FATIGUE BEHAVIOUR OF STEELS WITH STRENGTH LEVELS BETWEEN 350 AND 900 MPa INFLUENCE OF POST WELD TREATMENT UNDER SPECTRUM LOADING

L. Lopez Martinez*, A.F. Blom**, H. Trogen*** and T. Dahle****

The object of this paper is to summarize experimental results from an inter-Nordic project concerning spectrum fatigue of improved welded components. Steels with strength levels of 350 – 900 MPa were used both for constant amplitude and spectrum loading. Improvement techniques included shot peening, hammer peening, ultrasonic peening and TIG-dressing. Mean life improvements were obtained up to a factor of two in terms of applied stress.

INTRODUCTION

Two Nordic projects carried out under the last decade have produced a considerable number of fatigue test results under both constant amplitude and spectrum loading. The second of the projects, summarized in the current proceedings, include results for several parent plate strength levels as well as different fatigue life improvement techniques and combinations thereof for certain parent plate qualities.

Fatigue life improvement techniques studied and presented in the archival literature have shown a considerable degree of improvement on the fatigue strength of welded joints. Most, in fact almost all, of these investigations have been performed under constant amplitude loading where an effect of parent plate yield strength has been observed. Higher strength steels would normally show better fatigue life improvement, largely due to the larger magnitude of compressive stresses possible to introduce in these steels. However, under realistic service conditions the loading, for the vast majority of load carrying structural components, is not constant amplitude. It is apparent that spectrum load necessarily will cause redistribution of the residual stresses. It will occur when the nominal stress times local stress concentration at the toe/root of the weld will exceed yielding, see Ref. (1). It is not at all obvious that the effects of post weld treatment seen under constant amplitude loading can be transferred to the case of real service conditions.

* SSAB Oxelösund AB, S-613 80 Oxelösund, SWEDEN
** FFA, P.O. Box 11021, S-161 11 Bromma, SWEDEN
*** SSAB Tunnplåt AB, S-781 84 Borlänge, SWEDEN
**** ABB Corporate Research, S-721 83 Västerås, SWEDEN

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Three categories of improvements techniques exist, i.e. those which introduce beneficial compressive stresses at the weld toe, those which improve the geometrical shape of the weld toe and combinations of these two. Furthermore, several of these methods will also reduce the size of the local flaw population.

In this paper we present fatigue data for a range of materials. These results were obtained both under constant amplitude loading as well as under different type of load spectra. It is shown that the use of improvement techniques on welds subjected to spectrum loading may allow an increase in admissible stresses (=design stresses). This increase is found to be larger for higher strength steels. Hence, even under spectrum loading it may become possible to utilize higher strength steels, if the proper post weld treatment is carried out. The tolerance boxes for such procedures need to be further defined within a larger cooperative effort, preferably of international level. Thus, the data shown below should not be taken as design data even if the showed trends certainly are expected to be accurate.

MATERIALS AND TESTING

The materials used in this investigation have yield strengths 350, 590, 700 and 900 MPa. These steel grades include two (HSLA-steels) cold forming DOMEX 350YP and 590XPE and two quenched and tempered steels WELDOX 700 and 900. The mechanical properties and chemical compositions are shown in Table 1. For further details, see Ref. (2).

Fatigue testing was performed on a specimen with a longitudinal fillet welded attachment, Lopez Martinez and Blom (2), which was also used in former investigations by Blom (3) and Bogren and Lopez Martinez (4). Both constant amplitude and variable amplitude testing were carried out. The spectrum types are the same as used in earlier investigations (5), SP2 (0<R<0.9) and SP3 (R=-1). These are straight line range-pair counted spectrum both with irregularity factor I=1.0. The block length is 500 000 load cycles. The spectrum tests were carried out at ABB Corporate Research, The Aeronautical Research Institute of Sweden (FFA) and the Royal Institute of Technology (KTH) (Dept of Lightweight Structures) while the constant amplitude tests were performed at SSAB (Borlänge).

