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THE INFLUENCE OF ULTRASONIC IMPACT TREATMENT ON FATIGUE BEHAVIOUR OF WELDED JOINTS IN HIGH-STRENGTH STEEL

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ABSTRACT

The unabated growth of the steel industry and progressively increasing operating loads on metal structures generate a need for a search for optimum engineering solutions to improve the load-carrying capacity and reduce metal consumption. One way of resolving this problem is to utilise high-strength steels.

It is common knowledge however that the improvement of the steel strength is accompanied by the reduction in fatigue resistance of welded joints down to mid-strength steels and below.

This paper presents the results of the research aiming at the evaluation of the influence of various post-weld fatigue improvement techniques on the fatigue limit and life of welded joints in mid- and high-strength steels.

It has been demonstrated that the UIT method is the most efficient fatigue improvement technique that at the same time makes it possible to take advantage of high-strength steels in fabrication of welded structures operating under variable loading.

1. INTRODUCTION

Steel industries develop steels with higher and higher tensile strength. It is commonly adopted that the fatigue limit of the base material will increase as the ultimate tensile strength increases. Unfortunately, in the case of welded components with high stress concentration factors such as welded joints (except butt joints), the fatigue limit is slightly dependent on the steel grade.

It is widely adopted that a high stress concentration factor and weld defects are responsible for the fact that the ultimate tensile strength has no effect.

In order to increase the fatigue properties of welded components, it is possible to influence the following three parameters: the weld quality, local geometry and residual stresses. Post-weld treatment changes one or more of these parameters. The most common are grinding, shot penning, hammer penning and TIG dressing.

In this paper, a new technique called ultrasonic impact treatment (UIT) has been tested on two different steel grades. The process of UIT is shown in Fig.1.

The benefits of UIT have been shown in several studies[1-10]. The benefits of the UIT method as compared to the above-mentioned improvement techniques are shown in Ref.11. A comparison between the UIT technique and the use of low transformation temperature electrodes (LTT) is presented in Ref. 12. The results of the studies[13] show that the fatigue strength of weld details such as stiffeners and cover plates of actual bridge girders was significantly improved by UIT. The case studies[14,15] present the application of UIT on bridges in the USA. Also, studies have been carried out to compare the effect of Sand Blasting (SB), Laser Treatment (LT) and UIT on the fatigue limit of low- and high-strength steels.

2. EXPERIMENTAL RESULTS

All tests were performed on two grades formally named USIFORM 355 and USIFORM 700. USIFORM 355 is ferrito-perlitic steel with a yield stress of 355 MPa and an ultimate tensile strength of 500 MPa. Steel of USIFORM 700 grade has a yield stress and a tensile strength of respectively 700MPa and 800 MPa.

Fatigue tests were carried out on T-joint specimens made from 6 mm sheets for USIFORM 355 and 5mm sheets USIFORM 700 (Fig.2).

S-N curves have been plotted for as-welded specimens and specimens improved by ultrasonic impact treatment.

The UIT technique has been developed many years ago and applied to several specimens [16,17].

The specimens were treated using *Esonix* equipment to the UIT procedure developed by Applied Ultrasonics and NSTC. According to the procedure, a 27 kHz hand held tool was used and the configuration of the stress-relief groove, the size of the indenter and treatment conditions could be selected based on the welded joint type and fatigue test conditions.

Basically, the configuration of the stress-relief groove is determined by the weld toe angle in the as-welded condition. By the application of UIT the surface of the groove at the weld toe should be completely treated to obtain a uniform metallic lustre. The groove should cover the weld metal by not greater than 60% and not less than 30% and the base metal in the HAZ area by not greater than 70% and not less than 40% of the groove's width (or transverse length). Typically, the width of the groove is up to 2 diameters of the indenter. The maximum depth of the groove from the surface of the base metal is generally 0,6 mm, provided that the toe of the weld is completely treated, and depends on the weld quality and strength of the welded joint material.

The groove's cross-sectional dimensions and the relation between its transverse length across the weld and base metal are determined by the radius of the indenter, an angle at which the tool is located to the base metal surface and an oscillation angle of the tool relative to its axis in the groove' cross-sectional plane.

