broken line represents the increase for hammer and needle peened welds in the current IIW guideline [4].

The development of an IIW best practice guideline for post-weld improvement must also include relevant information concerning relevant equipment, proper procedures, material requirements, safety, training requirements for operators and inspectors, quality control measures and documentation.

Most equipment manufacturers offer 1-2 days of training with the delivery of a new treatment system. Neher [16] has proposed several relevant instructions concerning the HiFiT equipment which is typical when using HFMI. The tool should be held so that the axis of the indenters forms an angle of 60° to 80° with respect to the plate surface and an angle of 70° to 90° in direction of motion. Working speed is typically 3 to 5mm/s but this value will vary greatly for different equipment and applications. See Fig. 5. Visual inspection following treatment includes an evaluation of the quality of the groove and the groove depth. The resulting groove must be smooth and along all

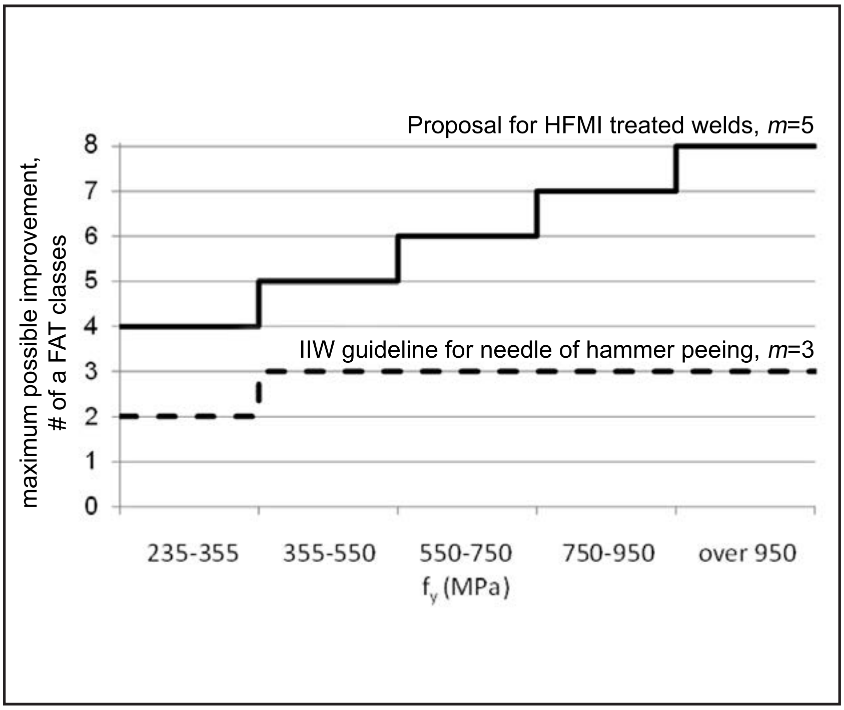

Fig. 4. Proposed maximum increase in the number of FAT classes as a function of f_y [22].