TABLE 1 – chemical compositions and tensile properties of steels

Chemical composition (wt%)									
C	Si	Mn	P	S	Al	Nb	Yield strength (MPa)	Tensile strength (MPa)	Nominal strength (MPa)
0.06	0.02	0.62	0.009	0.01	0.042	0.014	398	503	350
0.09	0.21	1,63	0.11	0.02	0.03	0.024	615	747	590
0.15	0.44	1.32	0.012	0.002	0.099	0.060	780	850	700
0.17	0022	1.40	0.020	0.003	0.060	0.030	900	1010	900

The thickness of the specimens was 12 mm, width 80 mm and length 650 mm. The attachment was 12 mm thick, 50 mm high and had 150 mm length. This specimen is classified as FAT 71 according to IIW Recommendations (6).

WELDING PROCEDURES AND IMPROVEMENT TECHNIQUES

Weld Parameters

The welding procedure was the same for all steels tested, i.e. MAG with 1.6 mm electrode, current 185 Amp (DC), voltage 23.5 and heat input approximately 1.5 kJ/mm with consumable PZ 6130 (Mison 25) without preheating. The welds on the sides of the stiffeners as well as at the corners have been produced in an alternating diagonal sequence in order to limit the interpass temperature (<250° C). The same welder has manufactured all test specimens. No root treatment or weld preparation for the series has been utilized except for the hammer peening series where full penetration welds were used to get the same failure mode as for the rest of the series. As the same filler metal has been used for all steels tested, a degree of mismatch may be present as far as residual stresses are concerned. This may influence the fatigue results, especially the tests run with constant amplitude, but would probably be of minor influence for tests run under variable amplitude regime.

TIG-dressing parameters

The parameters used for the TIG_dressing technique are based on earlier experience within SSAB (Oxelösund) and the IIW Recommendations, Haagensen and Maddox (7). The angle of application of the TIG-electrode was 90° and distance to the plate material was held at 2-2.5 mm during remelting and the distance to the weld toe was max 1.5 mm, see Lopez Martinez and Blom (2). The diameter of the electrode was 2.4 mm and the gas (Argon) flow rate 12 l/min, the current 156 Amp and voltage 14.8 Volts giving a heat input of 1.4 kJ/mm.

Hammer peening parameters

The hammer peening was performed at TWI, Cambridge, UK. All specimens were hammer peened using a lightweight pneumatic hammer, “Atlas Copco RRD57” normally sold as a chipping tool. A round-tipped tool with 6 mm diameter was used throughout. The hammer and the particular tool used in the present project are shown in Manteghi (8). The tool is normally sold as a descaling chisel, but its tip was blunted to produce a round tip of the required diameter for use in hammer peening. The hammer peening equipment was capable of delivering 31 blows per second and needed air supply of 620 kPa. The air consumption was 9.5 lit/sec. The angle and position of the tool relative to the weld toe were as illustrated in Ref. (8). The majority of specimens received four passes of hammer peening. This is the number of passes adopted in most known previous investigations. However, lighter, vibration damped hammer guns should facilitate slower travel speeds, and hence more thorough treatment per pass. Indeed, the equipment used in the present project was much lighter, weighing 3.4 kg only, and thus easier to handle than the pneumatic or electrical rotary hammers normally used.

Shot peening parameters

The shot peening was performed at the industrial blast cleaning facility at Volvo Construction Equipment, Eskilstuna, Sweden. The Almen intensity for this equipment corresponds to 8-10. The equipment uses cut-wire as cleaning medium. The cut-wire is continuously replaced, hence at least 60% of the used cut-wire is sharp enough to obtain an acceptable cleaning result in the stipulated time. The normal time for such blast cleaning process is approx. 5-10 minutes which gives a plastically deformed layer of 1/5 to 1/3 mm thickness. This is depending of the steel yield level as well as variation in Almen intensity.

Ultrasonic peening parameters

The ultrasonic peening was performed at Paton Electric Welding Institute, Kiev, Ukraine. A compact hand tool with a multicomponent working element is employed for ultrasonic impact treatment. The tool comprises a magnetostrictive transducer, a wave guide and a pin holder with striking needles. A semi-conducting ultrasonic generator is used as a power supply for the tool. The treatment deforms the surface in the region of interest (i.e. weld toe) by needles oscillating at ultrasonic frequencies.

