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Integrated Design and Manufacturing of Welded Structures

- Improved fatigue design procedures for welded structures
- Practical guidance of immediate value to industry

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Title: **INTEGRATED DESIGN AND MANUFACTURING OF WELDED STRUCTURES**, Report from NICe-project: QUALITY AND COST OF FABRICATED ADVANCED WELDED STRUCTURES - Q-FAB		
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Abstract: The current cooperative project, Q-FAB, which is based on findings from earlier Nordic projects, more than 20 research partners are working together to improve the design, fabrication and cost effectiveness of advanced welded structures. The welded structures being developed are highly optimised welded plate structures used in vehicles, energy systems and other demanding mechanical engineering applications where fatigue resistance is an important design consideration. Manufacturing partners in the present project represent construction equipment, diesel engine, forestry equipment, cranes, and truck components industries. Design and manufacture in these sectors are primarily for small to medium production volumes of between 50 to 1000 units per year. Automation in both welding processes and welding inspection in this sector has proceeded much slower than, for example, in the automobile industry where production volumes are measured in tens of thousands of units per year. Steel manufacturers from both Finland and Sweden are important partners in the project for supplying the project with material, material data and testing. The academic partners in the project are from five universities from all Nordic counties except Iceland. All the academic partners and many of the industrial partners are also regular contributors to The International Institute of Welding (IIW) and many activities and results earlier projects and Q-FAB are discussed and presented at IIW events. The national delegates in Commission XIII (Fatigue of welded components and Structures) from Denmark, Sweden, Norway and Finland are active members on Q-FAB and as of this year Prof Gary Marquis (head of the Finnish part of Q-FAB) from Lappeenranta Technical University is the chairman of Commission XIII. All of the foregoing projects have been presented in conferences, 1993 in Copenhagen, 1997 in Stockholm and 2002 also in Stockholm and proceedings were published by EMAS. Q-FAB was presented at a symposium “Integrated Design and Manufacturing of Welded Structures” 13-14 March 2007 in Eskilstuna Sweden, hosted by Volvo Construction Equipment, Nordic Innovation Center. And The Swedish Welding Commission. Key notes lectures from IIW Commission XIII were invited to this event. The results of the project will provide practical guidance of immediate value to industry, and exploitation will concentrate on the provision of information in a user-friendly and readily applicable form.. Although the project will address transportation structures, there is no doubt that the results will also be applicable to most industries involved with fatigue-loaded welded structures:		
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Executive summary

Since 1989, Nordic industries, research organisations and universities have co-operated in a series of projects related to the design and fabrication of welded structures. Q-FAB was started in late 2003 and is the fourth project in this series. The first project was mainly related to the fatigue behaviour during spectrum loading and in corrosive environments. The second project, started in 1994, contained investigations of high speed welding processes, weld improvement methods, FE-analysis, structural optimisation and testing of components. The third Nordic project "FE-Design 2000 - Improved Usage of High Strength Steel by an Effective FE-based Design Methodology for Fatigue Loaded Complex Welded Structures" was started in 1999. That project, which involved co-operation of 24 Nordic organisations from Sweden, Finland, Denmark, Iceland, and Norway, had the aim of improving lead-time, accuracy in fatigue analysis and improve material utilisation of fatigue loaded complex welded structures. The current cooperative project, Q-FAB, which is based on findings on earlier Nordic projects, has more than 20 research partners who working together to improve the design, fabrication and cost effectiveness of advanced welded structures. The majority of funding for this work comes from national sources and various industries.

The primary aim of the Q-FAB has been to reduce production costs by fabricating lighter weight components using high speed / high deposition rate welding processes while reducing component sensitivity to fatigue failure. Robot-based techniques will facilitate low volume production series and highly customised welded structures which are typical for Nordic metal products industries. High strength steels have been incorporated in many designs as a mean of reducing weight, product performance and operating costs. However, reduced weight increases operating stresses. More highly stressed components can operate in fatigue critical locations only by increasing the quality of the welds of by introducing novel post-weld improvement systems. The current project has made good steps in defining what constitutes weld quality for fatigue loaded structures based on a scientific understanding of factors that influence fatigue failure. To achieve the proper weld quality in serial production there is a need to reduce the occurrence of defects and automate NDE processes for welds. These must be accomplished at reasonable costs.

The study has achieved this by

- Improving the fatigue design procedures for welded structures
- Investigation of weld quality acceptance limits and their influence on fatigue
- Investigation of systems for automated assessment of weld geometry
- Demonstration of new weld improvement methods for high strength steels
- Development of procedures and analysis of residual stress fields
- Analysis of the occurrence of different type of defects and the development of simulation tools for predicting some defect types
- Investigation of the influence of modern steel cutting methods on surface quality and the fatigue strength of structures
- Development of operative competence within the participating organisations

Method

This study was divided in 8 work packages (WP:s) were the majority covering fatigue critical aspects of welding of structures. These are shown in Table 1.

Table 1. Work packages

WP	Description	Leading Org.	Partner
WP1	High-speed Welding Process Development and Defect Detection	HV	Volvo, LUT
WP2	Improvement of weld class system	LUT	KTH
WP3	Investigation of the thinness effect	SSAB	ALFGAM, HTU,
WP4	Residual stress prediction	MAN	KTH, LUT
WP5	Post-weld Improvement Techniques for Production Environments	NTNU	Volvo, SSAB
WP6	Welding Cost System Development	LUT	Volvo CE
WP7	Validation	Volvo CE	All
WP8	Exploitation and Dissemination	Volvo CE	

The work was performed at universities, research centres and at the participating industries. All the academic partners and many of the industrial partners are regular contributors to The International Institute of Welding (IIW) and many activities and results from earlier projects and Q-FAB were presented and discussed extensively at IIW meetings and events. The national delegates to IIW Commission XIII - Fatigue of Welded Components and Structures from Denmark, Sweden, Norway and Finland are active members in Q-FAB. The impact of Q-FAB is clearly seen in the strategic plans of this international organisation.

Advanced simulations regarding welding processes and residual stresses have been performed at KTH, HV, MAN, and DTU. Welding trials were performed at HV, NTNU, ESAB, Volvo CE, LUT and MAN. Fatigue testing of small scale specimens was performed at KTH, NTNU, DTU, LUT and SSAB. Analysis and experiments regarding automated measurements of defects and weld geometries are performed at Volvo CE, NTNU and LUT. Stress analysis and studies to define and implement weld quality rules have been mainly conducted at Volvo CE, KTH, LUT, Wärtsilä and MAN.

The project has had the majority of its funding from the participating industrial partners. Additionally the project has received public funding (9,5 MNOK) from national technology organisations in the participating countries. The majority of this public funding was to the numerous university members.

Main conclusions from Q-FAB

Many of the results of the project will provide practical guidance of immediate value to industry and exploitation will concentrate on the provision of information in a user-friendly form that is readily applicable. Dissemination has progressed via regular meetings in each country and at several international events. Smaller portions of the result are of a medium term nature which will lead toward implementation in 3-5 years.

Although the project has primarily addressed transportation, work vehicle, and energy related structures, there is no doubt that the results will be applicable to other industries involved with fatigue-loaded welded structures. The following major results have been achieved within the project:

<u>Increased understanding</u>

- Significant improvement has been achieved in the performance and understanding of fatigue life assessment of welded structures.
- A draft of a weld quality classification system for fatigue loaded structures based on a modern scientific foundation is under development.
- Spatter induced cold laps is still the most frequent defect in MAG-welding and work has been done to identify the process parameters which lead to this defect type.
- Automated assessment of weld geometry and the determination of weld quality can be unsafe in cases of the presence defects, especially cold laps defects.
- .

<u>Predictive tools</u>

- A simulation tool for testing the effect of variations and changes in welding parameters is under development and has been applied on simple weld geometries
- FE simulations of welding induced stresses are still quite demanding to computational capacity, but this project shows that many process related influences on residual welding induced stresses, and thereby fatigue resistance, can be investigated with moderate model size and calculation

<u>Improved weld quality</u>

- Two important methods of weld improvement have been investigated, i.e., grinding according to IIW and UIT (Ultrasonic Impact Treatment).
- Fatigue test of gas cut edges in thick sections showed fatigue limit higher than current design curves.
- In the case of improved welds, the failure location may shift to the root side so design methods must also have the capacity to assess these potential failures.
- Modern cutting methods for thick sections showed higher fatigue strengths that what is allowed in current design rules.