The indenter size and treatment parameters are selected based on the strength of the treated material to obtain the specified level of plastic deformation, induced favourable residual compressive stresses and the depth thereof. It should be noted that during UIT virtually no pressure on the tool is required. To perform the UIT treatment it is sufficient to specify or know the limits of the impact and return. It means that the impact energy and hence the treatment quality at a given point are independent of the operator (i.e. the pressure on the tool) and determined by UIT conditions only.

In present work, the following UIT conditions were used:

→	The frequency of the ultrasonic transducer (responsible for deformation resistance and material relaxation during impact)	27 kHz
→	Ultrasonic oscillation amplitude of the transducer under unloaded conditions	40 μm
→	Impact frequency under loaded conditions (responsible for linear rate of the treatment process, the depth of the plastic deformation and a groove profile in the longitudinal and transverse direction)	100-120 Hz,
→	Impact amplitude under loaded conditions (at 100 -120 Hz)	Up to 1,5 mm
→	Ultrasonic oscillation amplitude under loaded conditions (during impact)	30 μm
→	Quality factor of the oscillation system Transducer – Concentrator (of oscillating velocity) under unloaded conditions and between impacts (acoustic efficiency factor of the oscillating system)	150
→	Quality factor of the oscillation system Transducer– Concentrator– Indenter– Workpiece during impact (transducer energy efficiency factor during ultrasonic impact)	25
→	Relative factor of the ultrasonic transducer energy utilisation during impact	(150-25)/150*100=71%
→	Indenter: hardness diameter radius	HRC62…64 6.35 mm 3 mm
→	The tool is pressed against the treated surface with the force that is defined only by the weight of the tool. This in no way effects the treatment quality that depends only on the UIT conditions. The power of the tool	1200 W
→	The range of the tool oscillation angle during treatment relative the initial position of 45^o	35^o – 55^o
→	Treatment rate	not less 0.3 m/min

Welded specimens have been tested under 4-point bending loading using an 100 kN hydraulic machine as shown in Fig.3.

The advantage of the 4-point loading is to subject the part comprised between the two internal cylinders to the same bending moment. The welded side of the specimen is placed in such a way that the weld seams are loaded in tension.

The load ratio (R=Fmin/Fmax) of 0.1 was used for fatigue tests and the load was controlled until either the fracture of the specimen or $2x10^6$ cycles.

3. FATIGUE TESTS

Specimens in the as-welded and improved conditions were tested. First, specimens in the as-welded condition were tested to have the initial and reference data. Then the effect of sand blasting and UIT on the fatigue behaviour was studied.

The results of fatigue test have been analysed using the ESOPE software to determine the S-N curve equation and thus the conventional endurance limit at $2x10^6$ cycles.

3.1. AS-WELDED SPECIMENS

In order to determine the S-N curve, about 20 specimens of each grade were tested. As can been seen from Fig.4, the fatigue resistance of the as-welded specimens is somewhat dependent on the steel grade.
The endurance limit of S355 grade at $2x10^6$ cycles is 250 MPa, while for S700 it is equal to 220 MPa.

The weld shape cannot explain the difference in fatigue resistance. Figs. 5 and 6 show that the weld is smoother in the case of the S700 grade, which fatigue strength is slightly lower. The explanation can be found by magnification of the weld toe. For the S700 grade, the welding conditions selected have induced small cracks (Fig.7).

3.2. POST-WELD TREATMENT

Ultrasonic impact treatment was applied under conditions referenced above.

Fatigue tests were carried out on sand blasted specimens with the same welds. This process is sometimes used for oxide layer removal.

Since the weld shape of S355 steel is not optimised, the laser re-melting of the weld toe was also tested. Like TIG dressing, this operation decreases the stress concentration factor and can introduce local residual stresses. Unfortunately, because of the narrow zone treated the local residual stresses have not been measured.

From fatigue test results (Figs.8 and 9), it can be seen that the UIT technique increases the fatigue resistance in the high-cycle regime as well as for limit lives (100 000 cycles). Furthermore, the scatter is unchanged when this technique is applied.