TABLE 2 – Specifications for ultrasonic impact treatment, Ref. (9)

Tool for Ultrasonic impact treatment

Rated watt consumption	600-900W
Operation frequency of oscillation system	25-28 kHz
Bias current	15A
Oscillation amplitude of wave guide edge	25-30 µ
Treatment speed in manual mode	0,3-0,7 m/min
Overall dimensions of manual tool	455x180x75 mm
Manual tool's weight	3,5 kg
Tool's axial clamping force	20-40 N
Cooling	Liquid
Needle diameter	2-5 mm

Ultrasonic generator

Output power	600-1200 V
Main voltage	220, 380 V
Supply frequency	50 Hz
Operational frequency range	25-30 Hz

RESULTS

Evaluation of equivalent stress

One way to compare constant and variable amplitude fatigue test results is to represent the stress range in the spectrum by an equivalent stress. For as-welded (AW) joints it has been demonstrated in many investigations that this stress can be calculated using the Palmgren-Miner fatigue damage accumulation rule and a linear Basquin type of S-N curve with slope m. For AW condition the slope m is determined to be 3 based on regression analysis of constant amplitude tests. However, for improved welds a steeper slope ($m>3$) is to be expected due to the increased period of crack initiation and the modified residual stresses. For all improved test series in this investigation, the equivalent stress in determined with exponent $m=3$, and the results are plotted as equivalent stress range as a function of the number of cycles to complete fracture of the specimen. Furthermore, the regression analysis have been performed with all data (including run-outs) due to few data. This is still a conservative approach.

Evaluation of degree of improvement

The data sets are presented graphically and numerically by means of the calculated improvement effect. Each data point has been compared to the mean regression curve shown on the graphs which is based on the AW condition of the 350-steel tested with constant amplitude and not on the regression line from each series. The motivation is that fatigue data of the AW condition for any steel is assumed to lie within that scatter band and any other tendency is due to randomness of the data. Also, any effect of the treatment of parent plate before welding is supposed to disappear by the improvement techniques itself. We concentrate here on the effect of fatigue life improvement only for the variable amplitude tests as these have most original value.

Fatigue test results for As-welded condition

Figure 1 shows the as-welded data from the current investigation compared to data from literature. The parallel straight lines shown in this graph is from regression analysis of constant amplitude tests on 350-steel, the mean line and the lower and upper lines with -2σ to $+2\sigma$ [σ=standard deviation] from the mean line.

It is seen that some of the data, especially the 590-data all lie at the lower limit whereas the data for the 700 and 900-steels lie on the upper limit of the scatter band. The reason for this is not clearly understood but in the 590-steel it has been confirmed that the mill scale induces additional weld detects which are detrimental to the fatigue strength. This is shown in Figure 2 where 590-data are compared for specimens including the mill scale versus specimens that were blast cleaned.

DOMEX 350 steel TIG improved

Figure 3 shows results from TIG-dressed specimens , both CA and VA tests. The estimated regression line parameters for TIG (CA) are: log C=14.35 and m=3.66. The calculated improvement is only performed for the lower data points due to the large scatter and are shown in Table 3.

TABLE 3 Calculated improvement for TIG-remelted DOMEX 350 steel

Stress range (MPa)	Cycles to failure	Calculated improvement
175.1	3.936E+05	1.147
175.1	3.322E+05	1.084
175.1	4.435E+05	1.194
87.6	3.840E+06	1.226
87.6	4.991E+06	1.338
62.5	1252E+07	1.298
48.5	1.676E+07	1.109
48.5	1.552E+07	1.081
Mean improvement		1.185

DOMEX 590 steel TIG improved

Figure 4 shows results from TIG-dressed specimens, both CA and VA tests. The calculated improvement is shown in Table 4. Note the increase of the calculated improvement for this steel.