Implementation of the technical achievements in the development and manufacturing of welded structures will have beneficial effects on lead-time, cost, environmental, and safety aspects. The current project results will enable a higher payload with a reduction in the relative fuel consumption per ton of handled materials applied at welded structures in vehicles and other fatigue loaded structures.

Recommendations for further work

While the current project has contributed significantly to the competence of Nordic industrial partners, there are several issues which have gained attention during this project and should receive more research work in the future.

- Simulation tools to better understand those weld process parameters which lead to high quality welds should be further developed
- Non-destructive assessment systems for weld geometry determination should be developed from the currently semi-autonomous state toward being fully automated.
- Several weld improvement techniques for high strength steels show good promise, but currently they are fully manual. Robotised weld improvement methods must be developed.
- Methods and software for more efficient analysis of welding induced residual stresses must be developed.

PREFACE

This report describes the results and innovations obtained in a multi-year project sponsored by the Nordic Innovation Center (NICe), The Swedish Vehicle Research Program (PFF), the Knowledge Foundation (KK-stiftelsen), the Finnish Funding Agency for Technology and Innovation (TEKES), and a consortium of Nordic industrial partners. The overall budget, which consisted of research effort and financial support from the companies and institutes, was nearly 26 MNOK. The programme was initiated and managed as collaboration between industrial partners, research organisations and universities. Approximately 60 % of the total budget was provided by the industrial partners, 20 % from national funding agencies and 20 % from NICe. Financial support from the following organisations is gratefully acknowledged.

Organisation	Contract monitor
Nordic Innovation Center (NICe)	Mr Mads Schreiber
The Swedish Vehicle Research Program	Mr Gunnar Lindstedt
The Knowledge Foundation	Daniel Holmberg
TEKES	Mr. Janne Viemerö

INTRODUCTION

Since 1989, Nordic industries, research organisations and universities have co-operated in numerous projects related to the design and fabrication of welded structures. Q-FAB (Quality and Cost of Fabricated Advanced Structures) started in late 2003 and is the fourth in this project series. The first project focused on the fatigue behaviour of welded structures during spectrum loading and in corrosive environments. The major findings in this project included observations of the relaxation of welding induced residual stresses during spectrum loading and the documentation of the most frequent weld defect for high speed welding operations, i.e., the cold lap. The second project started 1994 and included investigations of high-speed welding processes, weld improvement methods, finite element (FE-) analysis, structural optimisation and component testing. Major findings in this project included systematic studies of cold lap formation due to different manufacturing processes and the influence of manufacturing quality on the fatigue strength of different welded joints and cut edges.

The third Nordic project FE-Design 2000 - Improved Usage of High Strength Steel by an Effective FE-based Design Methodology for Fatigue Loaded Complex Welded Structures started 1999 The project, which involved co-operation of 24 Nordic organisations from Sweden, Finland, Denmark, Iceland, and Norway, had the aim of reducing lead-time, improving the accuracy and reducing material utilisation for fatigue loaded complex welded structures. In this project alternate fatigue design and assessment methods were compared with respect to modelling effort and accuracy and the application fatigue crack growth simulations for complex welded structures.

The current cooperative project, Q-FAB, which is based on the findings of the earlier Nordic projects. More than 20 research partners are working together to improve the integration between material development, design and fabrication methods in order to produce optimised and cost effective advanced welded structures. The welded structures being developed are highly optimised welded plate structures used in vehicles, energy systems and other demanding mechanical engineering applications where fatigue strength is an important design consideration. Manufacturing partners in the present project represent construction equipment, diesel engine, forestry equipment, cranes, and truck components industries. Design and manufacture in these sectors are primarily for small to medium production volumes consisting of 50 to 1000 units per year.

Automated welding processes and automated welding inspection in this crucial industrial sector has proceeded much more slowly than, for example, in the automobile industry where production volumes are measured in tens of thousands of units per year. Steel manufacturers from both Finland and Sweden have been important partners in the project both to supply the project with material, material test data and to provide knowledge on the long-term trends in high strength steel development. Academic partners in the project consist of five universities from all Nordic counties except Iceland.

All of the academic partners and many of the industrial partners are also regular contributors to the International Institute of Welding (IIW). Many activities and results in FE-2000 and Q-FAB have been discussed and presented at IIW events and are included in many of the published recommendations and professional training curricula from this international body. The national delegates to IIW Commission XIII (Fatigue of welded components and structures) from Denmark, Sweden, Norway and Finland are active members in Q-FAB. In 2006 Prof. Gary Marquis from Lappeenranta University of Technology was selected as the chairman of this important commission.

Achievements from all of these projects have been presented at international conferences, 1993 in Copenhagen, 1997 and 2002 in Stockholm. Proceedings from these three events have been published by EMAS, UK. The results from Q-FAB were presented at the international symposium “Integrated Design and Manufacturing of Welded Structures” 13-14 March 2007 in Eskilstuna, Sweden. This event was hosted by Volvo Construction Equipment and sponsored by The Swedish Welding Commission, the Nordic Innovation Centre and Lappeenranta University of Technology. The keynote lectures for this event were given by the working group chairmen from IIW Commission XIII.

BACKGROUND AND AIM

The primary load-carrying structures for transport vehicles and equipment are typically complex welded steel and aluminium constructions. In modern wheel loaders, haulers, excavators or forest machines, 70-80 % of the vehicle weight consists of steel plates and steel castings in thickness 8 – 70 mm with welding as the primary joining technology. In ship engines, the main supporting structures are also fabricated from steel plates with thickness often exceeding 200 mm. Single welds in these structures can be up to 100 meters and, in the case of multiple welds, even more. In offshore structures the plate thickness may be up to 100 mm and weld lengths frequently exceed 100 meters.

During their operational lives, all of these structures are subjected to severe dynamic loading which can result in fatigue damage in the regions of the welds. Fatigue loading and fatigue damage is the most common failure mode for steel bridges, ships, trucks, cars, power generation plants, pressure equipment and many other mechanical structures. Because of its significance during the operation of structures, expertise to design against fatigue failure and developments in economical methods for improving the fatigue strength of welded structures are of great importance for all manufacturers of welded structures.

Material fatigue is a highly local phenomenon and involves a gradual deterioration in strength with life. Failure normally starts in small regions of the structure that are subject to high stress and where weld defects are “large”. From a fatigue point-of-view, however, a large may be only a faction of a millimetre in size and is never visible without special equipment. For welded structures it is well known that the local weld geometry, toe angle and toe radius as well as undercuts, lack of penetration and cold laps control the fatigue strength. There is no or very little influence of material strength on fatigue unless some form of post-weld treatment is applied. Based on an understanding of the fatigue process, the obvious means of improving the fatigue capacity of a welded structure is to improve the weld geometry and reduce defects by better understanding and control of the welding processes or to move the welds themselves to less critical and less stressed areas of the structures. In some cases a weld can be avoided completely by using cast steel components in critical regions.

The development of new generations of products requires a continuous increase in payload capacity, increased speed and increased demands on life. For construction equipment such as haulers and wheel loaders the introduction of improved drive train and suspension systems also increases the operation speeds with the result that the structures are subjected to more fatigue cycles and larger fatigue stresses. Furthermore, in cranes, excavators, wheel loaders and similar equipment, modern hydraulic systems increase the number of fatigue cycles per operating hour as cycle times are reduced. Improved maintenance and more reliable electronic and hydraulic components result in higher utilisation rates. This puts extra demands on the supporting structures. In case of off-shore units, there is a strong economic drive to safely extend the lives of production units.

The competing demands associated with lead-time, cost, quality and fuel consumption need to be balanced against those of durability and structural integrity in order to produce competitive products. This will require advanced design in high strength steels and a radically new approach to production engineering. However, higher operating stresses leads to increased sensitivity to fabrication defects, weld geometry (e.g. penetration, throat thickness, profile) and variations in material strength. With an increased strength at the surface, the root side may be the weakest point, and there is an obvious need to develop improved engineering methods to assess the fatigue behaviour of weld roots. The quality of fatigue critical locations in serial produced components can be guaranteed by the introduction of weld improvement technology and/or cost-effective NDE-tools.