The endurance limits for each grade at 200000 cycles and 2000000 cycles are given in the following table:

Cycles	USIFORM 355			USIFORM 700		
	Stress, MPa			Stress, MPa		
	As-welded	Sand blast	UIT	As-welded	Sand blast	UIT
2000000	250	290	380	220	360	500
200000	320	400	480	370	500	620

Compared to the resistance of specimen in the as-welded condition, the percentage of improvement is as follows:

Cycles	USIFORM 355		USIFORM 700	
	Improvement, %		Improvement, %	
	Sand blast	UIT	Sand blast	UIT
2000000	16	52	64	127
200000	25	50	35	67

The results confirm, if needed, the benefits of UIT treatment for high strength steel grades (Fig.10). The sand blasting operation without any shape modification gives a significant fatigue improvement by the introduction of residual stresses similar to shot penning.

4. GEOMETRY OF WELDS

The weld shape is characterised by the toe angle, toe radius and the undercut.

The fatigue resistance of the weld is higher with a low toe angle and a high toe radius, because these parameters decrease the stress concentration factor.

After the UIT treatment, the toe radius is increased and the undercut is introduced for S355 grade (i.e. the softer material) (see Fig.11). On measuring the weld shape of some specimens, the toe angle was about 60° for S355 grade and 40° for S700 grade. After ultrasonic impact treatment, the toe radius was about 1mm.

As for the undercut, this was less than 0.17 mm for S700 grade and close to 0.4 mm for S355 grade (see Fig.12).

The weld parameters for specimens in the as-welded and UIT treated conditions are summarised in the following table:

Grade	Type of Weld	No. of Specimen	Toe Angle (°)	Toe Radius (mm)
USIFORM 355	As-welded	8	63	*
		9	64	*
		11	80	*
		12	67	*
	UIT	14	63	0.95
		15	60	0.90
		17	69	0.8
		18	57	1.00
		20	63	0.8
		21	58	0.85
USIFORM 700	As-welded	6 left	38	
		6 right	40	
	UIT	23	41	2.00
		24	40	2.1
		26	39	1
		27	44	0.85

* Too small to be measured

4. CONCLUSION

- With this experimental program, the benefits of UIT for the use of high-strength steel have been shown. For USIFORM 700 steel the increase of the endurance limit at $2x10^6$ cycles is more than 120%. It should be noted that the improvement could have been more important in the case of sharper welds.

- The ultrasonic impact treatment technique is beneficial regardless of the weld shape, because it changes the local geometry.

- Because of the high level of residual stresses and the depth affected, UIT can be applied on welds with initial cracks.

- Thus, the UIT technique offers considerable possibilities to use high-strength steels in fabrication of welded structures.

5. REFERENCES

1. Janosch J.J., Koneczny H., Debiez S., Statnikov E.Sh., Trufyakov V.I., Mikheev P.P. Improvement of Fatigue Strength in Welded Joints (In HSS And Aluminium Alloys) by Ultrasonic Hammer Peening. IIW-1300-95. Welding in the World, March-April 1996, vol. 37, No. 2, pp. 72-83 (12 pages).

2. Mikheev P.P., Garf E.F., Kuzmenko A.Z., Zaitsev V.V., Statnikov E.Sh. Improvement of Fatigue Resistance of Tubular Welded Connections by Ultrasonic Peening. Equipment for Oil Industry, No. 2, Chicago, 1997.

3. Statnikov E.Sh. Comparison of Post-Weld Deformation Methods for Increase in Fatigue Strength of Welded Joints. IIW Doc.XIII-1668-97.

4. Statnikov E.Sh., Trufyakov V.I., Mikheev P.P., Kudryavtsev Yu.F. Specification for Weld Toe Improvement by Ultrasonic Impact Treatment. Doc. IIW-1346-96. Welding in the World, vol. 37, No.1.

5. Trufyakov V.I., Statnikov E.Sh., Mikheev P.P., Kuzmenko A.Z. The Efficiency of Ultrasonic Impact Treatment for Improving the Fatigue Strength of Welded Joints. IIW Doc.XIII-1745-98.

