# High Frequency Fatigue Testing of Butt Welds with a New Magnet Resonance Machine

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## Abstract

A new magnet resonance machine has been developed to carry out high frequency fatigue tests for transverse butt welds. The technology uses the first natural frequency of a resonance body which consists of two steel beams. Due to four magnets at the ends of the steel beams a harmonic cyclic loading is applied. The maximum frequency for the fatigue tests is 400 Hz. The system allows to test specimens with transverse butt welds up to $10^9$ cycles with moderate values for the mean force and amplitude.

The test program comprised more than 110 specimens for analysing several influences, namely: (i) frequency of the test machine, (ii) temperature at hot spots and (iii) steel grade of the specimens. In addition, a test series was carried out to compare the as welded and treated conditions of butt welds. Some test specimens showing fatigue cracks after $10^8$ cycles will be also documented.

***Keywords:*** *Fatigue tests, Magnet resonance machine, Butt weld, Giga cycle, High frequency, High strength steel*

## 1. Introduction

The fatigue resistance of transverse butt welds is very important for steel constructions which are subjected to dynamic loads. Therefore, the fatigue design is based on FAT-classes for several notch details according the Eurocode 3 [1] and recommendations of the International Institute of Welding (IIW) [2].

Stress amplitudes below the cut off limit of $N = 10^8$ cycles are considered to be non-damaging for constant amplitude loading. For a higher number of cycles ($N > 10^8$) only a few test series are available. Some welded constructions in the offshore industry, for example, steel towers of wind turbines, are loaded up to more than $10^9$ cycles. For these offshore constructions with variable amplitude loading, the consideration of the cut off limit is not allowed. The fatigue design must be carried out with FAT-curves extended until the range of Giga Cycle Fatigue (GCF).However, in this range, only a few data sets of experiments exist in literature. Additional fatigue tests would be helpful to ensure the accuracy of these extended fatigue curves. Therefore, a new magnet resonance machine was developed [4] to carry out high frequency fatigue tests up to GCF-range (see Fig. 1).

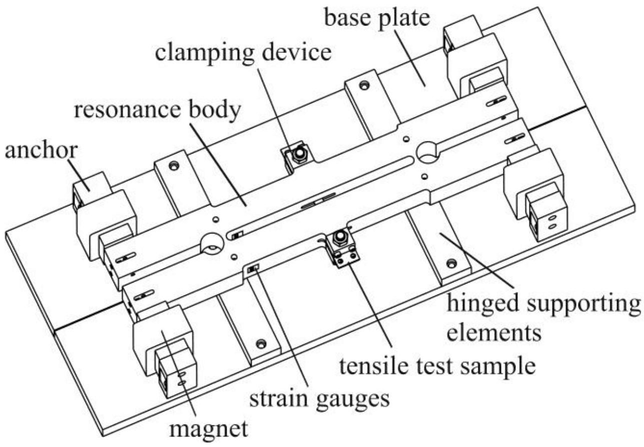


**Figure 1. 3D-model of magnet resonance machine**

Because of the maximum frequency of 400 Hz the time duration for a fatigue test can be reduced significantly using this machine. For example, a fatigue test up to $10^8$ cycles takes only a time of 3 days in contrast to 58 days for a test on a servohydraulic machine running at a frequency of 20 Hz (factor 1/20). Thus, it was possible to test specimens up to $10^9$ cycles at the Institute for Steel Construction of Leibniz Universität Hannover within a moderate time of a research project.

In the following chapters the technical details of the magnet resonance machine and several test results will be explained.

## 2. Test Setup

### 2.1. Details of the resonance machine

The magnet resonance machine uses the first natural frequency of two steel beams, which are manufactured from one solid body. The steel beams are also called resonance body as shown in Fig. 2. They are simply supported with hinge bolts in the points where the first beam bending mode has no deflections (nodes). Due to four magnets at the ends of the beams a harmonic cyclic loading is applied. Therefore, the beams are pushed simultaneously by the electromagnetic field in the positive half wave and pulled in the negative half wave of oscillation. The electromagnetic oscillation is carried out with no contact between the magnets and the resonance body.

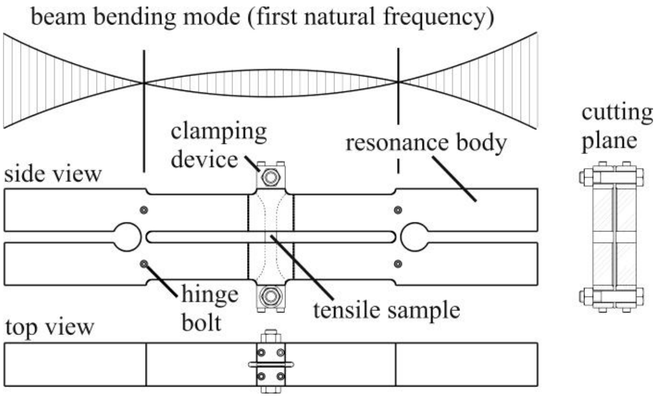


**Figure 2. Principle of the magnet resonance machine**

Before a test can be started the tensile sample is positioned through a slot in the middle of the beams and is pre-stressed with a certain mean force between them. When the mean force is reached the sample is clamped with bolts at both ends.