Nordic industrial enterprises have based their success and reputation largely on highly reliable and safe designs. Continued worldwide success will require further attention to life cycle costs (LCC) and improved management of fatigue related issues. The primary aim of the Q-FAB was to reduce production costs by fabricating lighter weight components using high speed / high deposition rate welding processes while reducing component sensitivity to fatigue failure. Robot-based production techniques will facilitate small series and highly customised welded structures that are typically of Nordic metal products industries. High strength steels may be used in advanced low weight designs in order to improve product performance and reduce operating costs. However, in order that the more highly stressed components can operate in fatigue critical locations, novel weld dressing systems will be developed. To achieve the proper weld quality in serial production there is a need to reduce the occurrence of defects and automate the NDE of welds, but at a reasonable cost. There is a further need to improve weld quality systems including establishing a more scientific foundation.

Implementation of the technical achievements in the development and manufacturing of welded structures will have beneficial effects on lead-time, cost, environmental, and safety aspects. The project will improve lead-time, ensure weight reduction and enable a higher payload with a reduction in the relative fuel consumption per ton of handled materials. The specific technical and economical targets were:

- Reduction of lead-time in product development by 10 %
- Reduction of structural weight of 10 %
- Reduction of production cost of 15 %
- Reduction of fuel consumption of 2-3 %
- Increase of relative weld fatigue life of 50 %
- Reduction of total life cycle cost of 15 %

The Q-FAB project started late 2003 and continued to the beginning of 2007.

PARTNERS

Manufacturing partners in the project represent construction equipment, diesel engine, forestry equipment, cranes, and truck components industries. Design and manufacture in these sectors is primarily for small to medium production volumes of between 50 to 1000 units per year. Automation in both welding processes and welding inspection in this sector has proceeded much more slowly than, for example, in the automobile industry where production volumes are measured in tens of thousands of units per year. However, it is known that increased use of robotic welding, with controlled processes combined with good design can result in fabricated structures of much higher and more consistent quality with respect to fatigue than for manual welding.

Partners

Volvo Construction Equipment (VCE)
Volvo Buses
ESAB
SSAB Tunnplåt
SSAB Grovplåt
Alfgam Optimering
The Royal Institute of Technology (KTH)
University West (HV)
Norges Teknisk Naturvetenskaplige Universitet
STATOIL
MAN B&W Diesel A/S (B&W)
Technical University of Denmark (DTU)
Lappeenranta University of Technology (LUT)
RUUKKI Metform
Wärtsilä Technology
Ponsee OY

The major steel manufacturer in both Finland and Sweden are partners in the project. The academic partners in the project come from 5 universities from all Nordic counties except Iceland. All the academic partners and some industrial partners are also participants in The International Institute of Welding (IIW) and many activities and results in Q-FAB are discussed and presented at IIW events.

WORKPACKAGE OVERVIEW

This study was divided in 8 work packages (WP:s) were the majority covering fatigue critical aspects of welding of structures. These are shown in Table 1.

Table 1. Work packages

WP	Description	Leading Org.	Partner
WP1	High-speed Welding Process Development and Defect Detection	HV	Volvo, LUT
WP2	Improvement of weld class system	LUT	KTH
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WP4	Residual stress prediction	MAN	KTH, LUT
WP5	Post-weld Improvement Techniques for Production Environments	NTNU	Volvo, SSAB
WP6	Welding Cost System Development	LUT	Volvo CE
WP7	Validation	Volvo CE	All
WP8	Exploitation and Dissemination	Volvo CE	

The work was performed at universities, research centres and at the participating industries. Advanced simulations regarding welding processes and residual stresses have been performed at KTH, HV, MAN, and DTU. Welding trials were performed at HV, NTNU, ESAB, Volvo CE, LUT and MAN. Fatigue testing of small scale specimens was performed at KTH, NTNU, DTU, LUT and SSAB. Analysis and experiments regarding automated measurements of defects and weld geometries are performed at Volvo CE, NTNU and LUT. Stress analysis and studies to define and implement weld quality rules have been mainly conducted at Volvo CE, KTH, LUT, Wärtsilä and MAN. The welding Cost WP was not started as it planned due to unexpected personal changes, but some cost issues are partly handled in connection to the other WP. The Validation WP was significantly integrated in the other WPs with substantial efforts within the improvement WP.

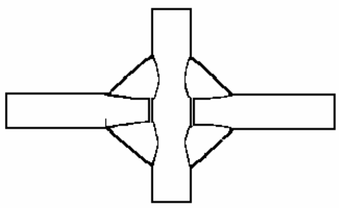
The majority of the funding project was from the participating industrial partners. Additionally, the project has received public funding (9,5 MNOK) from national technology organisations in the participating countries. The majority of this public funding was to the five university partners.

WP1. HIGH-SPEED WELDING PROCESS DEVELOPMENT AND DEFECT DETECTION

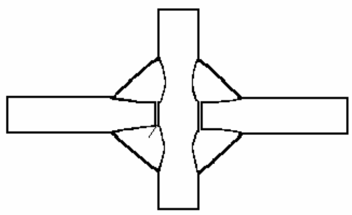
If the economic benefits of high productivity fabrication processes are to be realised, innovation in the form of novel arc welding techniques, consumables and shielding gases, will be required to achieve an increase in welding speed and deposition rate. For fatigue sensitive components, it is essential that an acceptable weld bead profile is produced without forming toe defects especially cold laps. The new welding processes investigated were based on the tandem arc process in which two wires, instead of the convention single wire, are used to achieve high welding speeds and high deposition rates. Proper process and quality control should guarantee a low defect rate and proper weld geometry. If this is not the case, cost effective and automated NDE/NDT systems must be developed. In addition, the ease-of–use, measurement cost and, more generally, the efficiency of the NDE methodology are crucial.

Testing and Analysis of Cruciform joints

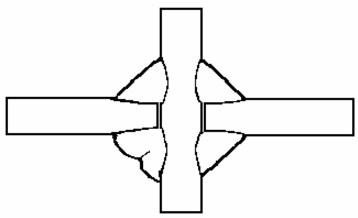
In this project fatigue testing and weld quality assessment of non-load carrying cruciform joints were carried out. The specimens were produced using different welding processes; robotic and manual flux cored arc welding (FCAW) and metal cored arc welding (MCAW) filler materials. The local weld geometry for all the specimens was measured, analyzed and the stress concentration factors were calculated. Residual stress measurement was carried out close to the toe region using the X-ray diffraction method and weld defects (cold laps) in the failed specimens was measured and characterized.



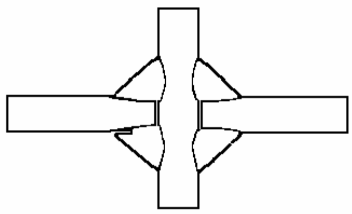
a) Crack at weld toe



b) Crack at root



c) Interbead crack



d) Cold lap

FIGURE 1. Different type of defects in fillet welds.

Introduction

It is known that the local weld geometry, toe radius and angle, undercuts and cracks strongly influence the fatigue strength. The local geometry affects the local stress concentration and together with defects of different types of fatigue cracks may form during cyclic loading and lead to the large scatter in fatigue life. Figure 1 shows different types of defects in fillet welds.

Test specimens

The test specimens were manufactured from plates that were cut up in more than 10 pieces each with the width and thickness of 12 mm and 12 mm, see figure 2. The cutting edges at the corners were smoothed to avoid cracking from cutting marks The pieces taken near the ends was not used for testing. The effective weld throat thickness was 6-7 mm and the leg length was 9 mm for the welds.

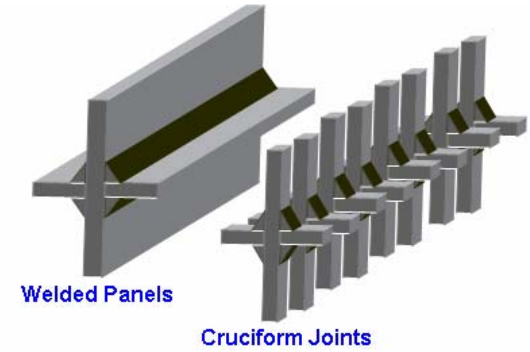


Figure 2**.** Manufacturing of test pieces.

