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Improving the Fatigue Performance of the Welded Joints of Ultra-Fine Grain Steel by Ultrasonic Peening *

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Abstract: Contrast tests were carried out to study the fatigue performance of the butt joints treated by ultrasonic peening, aiming at the improvement of ultrasonic peening treatment (UPT) on welded joints of a new material. The material is a new generation of fine grain and high purity SS400 steel that has the same ingredients as the traditional low carbon steel. The specimens are in two different states: welded and ultrasonic peening conditions. The corresponding fatigue testing data were analyzed according to the regulation of the statistical method for fatigue life of the welded joints established by International Institute of Welding (IIW). Welding residual stress was considered in two different ways: the constant stress ratio $R = 0.5$ and the Ohta method. The nominal stress-number (σ-N) curves were corrected because of the different plate thickness compared to the standard and because there was no mismatch or angular deformation. The results indicated that: 1) Compared with the welded specimens, when the stress range was 200 MPa, the fatigue life of the SS400 steel specimens treated by ultrasonic peening is prolonged by over 58 times, and the fatigue strength FAT corresponding to 10^6 cycles is increased by about 66%; 2) As for the SS400 butt joint (single side welding double sides molding), after being treated by UPT, the nominal S-N curve ($m = 10$) of FAT 100 MPa ($R = 0.5$) should be used for fatigue design. The standard S-N curves of FAT 100 MPa ($R = 0.5$, $m = 10$) could be used for fatigue design of the SS400 steel butt joints treated by ultrasonic peening.

Keywords: fatigue strength; ultrasonic peening; welded joints; ultra-fine grain steel
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Compared with traditional steel materials, the strength and toughness of the new generation of fine grain and high purity steel are one time higher. Welding technique is the main mean of steel structure manufacture. Hence, researches on fatigue performance of the new generation of steel materials have been focused on.

Researches are required for whether the fatigue life of the welded joints and structures made of new material has been improved and how to increase the fatigue strength of the joints.

Tests were carried out to study the fatigue performance of the butt joints treated by ultrasonic peening, aiming at the improvement of ultrasonic peening treatment (UPT) on welded joints of a new material. The material is a new generation of fine grain and high purity SS400 steel that has the same ingredients as the traditional low carbon steel.

1 Test

1.1 Preparation of the specimens

Specimens were prepared from the welded test plate of ultra-fine grain steel SS400 provided by Chief Department of Steel Research. The geometrical characteristics are shown in Fig. 1. The welding stuff was JS40CuA whose diameter was 0.1 mm. The mechanical properties of the base metal and the deposit metal are listed in Tab. 1 and Tab. 2 respectively.

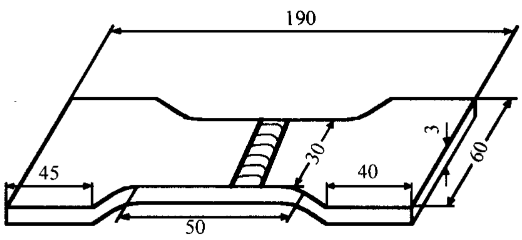

Fig. 1 Geometrical characteristics

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Tab. 1 Mechanical properties of SS400 steel

Yield strength σ_s/ MPa	Tensile strength σ_b/ MPa	Hardness HV_{150}/ ($kg \cdot mm^{-2}$)	Elongation rate δ/ %
365	480	130	31

Tab. 2 Mechanical properties of JS40CuA

Yield strength σ_s/ MPa	Tensile strength σ_b/ MPa	Reduction of cross-sectional area ψ/ %	AKV/ J (- 30 ℃)	Elongation rate δ/ %
520	610	78	120	26

The test plate was welded by pulse mixed arc gas (MAG) welding with single-side weld. Press the workpiece tightly to the iron plate inlaid with copper rods in slot shape, using the rich Ar gas as shielding gas. The welding parameters are listed in Tab. 3. There's no angular deformation or misalignment. All the circular transitions of the specimens were polished smoothly in order to prevent premature failure.