During a harmonic cyclic loading by the magnets the sample will get a stress range in longitudinal direction depending on the deflection of the beams. A microcontroller ensures that the oscillation will be permanently applied at the first natural frequency. While acting in resonance, these electromagnetic forces can be minimized. Depending on the pre-stressed mean force of the sample a pulsating load with a stress ratio $R \geq 0$ is also possible.

Fig. 3 shows the mechanical implementation of the described principle. The components are a power amplifier, an analogous amplifier for the strain gauges, a microcontroller and a base plate on which the resonance body and the four magnets are positioned. The resonance body is dimensioned in such a way that it endures a mean force of $F_m = 60$ kN and a amplitude force of $F_a = 50$ kN for the specimen.

The maximum frequency of $f_P = 400$ Hz will be reached for a specimen with a nominal cross section of $A_S = 200$ mm$^2$. The resonance body is manufactured of special tempered steel to assure a high endurance limit of the test device.

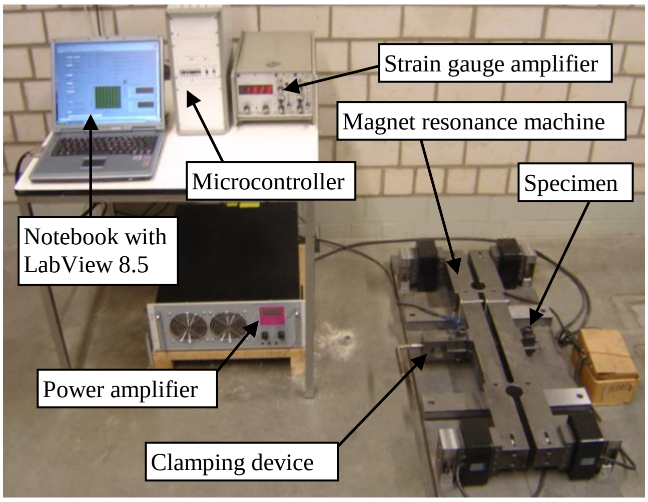


**Figure 3. Components of the magnet resonance machine**

Four strain gauges are positioned at the resonance body to measure (it might be estimating, but this too poor to write….) the actual load (stress) at the beams. The output signals of the strain gauges are amplified and sent to the microcontroller as input. The microcontroller can control with the help of these signals the power amplifier which generates the electromagnetic forces. The goal is to control the electromagnetic forces at every time step to maintain the oscillation at the first natural frequency.

A notebook with LabView 8.5 is used to monitor the test setup and to store the signals during the fatigue test. The mean force $F_m$ the amplitude force $F_a$ the frequency $f_P$ and the cycles N are stored in an ASCII-file.

In comparison to a typical servohydraulic test machine the duration for a fatigue test can be significantly reduced with this magnet resonance machine. The test duration for several numbers of cycles is compared in Table 1.

**Table 1. Duration for a fatigue test with different machines**

| Test machine | Frequency | test duration | | | |
|---|---|---|---|---|---|
| | $f_P$ [Hz] | $N = 10^6$ | $N = 10^7$ | $N = 10^8$ | $N = 10^9$ |
| servohydraulic | 20 | 833 min | 139 hours | 58 days | 82 weeks |
| magnet resonance | 400 | 42 min | 7 hours | 3 days | 4 weeks |

For example a fatigue test until $N = 10^7$ cycles takes 139 hours of time on a servohydraulic machine with $f_P = 20$ Hz. Using the magnet resonance machine, only 7 hours are needed for the same number of cycles. Thus, it is possible to test specimens up to $N = 10^9$ cycles with moderate values for the mean force and amplitude. The test duration for a giga cycle fatigue test (GCF-test) would be 4 weeks instead of 82 weeks.

More detailed information about the technology of this magnet resonance machine can be found in SCHAUMANN et al. [3]. First fatigue tests with the described magnet resonance machine were carried out by KEINDORF [6] in a range of $10^5$ up to $10^9$ cycles.

### 2.2. Test specimen

A test specimen with a transverse butt weld must have a special geometry to fulfil the requirements of the magnet resonance machine. Fig. 4 shows the parameter of the geometry which are used for the specimens. The dimensions are similar to the geometry for a static tensile test according to EN 10002-1 [6].

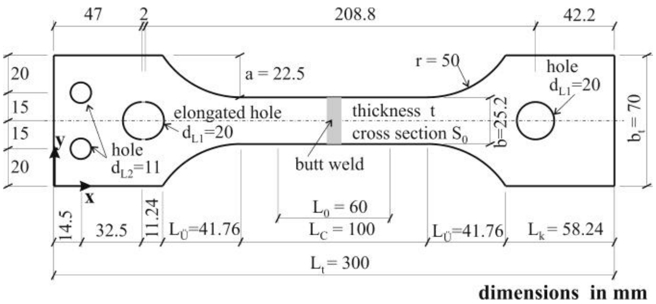


**Figure 4. Geometry of the test specimen with a butt weld**

The final geometry cutting is performed by water jet cutting to avoid temperature dependant effects at the edges during the cutting process. The width of the test sample is b = 25 mm (b = 25.2 mm before cutting) which is constant over a length of $L_C$ = 100 mm. The minimum length for the test section is estimated to $L_0$ = 60 mm. The sections for fixation are broadened to $b_t$ = 70 mm with a smooth transition to avoid stress concentrations at the edges.