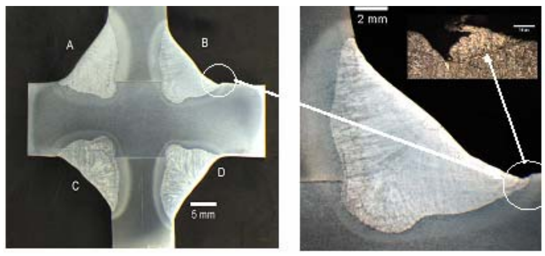
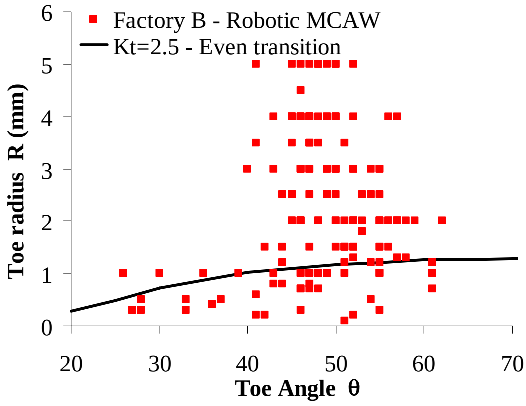


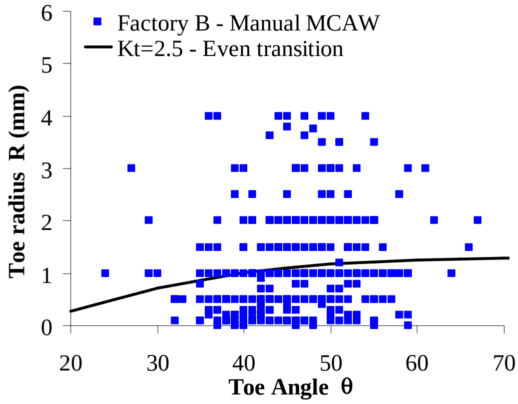
Figure 3. Weld profile and weld toe failure location together with initial flaw.

Local weld geometry

For the measurement of the local weld geometries, silicon imprint samples of every weld of the test specimens were made. After the stiffen silicon samples were cut up in several thin slices, copied and enlarged with a photocopier. Figure 4 shows the result of local weld geometry measurements, toe radius and toe angle, for the welds produced with the different welding processes; robotic MCAW, manual MCAW and manual FCAW, respectively. Measurements showed large scatter for manual MCAW but less scatter for welds fabricated with the manual FCAW process. The local stress concentration K_t at the weld toe is a function of toe radius and weld flank angle. In the diagrams the results above the line have a stress concentration factor less than 2,5 and thus regarded as an even transition. This is further discussed in the Chapter 2, WP2 Improvement of weld class system.



a)



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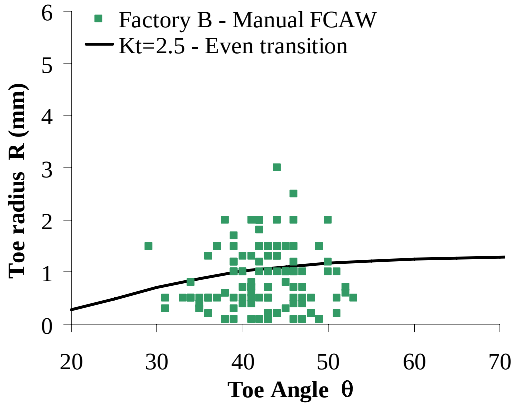


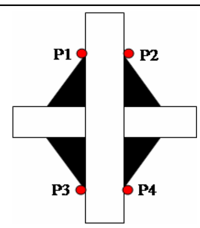
c)

Figure 4. Local weld geometry: a) Robotic MCAW; b) Manual MCAW; c) Manual FCAW.

Residual Stresses

Residual stress measurements were carried out on specimens from each batch using the X-ray diffraction technique. The measurements were made on the surface close to the weld toe (< 1mm) were the fatigue crack starts. Table 1 shows the variation of measurement results

Table 1. Measured residual stresses at the weld toe.

	MCAW			**FCAW**		
	Robotic	Manual	Shot Peened	Robotic	Manual	
P1 [MPa]	-102	-74	-213	-	-74	
P2 [MPa]	-102	12	-277	-	-35	
P3 [MPa]	-117	48	-154	-	119	
P4 [MPa]	62	-43	-243	-	-115	

Detection and characterization of weld defects

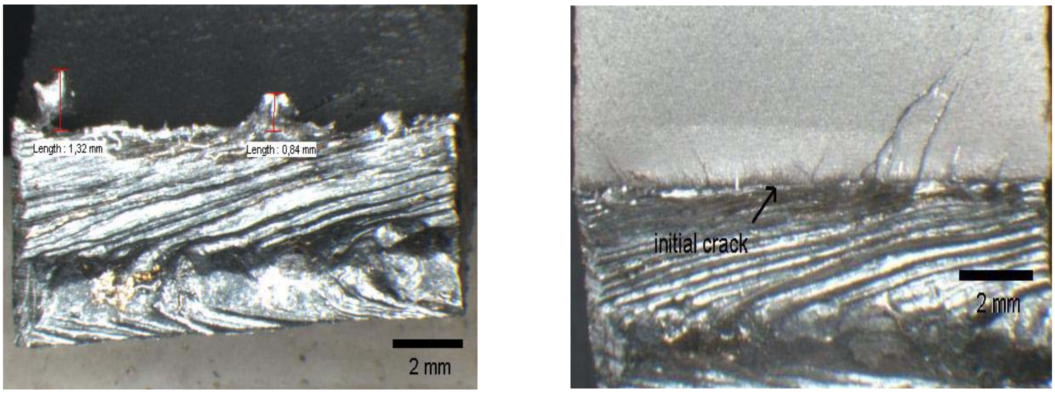


Fig.5 Weld defects from spatter and the initial crack

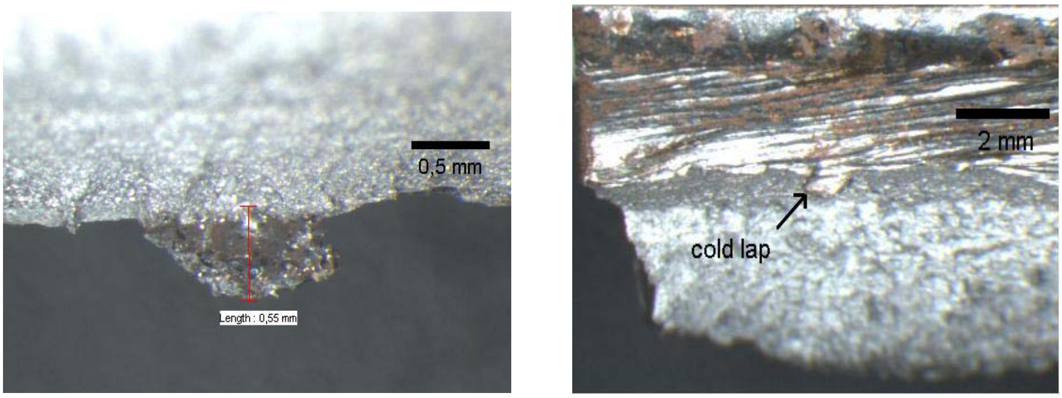


Figure 6. Crack starting point from a ~0.6 mm cold lap

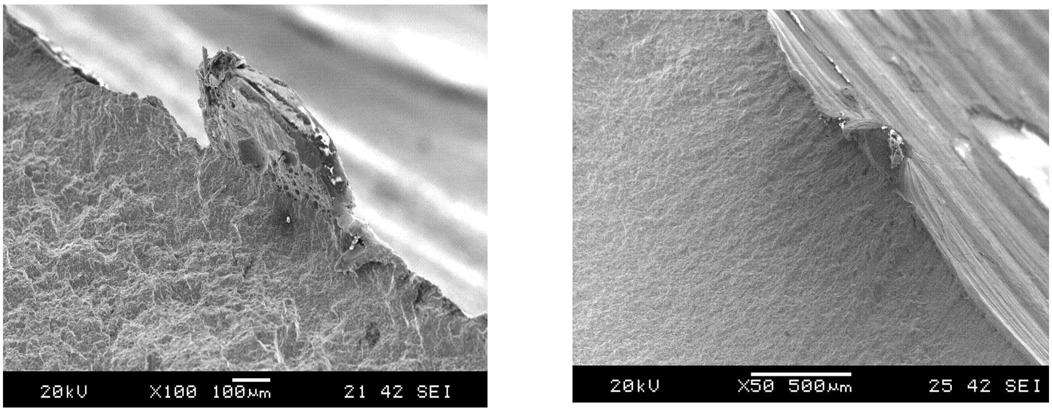


Figure 7. Cold laps detected with a SEM, both are fatigue starting defects.