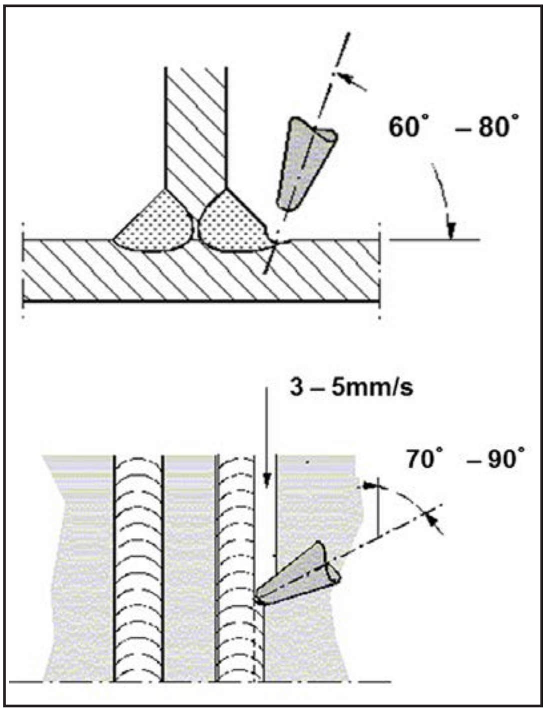

Fig. 5. Orientation of the HFMI tool with respect to the weld being treated

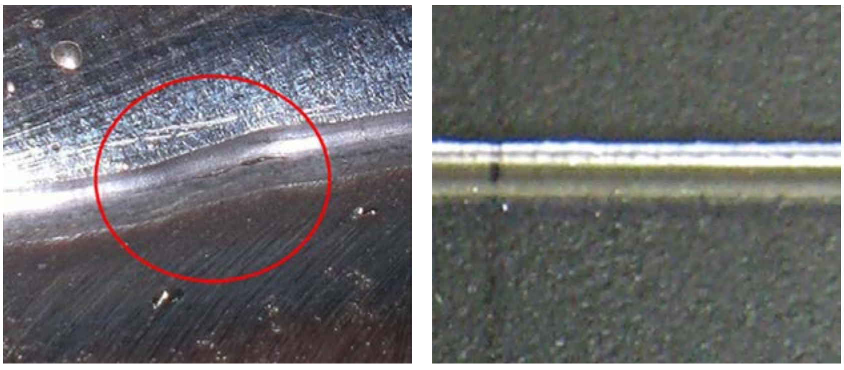

Fig. 6. The HFMI groove in a) shows a thin crack-like defect which reduces or eliminates the effectiveness of the HFMI treatment. b) shows a defect-free groove.

defined welds. No thin line representing original fusion line should be visible the groove. The resulting groove must be smooth and along all defined welds. Figure 6 shows examples proper and improper grooves. The thin crack-like line in the left-had picture indicates improper treatment. The depth of the groove must be approximately 0.2-0.4 mm, see Fig 7. Groove depth can be checked relatively easily by using simple depth gauges such as is shown in Fig. 8.

A Production Data Sheet (PDS, see appendix 3 in [4]) similar to a Welding Procedure Specification (WPS) should be prepared for the HFMI treatment. The PDS includes information concerning the component being treated, base and filler material, HFMI equipment type, indenter number, size and shape, inspection means, etc.

All of the available HFMI devices have variable power settings which can be adjusted depending on the material being treated, the number and geometry of the indenters, etc. As a quality assurance measure, the intensity should be recorded in the PDS. PITEC has developed a simple test for measuring the intensity of HFMI treatment [24]. The concept is similar to that used in the Almen strip test which is common for measuring the intensity of shot peening and blasting operations. The simple equipment used for this test is should in Fig. 9.

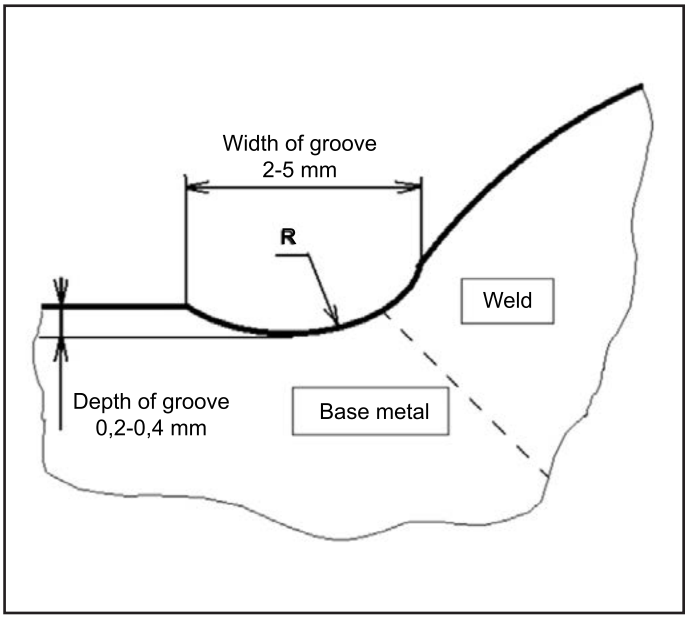

Fig. 7. The indentation depth following treatment should be 0.2-0.4 mm while the resulting width is typically 2-5 mm [23]