The holes with a diameter of $d_{L1}$ = 20 mm are necessary for the bolts to fix the sample between the clamping devices. The two holes with $d_{L2}$ = 11 mm at the left end are used to pre-stress the sample up to the mean force with an extra device (see SCHAUMANN et al. [3]).

An example of a specimen for a calibration test with strain gauges is displayed in Fig. 5. After the calibration test, the specimens can be used without any strain gauges to carry out a fatigue test. The transverse butt weld was manufactured by single sided arc welding with one lay.

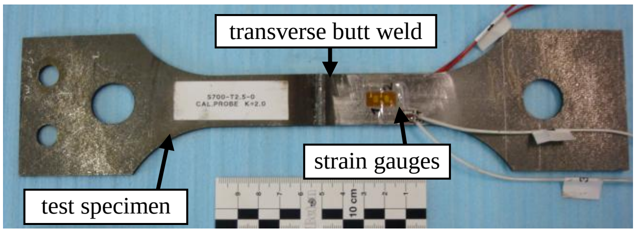


**Figure 5. Test specimens with a butt weld for the fatigue tests**

Fig. 6 shows a macro section of a butt weld, which was derived from a sample with a thickness of t = 2.5 mm and a steel grade S700 MC.

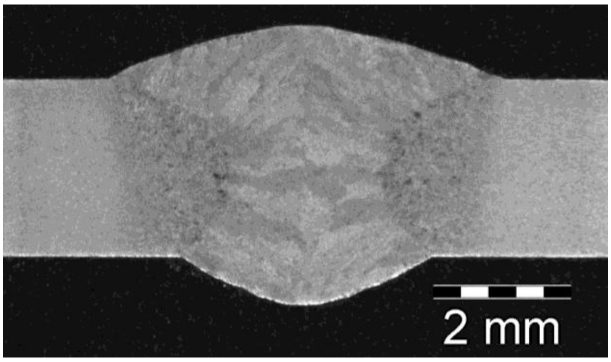


**Figure 6. Macro specimen of a transverse butt weld (S700-T25-Z3-2)**

The weld profile has no visible volumetric discontinuities. Furthermore, the shapes at the weld toe and weld root are uniformly rounded without any misalignments. The macro specimen in Fig. 6 is representative for the whole charge. Thus, a very good quality could be attested for all samples concerning the transverse butt welds.

### 2.3. Test program

Several fatigue test series were carried out at the Institute for Steel Construction of Leibniz Universität Hannover (Germany) and at ArcelorMittal Global R&D Gent (Belgium) to investigate the following issues:

**Table 2. Issues**

| No. | issue to be investigated |
|---|---|
| a) | comparison between low and high frequency fatigue tests to estimate the influence of the frequency |
| b) | comparison between normal and high strength steel to estimate differences in fatigue strength |
| c) | comparison between samples in as welded and treated conditions (high frequency hammer peening was used for post weld treatment) |
| d) | thermography tests to analyses the influence of temperature at the hot spots of the butt weld during a high frequency fatigue test |
| e) | realization of fatigue tests with variable amplitude loading with the new magnet resonance machine |
| f) | testing a wide range from low cycle over high cycle fatigue up to giga cycle fatigue with observed failure modes |

The first test series with the magnet resonance machine comprises 12 samples with a thickness of t = 3.0 mm and a steel grade S355. In parallel, fatigue tests were carried out simultaneously by ArcelorMittal for the same steel charge but with a servohydraulic test machine at a frequency of 15 Hz. Furthermore, two different stress levels were defined to estimate S-N-curves (50%-WÖHLER-diagram) for both test series. The most important parameters of this test program are summarized in Table 3.

**Table 3. Test series with S355 J2**

| Test machine | $f_P$ [Hz] | t [mm] | stress level | number of specimen | FAT $\Delta\sigma_C$ [MPa] | $\Delta\sigma_{test}$ [MPa] | $\sigma_m$ [MPa] |
|---|---|---|---|---|---|---|---|
| servo-hydraulic | 15 | 3.0 | Z3 | 6 | 71 | 3·71=213 | 130.2 |
| | | | Z4 | 6 | | 4·71=284 | 173.6 |
| magnet resonance | 380 | | Z3 | 6 | | 3·71=213 | 130.2 |
| | | | Z4 | 6 | | 4·71=284 | 173.6 |

The stress level Z3 and Z4 are defined in the field of low cycle fatigue. These stress ranges are multiplier of the normative value $\Delta\sigma_C = 71$ MPa which indicates the relevant fatigue class FAT71 by $N_C = 2\cdot10^6$ cycles. The fatigue curve has to be used for single sided butt welds with root inspection according to the IIW-recommendations [2]. For example the stress level Z4 is defined based on the following equation:

$$\Delta\sigma_{Z4} = 4\cdot 71 = 284 MPa \quad (1)$$

With regard to the parameter of the test program the samples are designated as follows:

<u>Example: S355-T30-Z4-X</u>

- S355: steel grade (S355 or S700)
- T30: thickness value of test specimen in mm multiplied by 10 (T40, T30 or T25)
- Z4: stress level (Z1, Z2, Z3, Z4 or Z5)
- X: number of specimen at the stress level

(1, … 6)

All fatigue tests were carried out with a constant amplitude loading and an initial stress ratio of R = 0.1 which is the ratio of minimum to maximum algebraic value of the stress in a cycle. The stress ratio will not be constant over the test duration because of the crack initiation and crack growth the stiffness of the specimen decreases. Thus, the pre-stressed mean force (mean stress $\sigma_m$) will also decreases together with the stress ratio:

$$R = \frac{\sigma_m - \sigma_a}{\sigma_m + \sigma_a} \quad (2)$$

This effect of decreasing stress ratio is characteristic for the magnet resonance machine and can not be avoided or controlled in contrast to a servohydraulic machine.

However, the influence of the frequency on the fatigue resistance of butt welds can be estimated based on comparing the results of the test series in table 3 with S-N-curves in a WÖHLER-diagram. Thus, the issue a) of table 2 could be investigated with these test series.

The fact b) of table 2 was investigated with an additional test series which included 26 specimens but with a steel grade of S700 MC (see table 4).

**Table 4. Test series with S700 MC**

| Test machine | $f_P$ [Hz] | t [mm] | stress level | number of specimen | FAT $\Delta\sigma_C$ [MPa] | $\Delta\sigma_{test}$ [MPa] | $\sigma_m$ [MPa] |
|---|---|---|---|---|---|---|---|
| servo-hydraulic | 15 | 2.5 | Z3 | 2 | 71 | 3·71=213 | 130.2 |
| | | | Z4 | 6 | | 4·71=284 | 173.6 |
| | | | Z5 | 6 | | 5·71=355 | 216.9 |
| magnet resonance | 380 | | Z3 | 2 | | 3·71=213 | 130.2 |
| | | | Z4 | 6 | | 4·71=284 | 173.6 |
| | | | Z5 | 4 | | 5·71=355 | 216.9 |

All specimens of table 4 were also tested at an initial stress ratio of R = 0.1. But in contrast to the test series with S355 the S700MC specimens have a thickness of t = 2.5 mm. Furthermore, an additional level Z5 was defined to analyse the fatigue behaviour of the high strength steel at higher stress amplitudes.

A third test series was carried out to investigate the influence of post weld treatment by high frequency hammer peening. This method involves post-weld deformation by mechanical impacts from single or multiple indenting needles. The objective of the treatment is to introduce beneficial compressive residual stresses at the weld toe zones and to reduce stress concentration by improving the weld profile. Furthermore, the area being treated is highly plastically deformed which has the effect of work hardening. Thus, with this additional test series the fact c) of table 2 could be investigated.

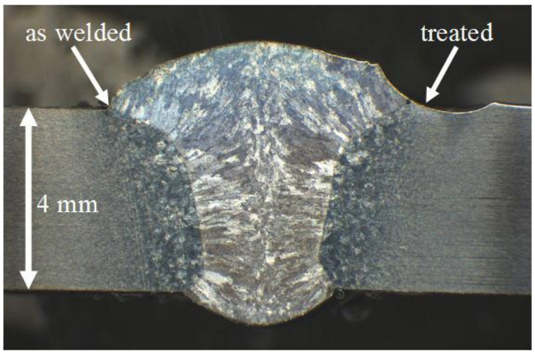


**Figure 7. Macro specimen of a transverse butt weld with a comparsion of as welded (left) and treated (right) conditions**

Fig. 7 shows the differences between weld toes in as welded and treated conditions. The transverse butt weld in Fig. 7 was finally treated at both weld toes before the fatigue test started. But the weld root was generally not treated at all test specimens.

The most important parameters of the test series are listed in table 5. Three stress levels (Z2, Z3 and Z4) were defined according to the FAT-class 71 for a single sided butt weld. A few fatigue tests were carried out with 380 Hz at the magnet resonance machine and additional tests with 20 Hz on a servohydraulic machine of Hannover to compare the results.

**Table 5. Test series with as welded and treated conditions**

| condition of butt weld | $f_P$ [Hz] | t [mm] | stress level | number of specimen | FAT $\Delta\sigma_C$ [MPa] | $\Delta\sigma_{test}$ [MPa] | $\sigma_m$ [MPa] |
|---|---|---|---|---|---|---|---|
| as welded | 20 and 380 | 4.0 | Z2 | 8 | 71 | 2·71=142 | 87.0 |
| | | | Z3 | 8 | | 3·71=213 | 130.2 |
| | | | Z4 | 8 | | 4·71=284 | 173.6 |
| | | | Z5 | 8 | | 5·71=355 | 216.9 |
| treated | 20 and 380 | | Z2 | 8 | | 2·71=142 | 87.0 |
| | | | Z3 | 8 | | 3·71=213 | 130.2 |
| | | | Z4 | 8 | | 4·71=284 | 173.6 |
| | | | Z5 | 8 | | 5·71=355 | 216.9 |

A thermography test was carried out only for one high frequency fatigue test to analyse the temperature at the hot spots of the transverse butt welds. However, the result can be used for issue d) of table 2 as a first answer to the question of whether the high frequency of the magnet resonance machine may lead to higher temperatures at the hot spots.