TABLE 4 Calculated improvement for TIG-dressed DOMEX 590 steel

Stress range (MPa)	Cycles to failure	Calculated improvement
129.8	1.812E+06	1.415
129.8	2.059E+06	1.477
110.3	5.486E+06	1.740
110.3	2.829E+06	1.395
90.9	1.213E+07	1.867
90.9	1.695E+06	0.969
64.9	9.637E+06	1.235
64.9	1.111E+07	1.295
Mean improvement		1.424

WELDOX 700 steel TIG improved

Figure 5 shows results from TIG-dressed specimens, both CA and VA tests. The calculated improvements are shown in Table 5.

TABLE 5 Calculated improvement for TIG-dressed WELDOX 700 steel

Stress range (MPa)	Cycles to failure	Calculated improvement
133.1	3.827E+06	1.862
133.1	3.829E+06	1.862
113.1	1.309E+07	2.384
113.1	3.234E+07	1.496
93.2	4.249E+06	1.349
66.6	3.790E+07	1.999
66.6	9.272E+06	1.250
66.6	1.496E+07	1.466
66.0	8.830E+06	1.220
66.0	5.220E+07	2.206
55.9	5.317E+07	1.880
Mean improvement		1.725

WELDOX 900 steel TIG-dressed

Figure 6 shows results from TIG remelted specimens, both CA and VA tests. The calculated improvements are shown in table 6.

TABLE 6 Calculated improvement for TIG-dressed WELDOX 900 steel

Stress range (MPa)	Cycles to failure	Calculated improvement
169.3	1.585E+06	1.765
169.3	1.518E+06	1.740
112.9	5.050E+06	1.731
112.9	6.340E+06	1.868
112.9	8.640E+06	2.071
112.9	7.380E+06	1.965
112.9	6.170E+06	1.851
90.2	1220E+07	1.857
90.2	2.884E+07	2.474
Mean improvement		1.893

Effect of shot peening

The effect of shot peening on specimens run with constant amplitude is illustrated in Figure 7. Shot peening has not given any significant effect on the fatigue strength for steels 350, 590 and 700.

Effect of ultrasonic peening and the its combination with TIG-dressing

The effect of ultrasonic peening is shown for steels 350 and 700 in Figure 8 and in Table 7 and 8, respectively. The effect of the combination TIG and ultrasonic peening is shown for 900 steel in Figure 8 and in Table 9.

TABLE 7 Calculated improvement for ultrasonic peening for DOMEX 350

Stress range (MPa)	Cycles to failure	Calculated improvement
360.0	9.610E+04	1.474
340.0	5.642E+04	1.166
290.0	4.100E+05	1.926
278.0	4.885E+05	1.958
190.0	2.000E+06	2.140
Mean improvement		1.733

TABLE 8 Calculated improvement for ultrasonic peening for WELDOX 700

Stress range (MPa)	Cycles to failure	Calculated improvement
294.0	2.052E+05	1.550
247.0	4.030E+05	1.631
241.0	6.350E+05	1.851
225.0	6.530E+05	1.745
211.0	1.050E+06	1.918
200.0	1.405E+06	2.003
162.0	2.000E+06	1.825
Mean improvement		1.789

DISCUSSION AND CONCLUSIONS

Influence of mill scale on fatigue properties

It is apparent that non-removal of the mill scale for the 590 steel led to significantly worse fatigue properties than when a blast cleaning process was used to remove the mill scale previous welding. Similar results have also been obtained for other steels. It appears that the detrimental effect of mill scale is general and connected to the prevalence of more and/or larger initial flaws.

TABLE 9 Calculated improvement for ultrasonic peening for WELDOX 900

Stress range (MPa)	Cycles to failure	Calculated improvement
410	1.171E+05	1.793
375	1.540E+05	1.797
363	1.516E+05	1.731
330	3.500E+05	2.079
325	2.912E+05	1.926
303	5.510E+05	2.221
275	5.200E+05	1.977
259	8.241E+05	2.171
234	1.335E+06	2.304
220	1.830E+06	2.406
Mean improvement		2.041

The effect of parent strength level for TIG-dressed specimens

The general effect of TIG-dressing is to improve the fatigue life of all tested specimens, both under constant amplitude and spectrum loading. This beneficial effect becomes larger for lower applied stress levels., i.e. at longer fatigue lives as well as for higher yield strength for parent plate.