After fatigue testing the fracture surfaces were studied. The aim was to locate the crack initiation and to determine the initial defects' type; size and characteristic. The crack initiation was often difficult to find. The majority of the defects found were cold laps beneath the spatter surfaces with different size and shape. Figures 5-7 show some examples of weld defects, spatter and cold laps, found.

Fatigue test results

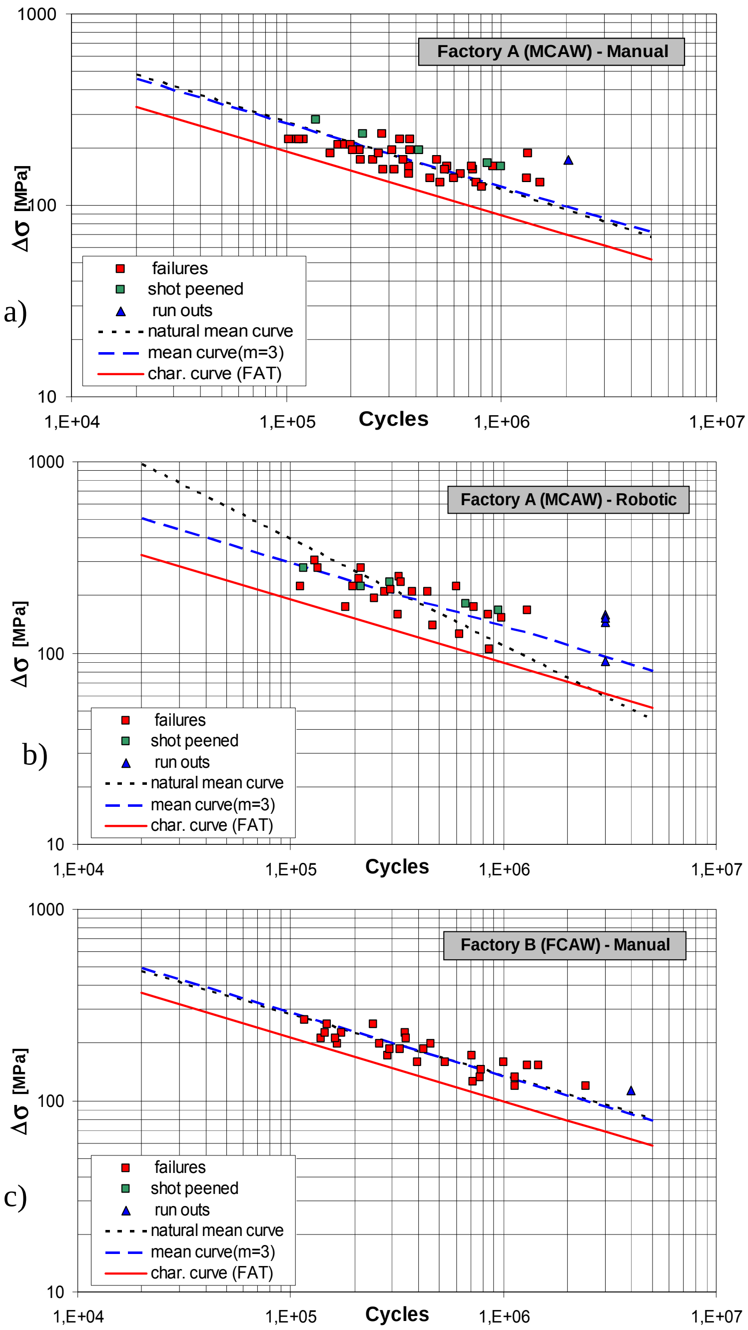


Figure 8. Fatigue test result compiled in S-N-curves: a) MCAW manual; b) MCAW robotic; c) manual FCAW.

The laboratory fatigue testing was performed in a conventional testing machine using typical loading conditions. As expected, all failures were from the weld toe. According to IIW [17] the fatigue class (FAT) for non-load carrying cruciform joints failed from the weld toe is FAT80 MPa. FAT is defined as the fatigue strength at $N_f = 2x10^6$ at 5% failure probability. Figure 8 shows the fatigue test result in stress range versus cycle's curves for the tested specimens.

Slightly higher fatigue strength is found for the robotic welds than for the manual MCAW. A large number of weld defects, e.g. spatter, slag and oxide were found in the robotic MCAW welds. This could be the reason for the large scatter observed in the fatigue test results for this batch, see figure 8. Weld defects, i.e., cold laps, were also found in the shot peened batches indicating that some weld defects survived the shot peening process. Smaller scatter was observed in the fatigue test result for the manual FCAW batch from factory B. This is possibly due to the post cleaning of the specimens after welding hence, small defects were found just in some of the specimens after the fatigue testing.

Table 2 summarise some of the test results with respect to weld geometry, defects and fatigue strength at $N_f = 2x10^6$ at 50% failure probability, witch is about 2 – 3 standard deviation above the FAT-curve. The difference in the number of standard deviation is depending on number of test specimens

Table 2. Results from fatigue testing of cruciform joints manufactured by factory A (manual and robotic MCAW) and factory B (manual FCAW), respectively.

mean value / stand. dev.	**(MCAW)**				**(FCAW)**	
	Manual		**Robotic**		**Manual**	
	As welded	**Shot Peened**	**As welded**	**Shot Peneed**	**As welded**	**Shot Peened**
K_t	3.4 / 1.2	2.9 / 0.3	2.5 / 0.5	3.3/0.5	3.2 / 1.0	--
Cold laps (mm)	0.09-0.15	0.09 /0.04	0.13-0.27	0.12 / 0.04	0.1-0.2	--
m – slope	2.8	3.6	2.8	3.9	3.1	--
Log C (m=3)	12.28 / 0.2	12.53 / 0.07	12.4 / 0.3	12.53/0.10	12.4 / 0.18	--
FAT (P_f 50%)	**72**	**107**	**74**	**101**	**81**	**--**

Simulation and detection of defects

Destructive testing

A destructive method based on the mechanical impact test was developed to provide fast evaluation of weld toe defects. In this method the specimens are first sliced to an appropriate dimension to fit a conventional impact test machine. After cooling in liquid nitrogen for ten minutes, they were hit by the pendulum of the impact device. Figure # illustrates schematically the experiment procedure.

a) b) c) d)

Figure 9. a) Bead on plate weld specimens, b) slicing the weld into specimens, c) hitting by impact test pendulum, d) microscopy of the fracture surface

Statistical evaluation of process parameter influence on cold laps occurrence

Through an experimental procedure designed by statistical test planning, it was determined that the two major types of cold laps (overlap and spatter) occur due to distinctly different weld parameter ranges and are influenced in slightly different manner by the weld parameter settings. As can be seen in Figure 10, when deposition rate is increased, the mechanism shifts from overlap dominated to spatter dominated, and cored wire becomes increasingly beneficial.

The factors with most pronounced effect on the overlap depth were the total wire feed speed (WFS) and the torch angle (TA). Interestingly, the effect of torch angle was reversed when switching to cored trailing wire compared with solid-solid. The contact tube to work piece distance (CTWD) had a minor effect but was still statistically significant. Also, for spatter defect depth, the total wire feed speed (WFS) and the torch angle (TA) were the dominating factors. Here, however, the effect of torch angle was strictly positive, while increased wire feed speed was only beneficial for spatter defects if cored trailing wire was employed.