Furthermore, issues e) and f) of table 2 are investigated at only a few fatigue tests until now to check the magnet resonance machine for requirements like variable amplitude loading and giga cycle fatigue.

The entire test program is comprised of more than 110 fatigue tests which were carried out at one magnet resonance machine and two servohydraulic machines.

## 3. Experimental Results

In the following chapters the results of the test series in table 3, 4 and 5 will be presented. Towards this objective, the fatigue strength is represented as S-N-curves in WÖHLER-diagrams.

### 3.1. Fatigue tests of transverse butt welds with S355

The test series with S355-T30 comprises the two stress levels Z3 and Z4 in low cycle fatigue (s. table 3). All specimens have a nominal thickness of t = 30 mm and a width of b = 25 mm (cross section A = 75 mm²). For example, the results of the fatigue test S355-T30-Z4-1 carried out at the magnet resonance machine are plotted in Fig. 8 depending on the number of cycles.

At the beginning of the fatigue test the specimen had to be adjusted to swing in resonance. After that the amplitude was increased up to the nominal value of $\sigma_{a,Z4}$ = 142 MPa within 5.000 cycles (amplitude force $F_a$ = 10.650 kN in Fig. 8). During this start phase the mean force and frequency decreased simultaneously. Furthermore, the stress ratio decreased from the initial value of R = 0.1 and reaches R = 0.0 after 45.000 cycles. The decrease in stress ratio, mean force and frequency continued until a crack propagates instable in the range of 300.000 cycles.

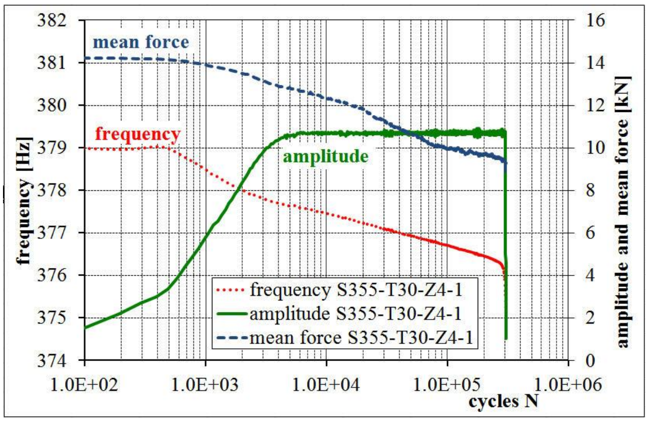


**Figure 8. Results of the high frequency fatigue test with the specimen S355-T30-Z4-1**

During the fatigue test the micro-controller ensured that the values for amplitude and stress range kept nearly constant. However, small fluctuations in the curve of the amplitude were visible, which were caused by the crack propagation. Therefore, the micro-controller must modify the parameters very fast for the changing resonance frequency and loss in stiffness in every cycle. So, the faster the control tools worked the smaller the fluctuations occurred. But a complete elimination of such fluctuations was not possible with this test procedure.

The magnet resonance machine stopped automatically when the mean force crosses the chosen lower limit of $F_m$ = 9.5 kN to avoid too high stress values in compression (R < 0.0). Thus, the final number of cycles in this fatigue test was N = 305.825. The other fatigue tests at the stress level Z3 and Z4 showed similar behaviour. The S-N-curves of the test series with 15 Hz and 380 Hz are plotted in Fig. 9 as 50%-WÖHLER-curves and compared to the fatigue class FAT71 according to IIW [2].

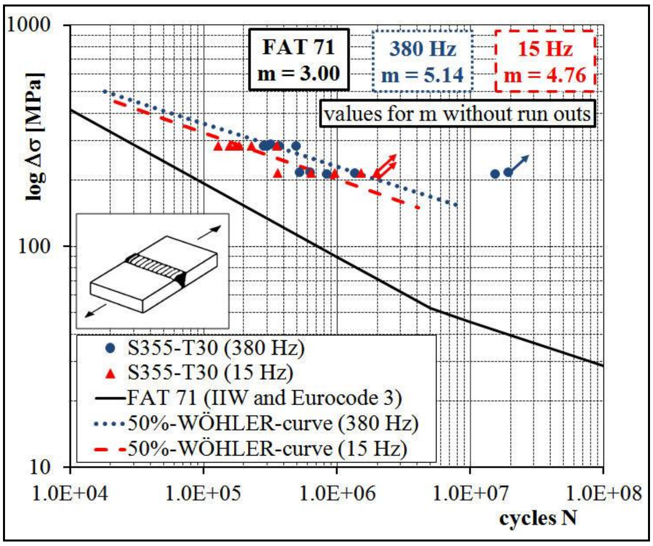


**Figure 9. S-N-curves for test series S355-T30 with 15 Hz and 380 Hz**

The slope of m = 5.14 for fatigue curve concerning the tests with the magnet resonance machine (380 Hz) is significantly higher compared to the standard definition of m = 3.00. However, a higher slope of m = 4.76 was also obtained for the fatigue tests carried out using the servohydraulic machine (15 Hz). In both cases the results of run outs are not considered for the calculation of the slope m.