The calculated improvement for 350 MPa steel is a 20% improvement both for CA and VA, for 590 MPa steel is 40% improvement, for 700 MPa steel the improvement is 70% and for 900 MPa steel the improvement is 90%. This shows a clear influence of parent plate yield strength. This is due to the improved weld shape, lower stress concentration and lower residual stress level after TIG-dressing.

Effect of different improvement techniques

- Shot peening gave no or marginal effect for all steels studied.
- Hammer peening gave a mean improvement of 1.7 for the 700 steel.
- Ultrasonic peening gave a mean improvements of 1.7 and 1.8 for the 350 and the 700 steel, respectively.
- Ultrasonic peening combined with TIG-dressing gave a mean improvement of 2.0 for the 900 steel.

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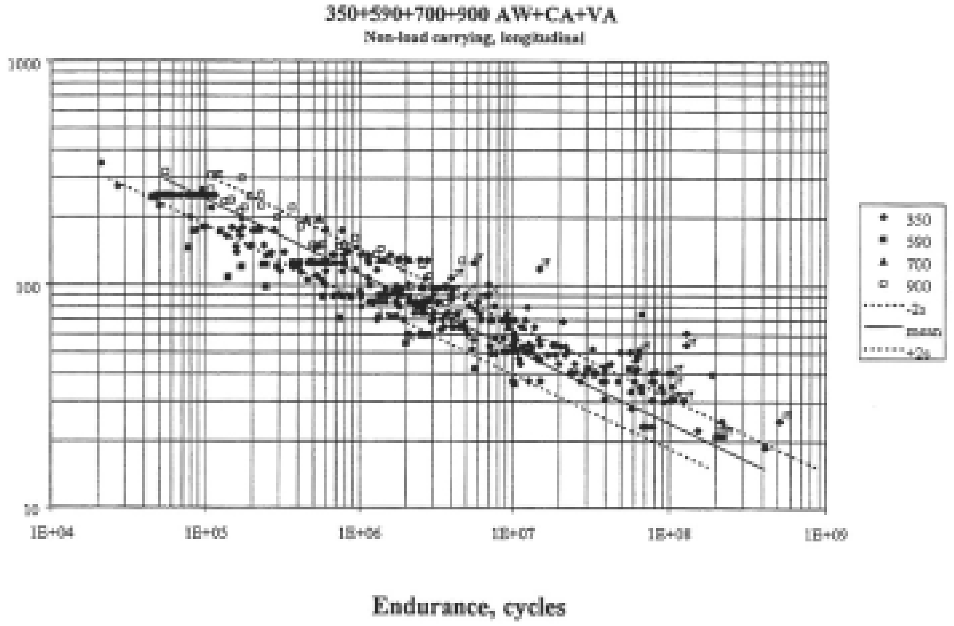

Figure 1 Summary of CA and VA tests on as welded non-load carrying, longitudinally stiffened welded joint specimen, current data compared to literature