Tab. 3 Welding process parameters

Shielded gas flow rate/ ($L \cdot min^{-1}$)	Gap/ mm	Wire feed rate/ ($m \cdot cm^{-1}$)	Heat input/ ($kJ \cdot cm^{-1}$)
20	1.6	4.2	2.99

1.2 Fatigue testing

Tests of the welded joints were carried out on the 10 t HF Fatigue Testing Machine. The static load accuracy of the testing machine for full measuring range is ±0.2 %. The accuracy of the dynamic load amplitude of vibration is ±2 %. Load application: tensile loads, the frequency is 101—103 Hz.

Specimens were divided into two groups: the first group was as welded and the second was the specimens of which each weld toe of the four beads was treated by ultrasonic peening.

In order to use small size specimen to simulate the actual situation of large size welded structure containing high residual welding stress, the contrast test of the specimens fore and after UPT was carried out. Two methods were used for considering the welding residual stress. One is in accord with the corresponding regulation (loading in the condition of constant stress ratio $R = 0.5$) established by International Institute of Welding (IIW) and the other is transforming the stress amplitude according to the fixed maximum load $\sigma_{max} = \sigma_s$ (the yield strength of base metal) put forward by Ohta. Then the effects of the fatigue strength and the results of the UPT were compared when these two methods were used.

1.3 Method and parameters of ultrasonic peening

Ultrasonic peening gun aimed at the weld toe of the specimen and was basically perpendicular to the weld. The peening needles were arranged along the weld. Slight pressure was applied on the peening gun in order to direct the peening treatment by the dead weight of the gun.

The excitation current is 0.9 A, and the speed of treatment is 1.0—1.5 m/ min. Welds should be treated back and forth twice. During the peening process, the gun should be basically perpendicular to the weld, swaying in a certain angle, so that smoother transition shape of the weld toe can be gained.

2 Analytical results of the test

2.1 Statistical analysis method

The corresponding fatigue testing data of the SS400 steel butt joints fore and after ultrasonic peening should be analysed according to the regulation of the statistical method for fatigue life of the welded joints established by IIW.

This method assumes that the results of the fatigue testing are in accordance with normal distribution. Two nominal stress-number (σ-N) curves, whose slope ratio is m, and respectively corresponding to K times of plus-minus standard deviation, form a data dispersion band. Thereinto, eigenvalue K is a parameter, which is greatly related to the quantity of the data, the probability of falling into the dispersion band and the confidence. The surviving fraction is authorized by IIW, that is 95 % (the confidence is 75 %), the eigenvalue K is given in the document.

The nominal value is calculated as follows:

1) Calculate all the stress range $\Delta\sigma$ and the cycle index N (in logarithm with the base-number 10) of the fatigue testing data points.

2) Calculate the exponent m and the constant lg C regressively, using the power function model:

$$m \lg \Delta\sigma + \lg N = \lg C \tag{1}$$

3) Assuming that C_i is the logarithm of the testing data, using m that obtained above, calculate the average C_m of lg C and the standard deviation Stdv:

$$C_m = \frac{\sum C_i}{n} \tag{2}$$

$$\mathrm{Stdv} = \sqrt{\frac{\sum (C_m - C_i)^2}{n - 1}} \tag{3}$$

4) Calculate the eigenvalue C_k:

$$C_k = C_m - K \cdot \mathrm{Stdv} \tag{4}$$

2.2 Testing results

The fatigue results of the first group are shown in Tab. 4, and those of the second group are shown in Tab. 5, the contrast graph is drawn in Fig. 2.

2.3 Statistical analysis

The corresponding fatigue testing data in Tab. 4 and Tab. 5 were analyzed according to the statistical method above; *m* was sampled respectively as the value *m* of the average (surviving fraction is 50 %) σ-N curves obtained by regressing the fatigue testing data. The results are listed in Tab. 6, where FAT_C is the corrected FAT value. Tab. 6 shows that, as for the welded joints, the FAT values of the corresponding testing results obtained from the two methods, considering the effect of high residual stress, are approximately the same, and they can be fitted together.