6. Haagensen P., Statnikov E.Sh., L.Lopez-Martinez. Introductory Fatigue Tests on Welded Joints in High Strength Steel and Aluminium Improved by Various Methods Including Ultrasonic Impact Treatment (UIT). IIW Doc.XIII-1748-98.

7. Statnikov E.Sh. Guide for Application of Ultrasonic Impact Treatment for Improving Fatigue Life of Welded Structures. IIW Doc. XIII-1757-99.

8. Statnikov E.Sh., Stepanov V.G., Klestov M.I., Shevtsov E.M. Residual Stresses in Welded Joints of Yu3 (Ю3) Steel Hardened by Ultrasonic Impact Tool. “Shipbuilding Technology”, 1974, No. 7, pp. 32-34.

9. Statnikov E.Sh., Stepanov V.G., Klestov M.I., Shevtsov E.M. Corrosion-fatigue strength of Yu3 (Ю3) Steel Hardened by Ultrasonic Tool. “Shipbuilding Technology”, 1975, No. 1, pp. 70-74.

10. Statnikov E.Sh., Mikheev P.P., Nedoseka A.Ya, Parkhomenko I.V., Kuzmenko A.V. Benefits of Ultrasonic Impact Treatment for Increasing Fatigue Resistance of Welded Joints. “Automatic Welding”, Kiev, 1984, No. 3, pp. 34-39.

11. Statnikov E.Sh., Muktepavel V.O., Blomqvist A. Comparison of Ultrasonic Impact Treatment (UIT) and other Fatigue Life Improvement Methods. IIW-Doc.XIII-1817-00.

12. Huo Lixing, Wang Dongpo, Wang Wenxian, Zhang Yufeng. Ultrasonic Peening and Low Transformation Temperature Electrodes Used for Improving the Fatigue Strength of Welded Joints. IIW Doc. XIII-1894-01.

13. Fisher J.W., Statnikov E.Sh., Tehini L. Fatigue Strength Improvement of Bridge Girders by Ultrasonic Impact Treatment (UIT). IIW Doc.XIII-1916-02.

14. Statnikov E.Sh., Kelner L., Baker J., Croft H., Dvoretski V.I., Muktepavel V.O. Repair Case Study. XIII WG5-18-98.

15. Statnikov E.Sh., Tehini L. Repair of Fatigue Loaded Welded Structures. IIW Doc. XIII-WG5-1873-01.

16. Statnikov E.Sh. Applications of Operational Ultrasonic Impact Treatment (UIT) Technologies in Production of Welded Joints. IIW Doc.XIII-1667-97.

17. Statnikov E.Sh, Zhuravlev L.V., Alexeyev A.F., Bobylev Yu.A., Shevtsov E.M., Sokolenko V.I., Kulikov V.F. Ultrasonic Head for Strain Hardening. Author’s Certificate No. 472782. Application date 04.07.72, “Bulletin of Inventions” No. 21, 1975.