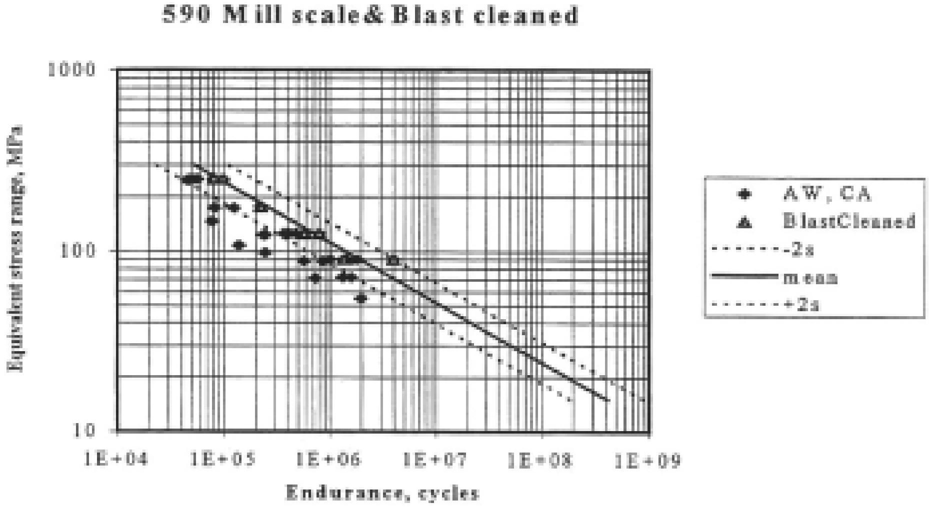

Figure 2 Effect of pre-treatment (sand-blasting) on fatigue behaviour of 590 steel

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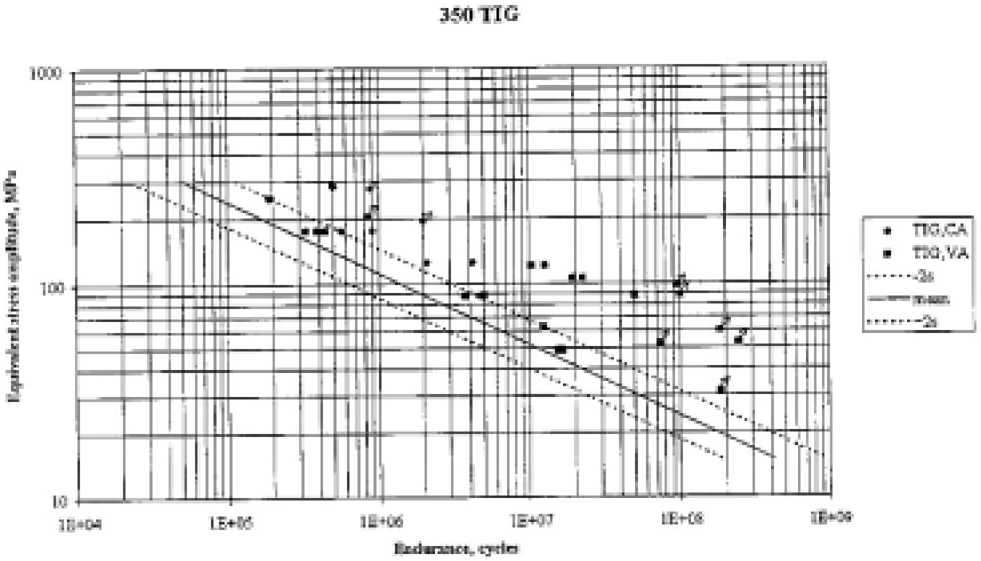

Figure 3 TIG remelted 350 steel results, constant amplitude and variable amplitude tests compared to the reference scatter band

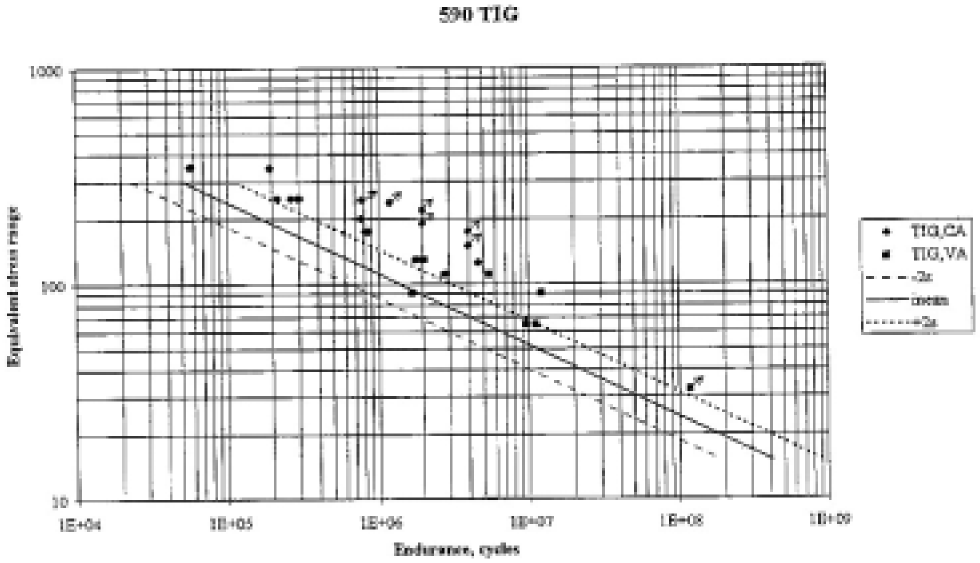

Figure 4 TIG remelted 590 steel results, constant amplitude and variable amplitude tests compared to the reference scatter band