The fatigue strength of the S355 test series is more than doubled compared to the corresponding value of FAT71 with $\Delta\sigma_c$ = 71 MPa for N = $2{\cdot}10^6$ cycles. Further fatigue tests will be necessary at lower stress ranges if the endurance limit needs be determined.

### 3.2. Fatigue tests of transverse butt welds with S700

The test series with S700-T25 comprises three stress levels (Z3, Z4 and Z5) in the range of low cycle fatigue (see table 4). The S-N-curves for specimens tested with 15 Hz and 380 Hz are plotted in Fig. 10 compared to the fatigue class FAT71.

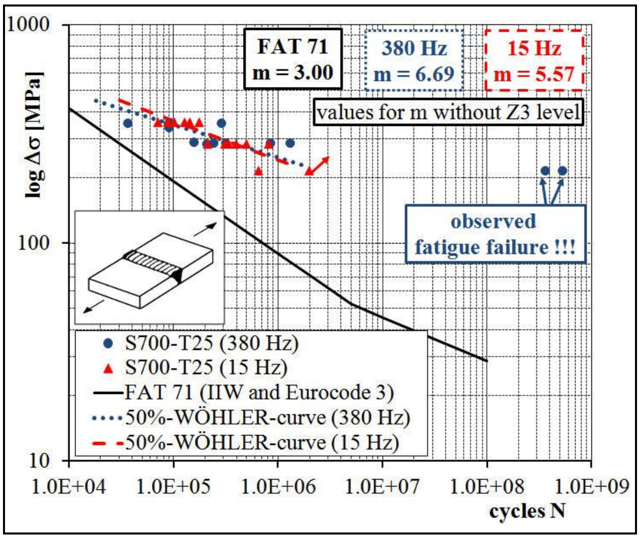


**Figure 10. S-N-curves for test series S700-T25 with 15 Hz and 380 Hz**

Although, the slope of the S-N-curves were calculated without consideration of the stress level Z3 the values of m = 6.69 (380 Hz) and m = 5.57 (15 Hz) are much higher than the normative value of m = 3.0. The good quality of the transverse butt welds (see Fig. 6) could be a reason for the higher fatigue strength. If misalignments at the weld profile are small or even more negligible the stress concentrations are low at the weld toe and weld root which also leads to higher fatigue strength. The factor of relative fatigue strength is defined by

$$factor = \frac{\Delta\sigma_{C,test}}{71\,MPa} \quad (95\%\ survivability,\ N_C = 2\cdot 10^6) \quad (3)$$

The factor is defined for a fatigue strength at $N_C = 2{\cdot}10^6$ with a survivability of 95%. Table 6 summarizes the results for the test series with S355-T30 and S700-T25.

**Table 6. Fatigue strength for a survivability of 95%**

| test series | t [mm] | $f_P$ [Hz] | FAT [MPa] | slope m of S-N-curve | $\Delta\sigma_{C,test}$ [MPa] | factor of relative fatigue strength |
|---|---|---|---|---|---|---|
| S355-T30 | 3.0 | 15 | 71 | 4.76 | 145 | 2.0 |
| | | 380 | | 5.14 | 157 | 2.2 |
| S700-T25 | 2.5 | 15 | | 5.57 | 182 | 2.6 |
| | | 380 | | 6.69 | 200 | 2.8 |

The slopes of S-N-curves derived by the magnet resonance machine are higher compared to the values for the servohydraulic machine. The decreasing stress ratio R during a fatigue test with the magnet resonance machine could be a reason (loss in stiffness of the test rig due to crack growth). Since, the ratio decreases from R = 0.1 slowly to R < 0.0, the mean stress and upper stress will also decrease simultaneously when the stress amplitude remains constant (see Eq. (2)). Thus, this effect must be considered when the results are compared in table 6 with S-N-curves derived by a servohydraulic machine with R = 0.1 = constant.

The relative factors of fatigue strength are comparable between low and high frequency fatigue testing when the same steel grade is analysed. Furthermore, all test series have a fatigue strength which is more than double compared to the corresponding value of FAT71 with $\Delta\sigma_c$ = 71 MPa for N = $2{\cdot}10^6$ cycles. Therefore, the thinness effect according to the recommendations of IIW [2] can be the cause of higher fatigue strength. MASHIRI et al. [7] indicated that the fatigue strength increases for test specimens with a thickness lower than the reference thickness of $t_{ref}$ = 25 mm. For example an increased factor of 1.6 for the relative fatigue strength is possible for cruciform welded joints with a thickness of t = 5 mm. Since, the tested samples having a thickness of t = 3.0 mm (S355) and t = 2.5 mm (S700) are rather thin, an increased fatigue strength by a factor of 2 compared to FAT71 seems to be feasible.

The fatigue strength of the high strength steel S700 (factor 2.6 and 2.8 in table 6) is higher compared to the test series with S355 (factor 2.0 and 2.2). This fact was confirmed with both test machines or in other words with low (15 Hz) and high frequency fatigue testing (380 Hz).