Figure 1 – UIT process

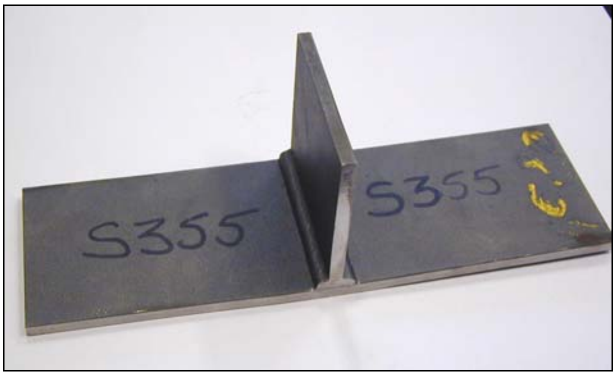

Figure 2 – Test specimen

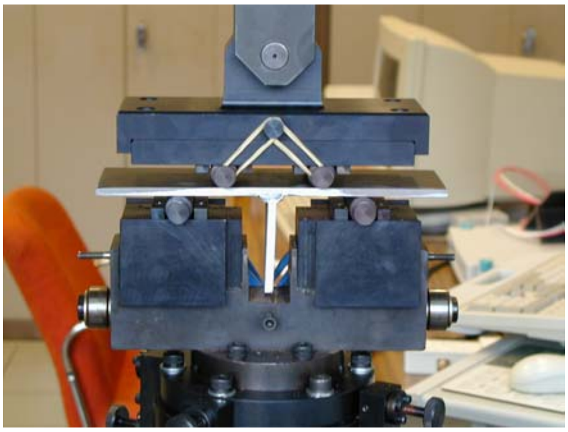

Figure 3 – 4-point bending test setup

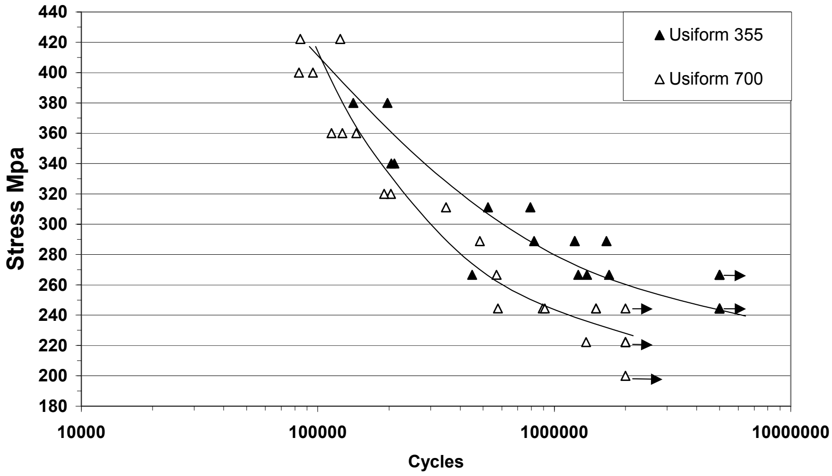

Figure 4 – SN curves for as-welded specimens

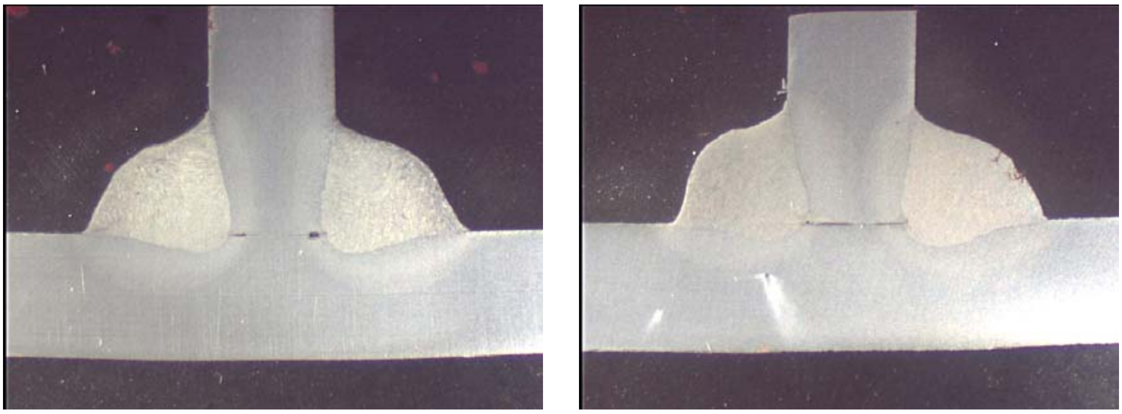

Figure 5 – Weld shape for S355 grade

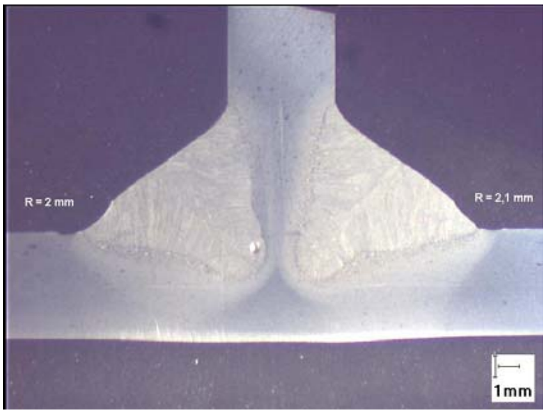

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Figure 6 – Weld shape for S700 grade