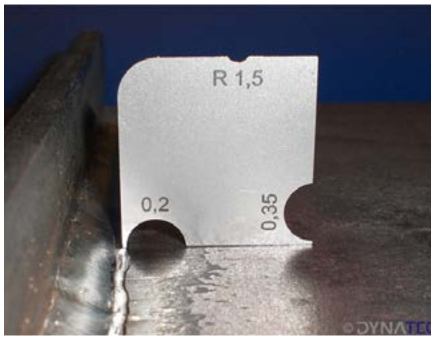

Fig. 8. Depth inspection using simple gauges. The gap between the base plate and the gauge in the right-hand picture indicates that 0.2 mm has not been achieved

International Collaboration

The development of a new IIW best practice guideline concerning HFMI-based fatigue strength improvement of welded components has involved many partners from many countries. Table 1 lists the countries which have been involved in various phases of development of the best practice guideline. Most of the 12 countries involved had several partner organisations contributing to the research. All contributions have been self-financed in that the IIW provides a strong network but does financially support research goals. Such strong multinational cooperation which involves the joint efforts and commitment of industry, research institutes and universities can only be accomplished in organisations like the IIW. This simple example illustrates the mission of the IIW in action "*To act as the world-wide network for*

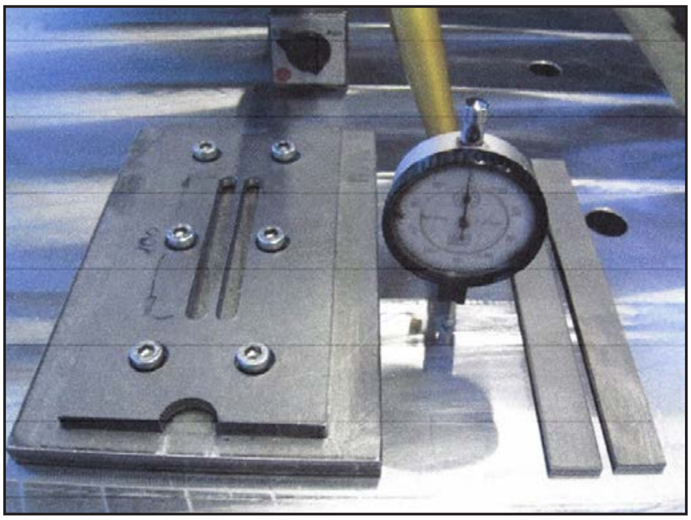

Fig. 9. Equipment needed to perform the Almen test-type calibration procedure developed by PITEC [24].

Table 1: Scope of countries involved in various phases of the development of a best practice guideline concerning HFMI.

International cooperation	Austria	Canada	China	Finland	France	Germany	Norway	Russia	Sweden	UK	Ukraine	USA
Technology development		×			×	×		×			×	×
Initial test data	×	×	×	×	×	×	×		×	×		×
Specialized data				×		×			×	×		
Data synthesis				×		×			×			
Quality assurance						×						
Guidance on training												
Drafting of guideline				×					×			

knowledge exchange of joining technologies to improve the global quality of life".

Conclusions

The IIW's technical working units provide unique forums for knowledge exchange for experts and professionals from industry, research institutes and world-leading universities. Commission XIII has been active in developing best practice guidelines for the fatigue strength improvement of welded structures. A new guideline on the implementation of high frequency mechanical impact treatment, especially for high strength steel welded structures is being prepared. Aspects of this guideline and the unique international nature of the IIW which has made it possible are described.

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