### 3.3. Observed fatigue failure in range of giga cycles

Some specimens with S700 were tested at the stress level Z3 ($\Delta\sigma_{Z3}$ = 3·71 = 213 MPa) to compare the results to the S355 test series. However, the S700MC sample had a very good fatigue resistance at this low stress level. Thus, no fatigue cracks occurred in low cycle fatigue in contrast to the S355 test specimens. Normally this kind of test specimen is declared as a run out when it is tested in a servohydraulic machine up to $10^7$ cycles (see Fig. 10). But in this case the magnet resonance machine was not manually stopped to answer the question whether fatigue cracks would occur in high cycle fatigue. The question can be answered by Fig. 11 which shows the results for S700-T25-Z3-2. The fatigue crack occurred after $N = 0.364 \cdot 10^9$ cycles, which is in the giga cycle fatigue (GCF) range.

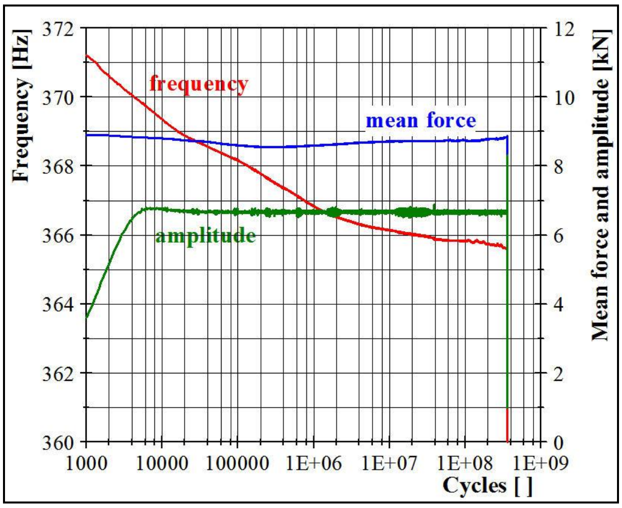


**Figure 11. Results of the giga cycle fatigue test S700-T25-Z3-2**

The mean force curve showed no significant decrease during the test. However, the frequency decreased continuously with each cycle. Since the frequency is the natural frequency of the system "resonance body + clamped test specimen" it can be used as an indicator for crack growth because the decrease of frequency is caused by a loss of stiffness (decrease of cross section due to a crack growth).

This result demonstrates that no cut off limit exists generally at $10^8$ cycles for constant amplitude loading. The observed fatigue failure in GCF is not an unusual phenomenon for this test series because the specimen S700-T25-Z3-1 has also a fatigue crack in this range (see Fig. 10). For this specimen the final number of cycles was $N = 0.526 \cdot 10^9$ and the test duration was only 16.5 days.

### 3.4. Results for as welded and treated conditions

A further test series called S355-T40 was carried out to investigate the influence of post weld treatment by high frequency hammer peening. Therefore, half of the specimens were treated at both toes of the transverse butt welds. The weld roots were not treated. The other group of specimen was tested in as welded condition. All specimens of this test series have a nominal thickness of t = 4.0 mm (see table 5).

The stress levels Z4 and Z5 are in low cycle fatigue and were tested by 20 Hz at a servohydraulic machine. The stress levels Z2 and Z3 in range of high cycle fatigue were mainly carried out with the magnet resonance machine at 380 Hz and in addition with the servohydraulic machine at 20 Hz. All test results are summarized as S-N-curves in Fig. 12.

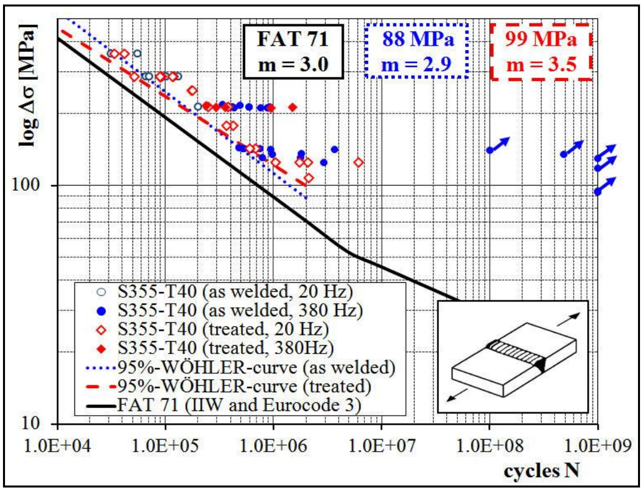


**Figure 12. S-N-curves for the test series S355-T40 with as welded and treated conditions**

In comparison to the corresponding fatigue curve FAT71 with a slope of m = 3.0 the curve for as welded conditions agree very well with m = 2.9. The fatigue strength of $\Delta\sigma_{C,test,as\ welded} = 88$ MPa concerning a survivability of 95% fulfil the requirements for FAT71 according to IIW. The fatigue cracks occurred at the weld toe and at the weld root as it is shown in Fig. 13.

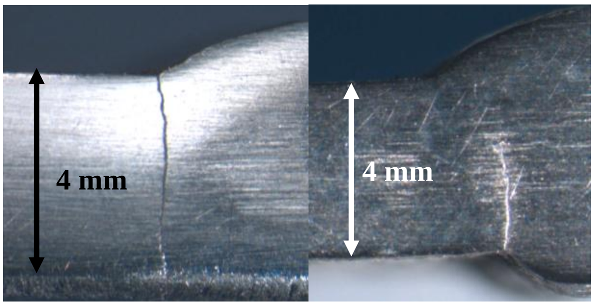


**Figure 13. Fatigue cracks at the toe (left) and at the root (right)**

The S-N-curve for treated conditions has a higher slope (m = 3.5) and the fatigue strength $\Delta\sigma_{C,test,treated} = 99$ MPa is also better. But the enhancement due to the post weld is only moderate because the untreated weld root was always critical. Thus, all fatigue cracks for the group of treated specimens were observed at the weld root.