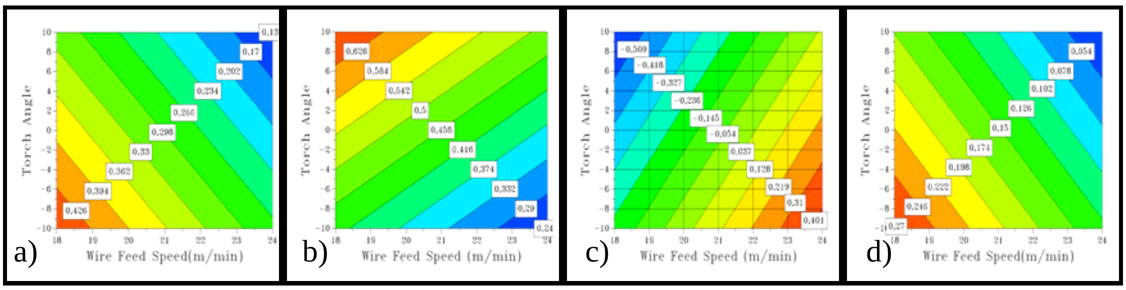


Figure10. Statistical model representing a) depth of overlap for solid-solid wire b) depth of overlap for solid- cored wire c) depth of spatter for solid-solid wire d) depth of spatter for solid cored wire

Melt Simulations

The research outcome can be split into both general and directly applicable results. Despite the practical result orientated nature of the project, the results are nicely balanced between both areas. The main results can be summarized as follows:

General results

- The effect on the welding pool's shape and dynamics has been used for physical descriptions of the melting and hardening during welding.
- A description and classification of cold lapses, which are formed in two distinct ways:

  Overlap: An overlap is formed as the molten metal spills over as it is pressed against the edge of the weld pool by gas pressure or process fluctuations, as a result of the welding pool hardening before the base material, see figure 11.

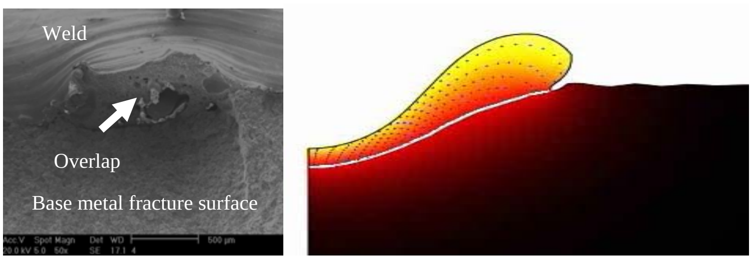


Figure 11. Picture of overlap and simulation of overlap

  Spatter: Spatter or spray from the welding process comes into contact with cold metal in front of the weld pool, se Figures 12-13 Spatter is the dominant defect type for high velocity industrial welds.

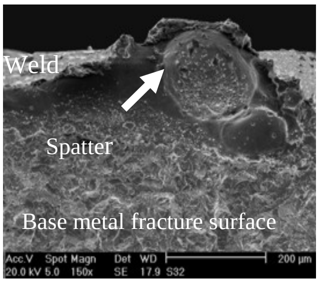


Figure 12. Fracture surface, showing spatter type cold lap

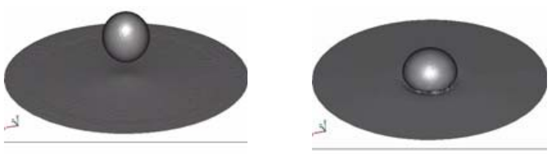


Figure 13. Simulation of spatter droplet impacting on a cold metal surface

- A methodology for numerical simulations (see figure), which can be implemented in commercial software, has been thoroughly tested and employed in evaluating the impact of different parameters.

- Parametric studies show that splatter is strongly dependent on the weld arc's influence on the outside of the weld pool, which has led to the formulation of more advanced projects.
- A calculation technique based on the level set method has been developed to investigate adhesion. This methodology allows simulation of spatter, see picture series.

Directly applicable results

- A simulation tool for testing the effect of variations and changes in parameters and their characteristics has been developed.
- This tool has furthermore been adapted to metal deposition simulation in titanium, see Figure, 14 which can be used in determining the geometry and heat distribution used for further material simulations of the finished products' material characteristics.

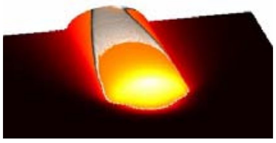


Figure 14. Simulation of metal deposition

It provides an improved process window description of automated tandem-MIG welding.

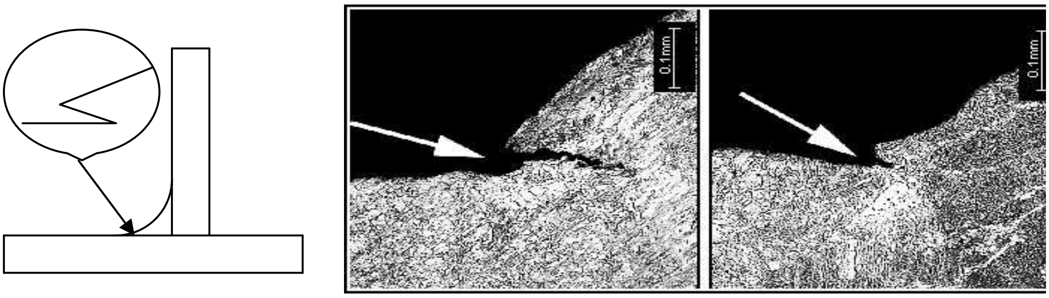
WP2 IMPROVEMENT OF WELD CLASS SYSTEM

Current weld class system and its problems

There is very little information available for relating fatigue strength and weld quality class. Current weld quality rules are not directly connected to fatigue design rules. The acceptance limits in the weld quality classes are not, in general, based on scientific evidence related to the effect on structural integrity of the feature concerned. The application of the weld quality class system in production is difficult and different operators often come to different conclusions about the acceptance of a particular feature. The scatter in assessing the weld classes in manual welding makes the current situation quite unreliable. A particular type of defect that is associated with high-speed welding is the weld toe cold lap. Its presence severely limits the scope for applying weld toe fatigue life improvement techniques and any benefit of a good fillet weld profile is lost. However, this type of the defect is difficult to find without advanced NDE and it needs to be defined properly also in the classification rules. The objective of this work-package has been to develop and verify the theoretical foundation for a fatigue based classification systems for welds.

The quality of a production weld should be indicated on the production drawings and checked during fabrication according to a weld class system. The system describes many different error types, see an example in Figure 15, and for each of these there are different levels of acceptance depending on the quality level, stated as a letter like A, B, C etc, see

Figure 16 below. Many weld class systems exist, but the foundation of these goes back to 1970-1980 and investigations made show that the connection between the quality levels and the fatigue life is weak.



a) b) c)

Figure 15. a) Schematic illustration of imperfection in a weld with good weld profile b) Cold laps with 0.15 mm depth c) Cold laps with 0.04 mm depth.

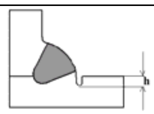
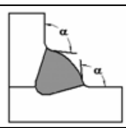
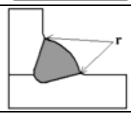
No.	**ISO 6520 -1 ref.**	**Imperfection Designation**	**Type of joint**	**Limits for imperfections for quality levels**		
				D	**C**	**B**
1.7	5012	Continuous undercut Intermit. undercut		h ≤ 0,2 t, but max. 1mm	h ≤ 0,1 t, but max. 0,5 mm	Short imperf: h ≤ 0,05 t, but max 0,5 mm
1.12	505	Incorrect weld toe		≥ ∝ 90°	≥ ∝ 105°	≥ ∝ 120°
?	?	Connection radius		Not defined		

Figure 16 Weld class examples from current revision of EN-25817 (Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) - Quality levels for imperfections"),

In a master thesis work, the acceptance limits in Volvo’s system, STD5605, and the international system ISO5817 were analyzed using linear fracture mechanics with the results shown in Figures 17 and 18, see Karlsson and Lenander [24].