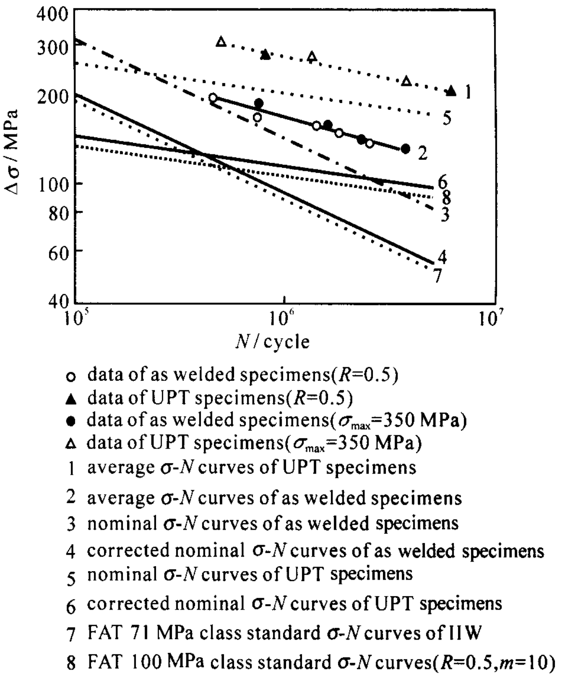

Fig. 2 Contrast σ-N curves

Tab. 4 Test results of UPT and as welded (Group 1)

No.	Group	Fatigue life $N/10^6$cycle	Fracture location	Stress range $\Delta\sigma$/ MPa
1	As welded	0.451	Weld toe root	170 —360
2	UPT	27.464	No fracture	160 —360
3	UPT	25.643	No fracture	160 —360
4	As welded	0.743	Weld toe root	190 —360
5	UPT	26.463	No fracture	180 —360
6	As welded	1.390	Weld toe	160 —320
7	As welded	1.786	Weld toe root	150 —300
8	As welded	2.436	Weld toe root	140 —280
9	UPT	5.894	Base metal	160 —360
10	UPT	0.797	Weld toe root	85 —360

Tab. 5 Test results of UPT and as welded (Group 2)

No.	Group	Fatigue life $N/10^6$cycle	Fraction location	Stress range $\Delta\sigma$/ MPa	Stress ratio R
1	As welded	1 603	Weld toe root	190 —350	0.54
2	As welded	747	Weld toe root	160 —350	0.46
3	As welded	3 687	Weld toe root	225 —350	0.64
4	As welded	2 296	Weld toe root	215 —350	0.59
5	UPT	1 402	Base metal	75 —350	0.21
6	UPT	491	Weld toe root	50 —350	0.14
7	UPT	3 687	Weld toe root	120 —350	0.34

Tab. 6 Statistical result of fatigue test data

Group	Fatigue strength $\Delta\sigma$/ MPa (2×10^6cycle)	Fitting method	m	C_m	C_k	$FAT_{95\%}$	FAT_C	Stdv
UPT	246	$m=10$	10	0.209×10^{31}	0.162×10^{30}	193	126	0.298
		The average slope ratio of S-N curves	7.25	0.457×10^{24}	0.143×10^{24}	211	138	0.139
As welded	148	$m=3$	3	0.562×10^{13}	0.244×10^{13}	112	73	0.124
		The average slope ratio of S-N curves	4.6	0.183×10^{17}	0.897×10^{16}	126	82	0.048 1

3 Analysis and discussion

3.1 Comparison of the methods considering the welding residual stress

The average σ-N curves whose surviving fraction is 50 % were fitted out according to the testing data in Tab. 4 and Tab. 5. The two groups of the testing data of as welded specimens were analyzed respectively, then they were fitted out together. The results are listed in Tab. 6, which indicated that, compared with the slope *m* of the σ-N curve obtained according to the fixing stress ratio $R=0.5$, the *m* from the Otha method considering the effect of the welding residual stress is smaller, that is, the curves are steeper. If the testing data fall into the same dispersion band, they can be fitted together. The results from the two methods considering the welding residual stress are nearly the same. This conclusion is only applicable to the butt joints. As for other higher strength steels or other types of joints, the conclusion should be proved by tests.

3.2 Effects of the UPT

Tab. 4 and Tab. 5 show that, except several specimens fractured at the base metal, most of the cracks generated from the root of the weld toe. Hence, the root of the weld toe is the weakest part of butt joint welded by single side welding double sides molding technique. The conclusion can be drawn from Fig. 2 that the fatigue performance of SS400 steel butt joints treated by UPT was improved significantly; compared with as welded joints, the fatigue life was improved by more than 58 times when the stress range was 200 MPa. Tab. 6 shows that, the $FAT_{50\%}$ of the as welded joints whose surviving fraction was 50 % was 148 MPa; when treated by UPT, the $FAT_{50\%}$ was 246 MPa. Consequently, compared with as welded joints, the $FAT_{50\%}$ of SS400 joints treated by UPT was increased by 66 %.