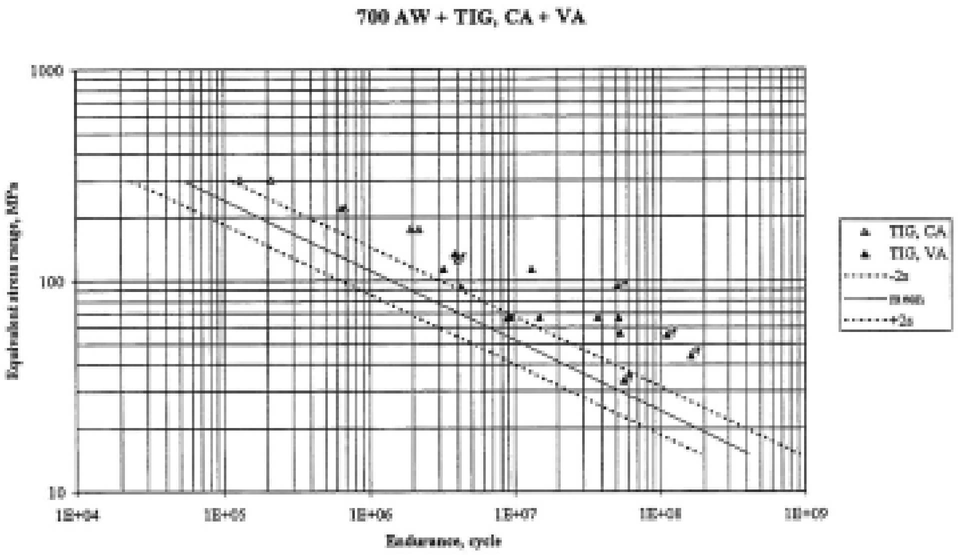

Figure 5 TIG remelted 700 steel results, constant amplitude and variable amplitude tests compared to the reference scatter band

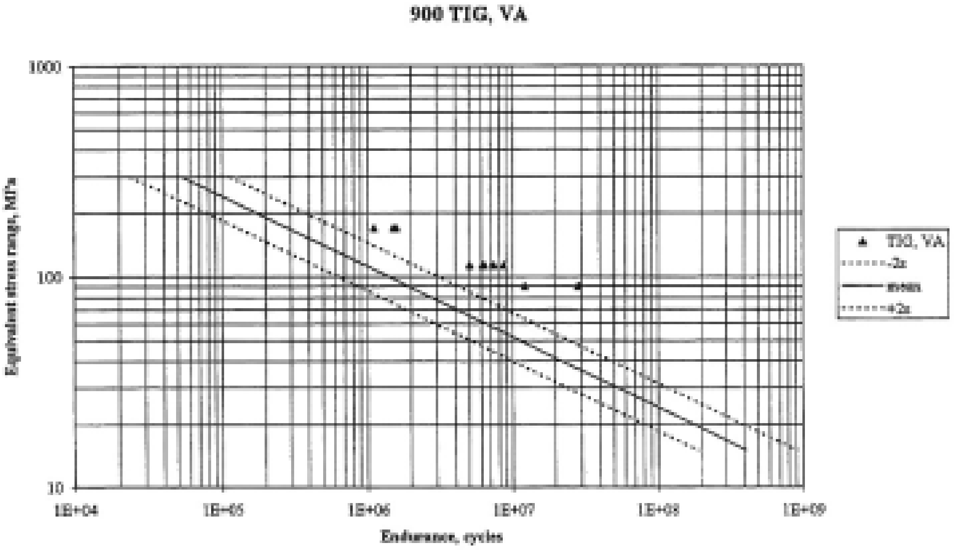

Figure 6 TIG remelted 900 steel results, constant amplitude and variable amplitude tests compared to the reference scatter band