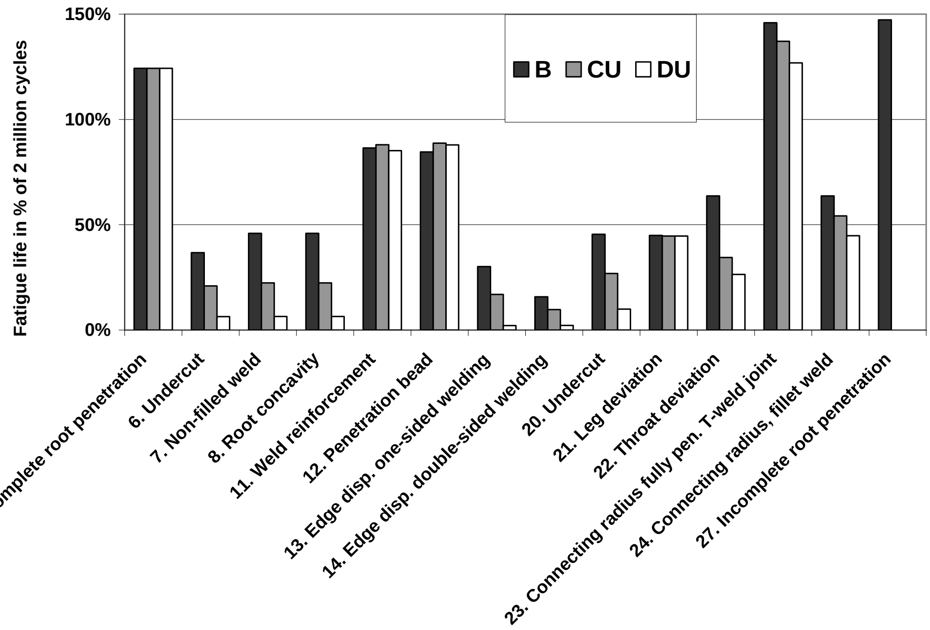


Figure 17 The fatigue life in Volvo's weld class system STD 5605 as a function of different error types and their different quality levels B, CU and DU.

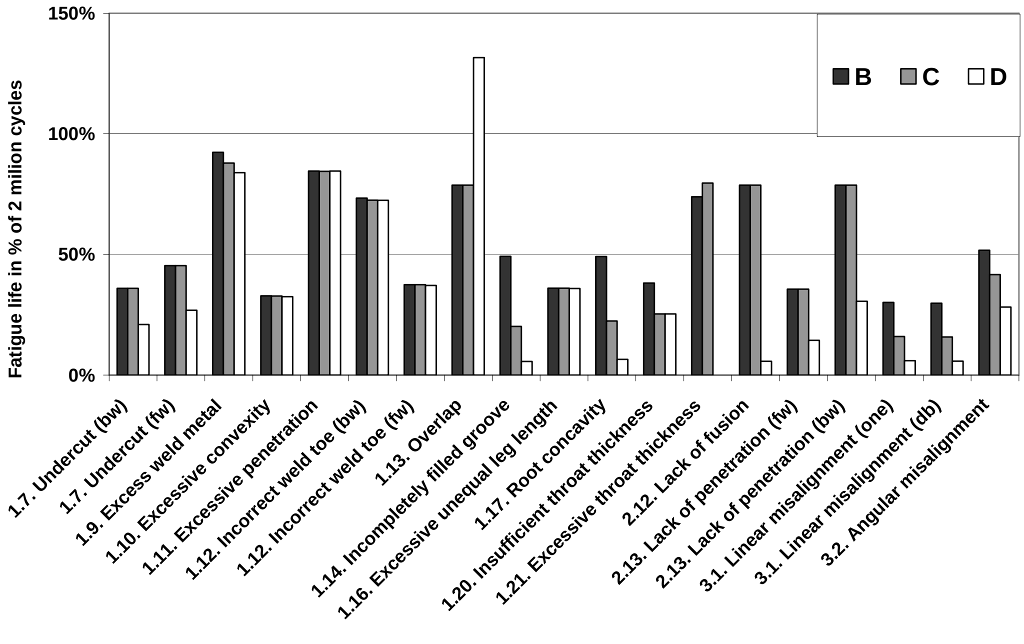


Figure. 18. The fatigue life in the international weld class system ISO5817 as a function of different error types and their different quality levels B, C and D.

According to Figures 17-18 it is obvious that some of the defect types have an influence on the fatigue life and some do not (same height for black-grey-white column).

Furthermore, some defect types lead to long fatigue lives while others lead to short lives for the same quality level. This indicates that some defect types are critical and others are not. One clear result is that the systems are inconsistent.

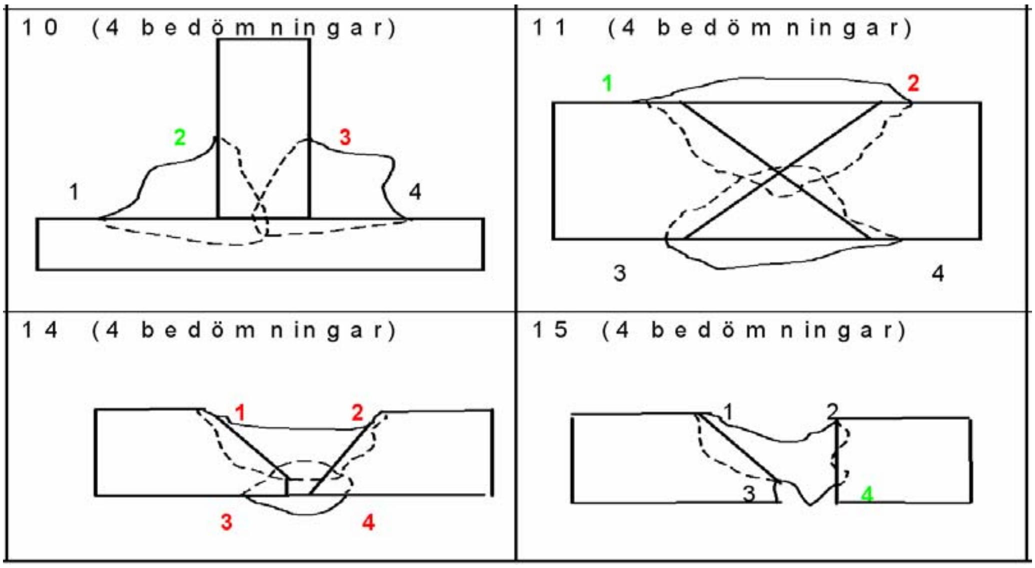


Figure 19. Four examples with in all 16 of the 80 transitions and the opinions marked in colour at each point. Green colour indicates consensus and red 2 no consensus.

The fatigue life on the toe side of a weld is, to a very high degree, determined by either the weld profile (smooth transition) or the existence of defects (like cold laps or undercuts). In the weld class system the term ‘smooth’ transition is prescribed and this has caused many interpretation problems. The reason for this is that the term ‘smooth’ is not quantitative. When a weld is assessed by a production worker, the result is subjective with a big scatter. In one exercise over 80 weld profiles were shown to different categories of personal within Volvo in a round robin-like test. They were asked for their opinion as to whether the profiles were smooth or not, see Figure 19 for an example. In weld profile 14 (lower left) all 4 points are in red indicating that the opinion was divided into two equal groups and thus no consensus weather it was smooth transition or not were reached. Green colour indicates consensus.

Automated geometry measurements

As seen, the requirement of a ‘smooth’ transition does not work well as a weld quality parameter and for this reason needs to be revised. One suggestion often mentioned and investigated, is to use the weld profile geometry, determine the toe radius together with the angle and calculate an equivalent stress concentration factor. This value could then serve as an acceptance limit for this feature. Several commercial vision systems, which use different light sources, cameras and computer programs able to create a 3D surface of any geometry, are today available. One example is shown in Figures 20 and 21, where a profile of the weld is created from a commercial vision system.

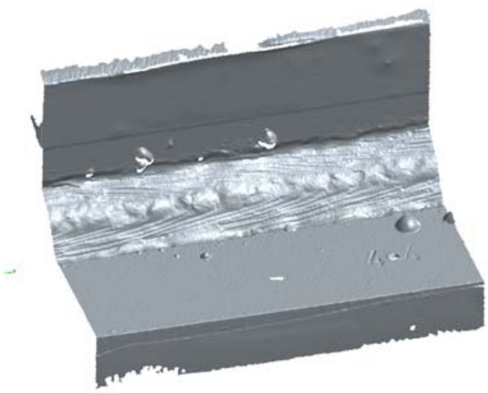


Figure 20. A computer created picture the outer geometry of a weld. Appr. 400.000 points are building the picture.