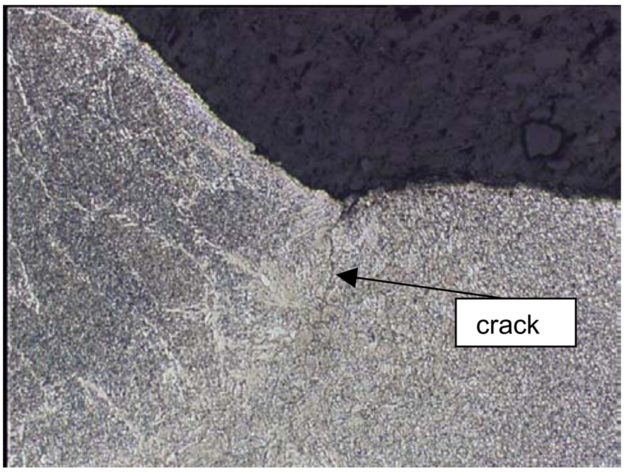

Figure 7 – Detail of the weld toe for S700 grade

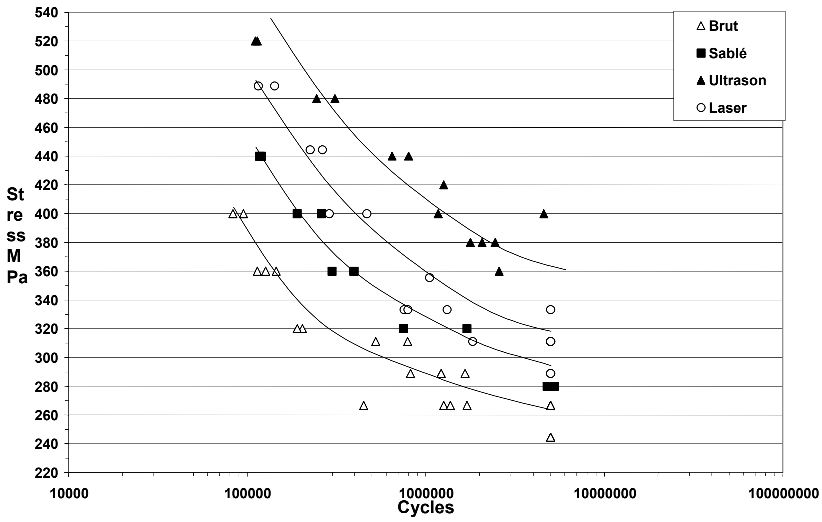

Figure 8 – Evolution of SN curves for different post treatment operations for S355 grade

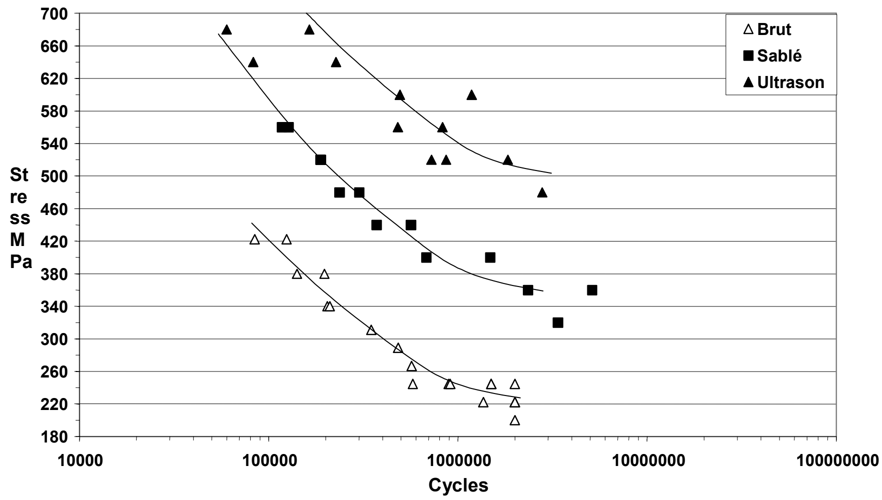

Figure 9 – Evolution of SN curves for different post treatment operations for S700 grade