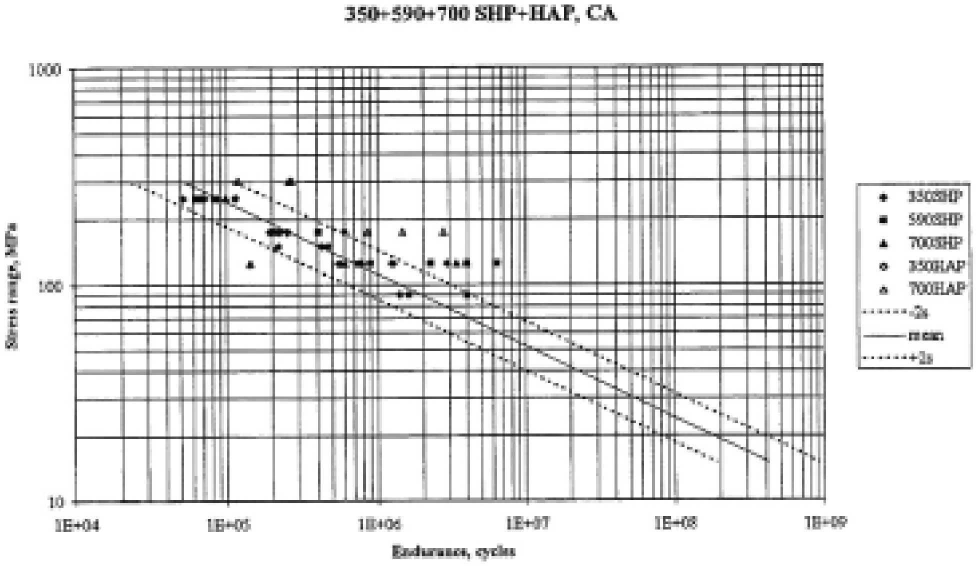

Figure 7 Effect of shot peening and hammer peening on steels 350, 590, 700 and 900 on specimens run at constant amplitude

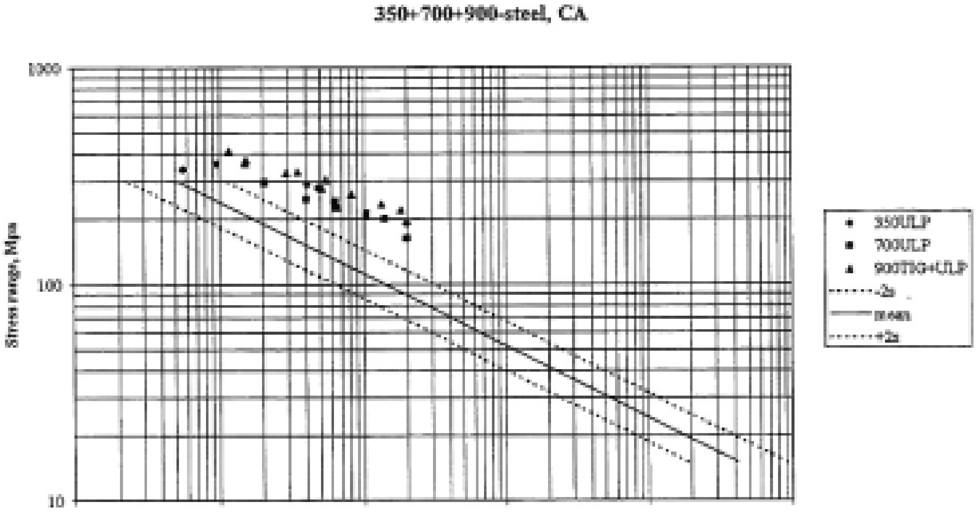

Figure 8 The effect of ultrasonic peening on steels 350, 700 and the combination of TIG and ultrasonic peening on 900 steel on specimens run with con stant amplitude