4 Fatigue design

4.1 Correction of the nominal σ- N curves

The standard of fatigue design σ-N curves has taken some degree of mismatch and angular deformation into consideration, while the specimens in this test and document have no such problems as welding quality. So it is necessary to correct the nominal σ-N curves gained from the testing results, considering the effect on the fatigue performance of the possible factors such as mismatch and angular deformation. According to the document, the regulation of the fatigue design established by IIW recommends that the nominal σ-N curves should be divided by 1.15 when some degree of mismatch and angular deformation is taken into consideration.

4.2 Plate thickness correction

Specimens in this paper are made of medium-thick plate which is of 3 mm. So when the testing results are compared with the standard σ-N curves of the corresponding strength level in the fatigue design regulation established by IIW, the plate thickness should be corrected. As a matter of fact, the fatigue strength of the joints whose fatigue cracks generated from the weld toe decreased while the plate thickness increased, because the stress concentration degree increased as the plate thickness increased. The standard σ-N curves of the corresponding strength level in the fatigue design regulation established by IIW were drawn according to the test results in which the plate thickness was 15—25 mm. The following formula is recommended to correct the nominal σ-N curves of the testing results when the effect of the plate thickness is considered:

$$S_T = S\left(\frac{25}{T}\right)^n \tag{5}$$

where S_T is permissible stress range of plate thickness T; n is thickness exponent, when the crack generates from the weld toe, the exponent n of the as welded butt joint is recommended to be sampled as 0.2 by IIW.

As the transition radius ρ of the weld toe treated by UPT increased, the thickness effect decreased to some degree. Up to now, the thickness exponent of the joint treated by UPT has not been given by the design regulation, so it was conservatively sampled as 0.2 in this paper. Then the nominal σ-N curves obtained from the testing results in all kinds of conditions were corrected according to the thickness correction formula above.

4.3 Discussion of the fatigue design

Fig. 2 shows that, as for SS400 steel as welded butt joint, the corrected nominal σ-N curves are a little higher than those whose strength level is FAT 71 MPa recommended by the fatigue design regulation established by IIW. The regulation happens to suggest that, as for the butt joints welded by single side welding double sides molding technique, the nominal σ-N curves of FAT 71 MPa should be used for fatigue design. Hence, the conclusion is though the fatigue testing results show high fatigue strength (the surviving fraction is 95 %, the value of FAT is as high as 112 MPa if untreated by thickness correction), it is not caused by the testing material, but by the usage of thin plate (T = 3 mm) in the test. Consequently, compared with the common steel, the high frequency fatigue performance of the structures and joints welded by arc welding, whose material is ultra-fine grain steel, has no difference.

Research shows that, as for the welded joints treated by all kinds of improving methods for fatigue performance, it is no longer suitable to analyse the testing results according to the unchangeable rule $m = 3$. The slopes of the standard fatigue design σ-N curves of these joints should be sampled as another value. In this paper, it is suggested that as for the butt joints treated by UPT, the nominal σ-N curve whose m is 10 should be used for fatigue design. The classification of the strength level and the usage of the curves are the same as the as welded joints. Tab. 6 and Fig. 2 indicate that, the corrected nominal σ- N curves

($m = 10$) of SS400 steel butt joint specimen treated by UPT are higher than the nominal σ-N curve whose strength level is FAT 100 MPa ($R = 0.5$) . As a result, we preliminarily suggest that as for the butt joint welded by single side welding double sides molding technique, after being treated by UPT, the nominal σ-N curve ($m = 10$) of FAT 100 MPa ($R = 0.5$) should be used for fatigue design.

5 Conclusions

1) When the stress range is 200 MPa, compared with the as welded specimens, the fatigue life of the SS400 steel specimens treated by ultrasonic peening is prolonged by over 58 times, and the fatigue strength FAT (the fatigue strength corresponding to 2×10^6 cycles) is increased by about 66 %.

2) As for the high quality butt joint welded by single side welding double sides molding technique, after being treated by UPT, the nominal σ-N curve ($m = 10$) of FAT 100 MPa ($R = 0.5$) should be used for fatigue design.

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