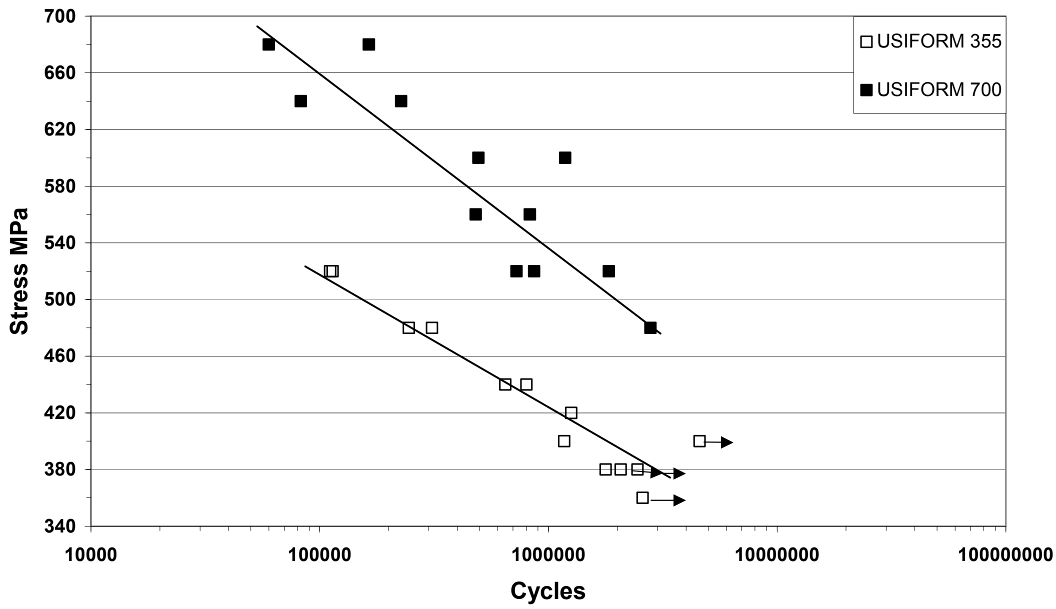

Figure 10 – Comparison of fatigue strengths for UIT joints

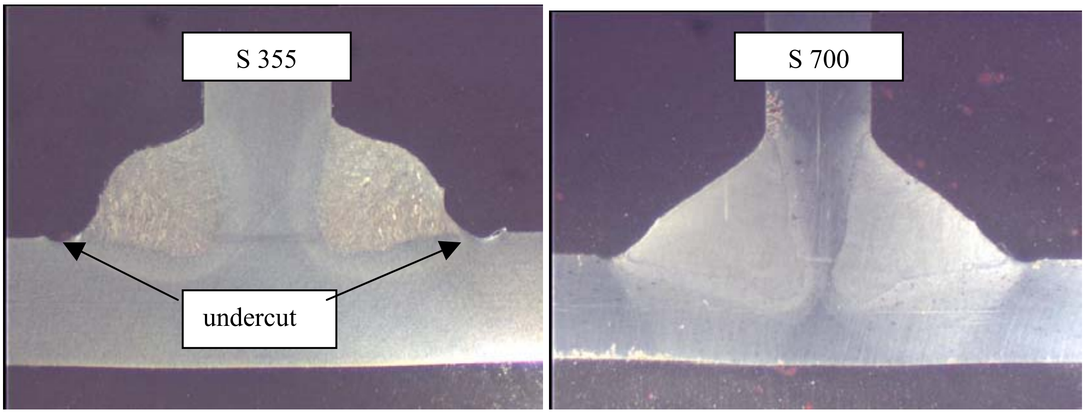

Figure 11 – Weld profile after UIT

Figure 12 – Example of S355 weld shape after UIT
(toe radius = 0.90mm, undercut depth = 0.4mm)