Because of the small number of test specimens for each stress level a significant difference between the results derived by 20 Hz and 380 Hz can not be estimated. Based on the results in Fig. 12 the trend seems to be acceptable for both test frequencies. However, the magnet resonance machine can be used for tests in range of giga cycle. For example some run outs between $10^8$ and $10^9$ cycles are presented in Fig. 12, which were carried out at the magnet resonance machine.

### 3.5. Temperature during high frequency fatigue testing

For one high frequency fatigue test a measurement with a thermography camera was carried out. Therefore, the transverse butt weld was sprayed with a special coat (see Fig. 14 left) to get a high absorption for the infrared camera.

Before the fatigue test the camera was calibrated with a digital thermo element comparing the surface temperature of the resonance body and test specimen. The reference temperature was estimated as an average value of 20.3°C as it is shown in the middle of Fig. 14. But the weld toes have a lower temperature because of shadow effects.

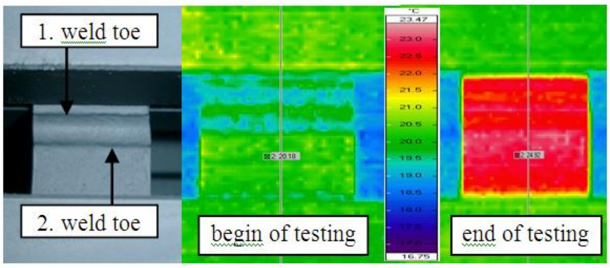


**Figure 14. Temperature plots of a thermography camera**

During the fatigue test the surface temperature increases slowly. The hot spots were located at both weld toes which indicates higher stress concentrations compared to the base material. At the end of testing a fatigue crack was observed at 326.500 cycles. At this time the surface temperature at the weld toes were measured between 24 and 26°C. This corresponds to an increase in temperature of nearly 5°C compared to the start temperature. The test frequency of the magnet resonance machine was 383 Hz.

### 3.6. Variable amplitude loading with the magnet resonance machine

A single fatigue test was carried out with variable amplitude loading to demonstrate the facilities of the magnet resonance machine. Therefore, a test specimen S355-T40 was analysed at the stress level Z2 ($\Delta\sigma_{Z2}$ = 142 MPa) which corresponds to an amplitude force of $F_a$ = 7.1 kN. This value was set to 100% reference at the beginning of the test as it is shown in Fig. 15. After the first 200.000 cycles the amplitude force was varied to different levels like 75% and 50%. At the end of the test an overload with 125% was simulated. During the increase of the amplitude force from 100% to 125% the mean force immediately decreased until the test was automatically stopped by reaching a pre-defined limit for the mean force.

However, this single test demonstrates that variable amplitude loading is possible with the magnet resonance machine. Since, time depending stress cycles can be defined in LabView (micro-controller) the magnet resonance machine can also be used for high frequency fatigue testing transverse butt welds with real time histories of stress cycles.

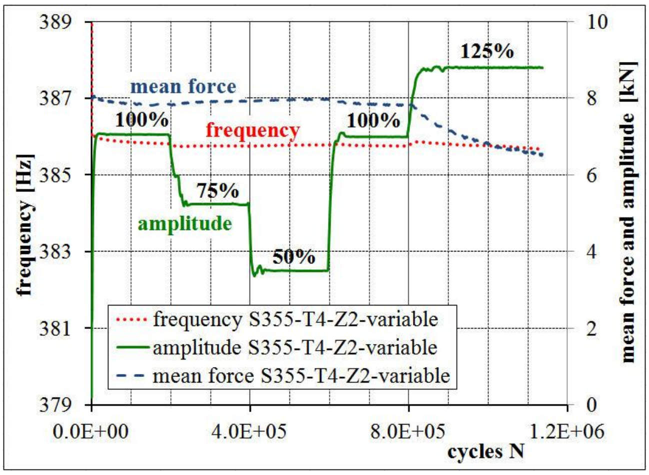


**Figure 15. Fatigue test with magnet resonance machine for variable amplitude loading**

## 4. Conclusion

Several high frequency fatigue tests were carried out at transverse butt welds with a new magnet resonance machine. Due to the maximum frequency of 400 Hz the test duration can be reduced significantly compared to servohydraulic machines. A benchmark test with normal and high strength steels showed that both types of machines deliver S-N-curves which are in very good agreement. However, the slope of the curves measured with the magnet resonance machine is higher because the stress ratio decreases during a fatigue test which is caused by the loss in stiffness when the crack growths. Some specimens were tested only in 30 days up to $10^9$ cycles with observed fatigue cracks. The increase of surface temperature at hot spots of the weld was measured as average value to 5°C during a test with 380 Hz. Furthermore, it was demonstrated that the magnet resonance machine can also be used for variable amplitude loading.

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