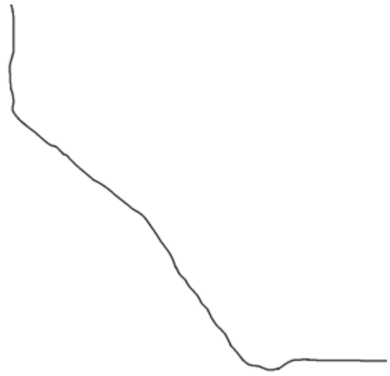


Figure 21. A section through the geometry taken from the picture in figure 20

Some of the existing systems are commercial, while others still are under development. There is still a need for further improvement, since requirements on accuracy, ease of use in handling and automation is not yet good enough. In WP5 some applications of the scanning technology is demonstrated see page 40.

Proposal of new weld class system

The above description of the problems in currently used weld classes has led to new proposal which gives a better connection between the quality level and the fatigue life. The proposed system has three quality levels for fatigue loaded welds and one for static loaded welds. The main purpose is that they should be used mainly for the outside (toe side) of the weld. Inside (root side) of the weld is treated directly using measures on the drawing as demands on the penetration and is therefore not part of the new weld class system.

The principals governing the choice of the acceptance limits can be described by:

- A clear relation between acceptance limits and fatigue strength.
- Different weld defect types and geometry limits within one quality level gives equal fatigue strength.
- A constant increase in fatigue strength between quality levels.

Volvo’s current weld class system is founded on the previous fatigue design guideline system which relates stress level and fatigue life. However, the stress value used in this guideline is the so-called nominal stress level which is a stress value remote from the weld. This stress is then connected to the weld class system using a factor for the actual type of weld and quality level. In principal this is a good system but there are many practical difficulties involved in implementing the system.

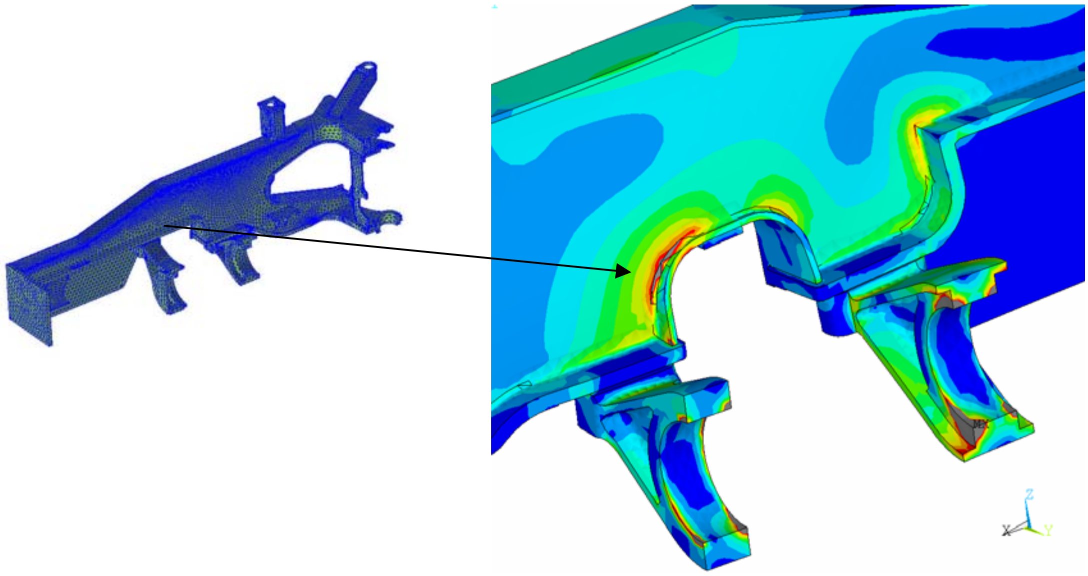


Figure 22. Stresses in a frame to a construction machinery, near the attachment of the axle housing, red colour corresponds to high and blue low stresses.

For complex welded structures with many attachments and loading locations, e.g., see Figure 22, the stress value is continually changing. A nominal stress value is difficult or impossible to define. Even if a nominal stress can be defined, one must select from a catalogue of details, the geometry most closely resembling the actual welded detail. In many cases the actual weld has little similarity to one of the geometries shown in the standard. Experience and engineering judgement must then be used. From the assumed nominal stress and the assumed fatigue class of the detail, the fatigue life of a toe side failure can be computed.

Another problem with the nominal method is that it is only applicable to the toe side of the weld. In many types of weld, like an ordinary fillet weld with zero or partial penetration, there is also a root gap which behaves like a defect in some loading conditions. The root side of the weld is frequently neglected in the design process. In the future root side failure may become more common as efforts are made to increase the overall fatigue life of a structure by controlling the toe side defects or using post-weld improvement technologies..

All the above mentioned drawbacks using the nominal stress method in design can be avoided if local based methods are being used. There are at least two such methods: linear fracture mechanics and the so called effective notch method, which have proven to work well. In these methods, the results are taken in direct connection to the weld and all drawbacks in the nominal method are avoided.

Quality of cut edges

The fatigue performance of cut edges have come into the light since improvements of welds and introducing of high strength steel have in some cases pointed out cut edges as the weakest link. Design data for cut edges was mainly developed 20-30 years ago. Experience from existing structures indicates that the current design data may be conservative due to improvements in the cutting processes. This motivates the development of new design data which reflect the actual quality of today's cutting processes. Figure 23 shows gas cut test beams before fatigue testing, some of the plates were equipped with Almen-strips to measure the level of residual stresses which are developed during shot peening operation.

Figure 23. Gas cut beams produced at Volvo CE for fatigue testing.

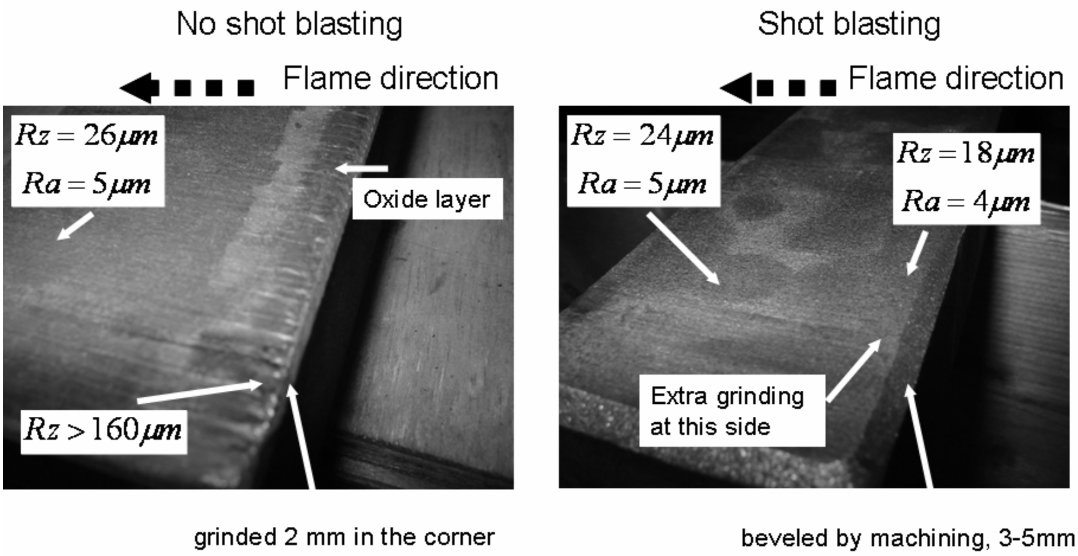


Figure 24 Surface and edge conditions for the gas cut beams.

There are several texture parameters for characterization of surfaces. Two common measures are Ra and Rz which indicate the height of the surface roughness normal to the plate edge. For fatigue design purposes the horizontal characteristic length may also be of interest. There are also hybrid parameters which are combinations of spacing and amplitude parameters. In Figure 24 the surface roughness and edge conditions are shown for two different batches indicating that the shot peening does not affect the surface roughness but the grinding of the edges obvious improve the surface significant. Figure 25 shows the test rig used for fatigue testing of these bars.

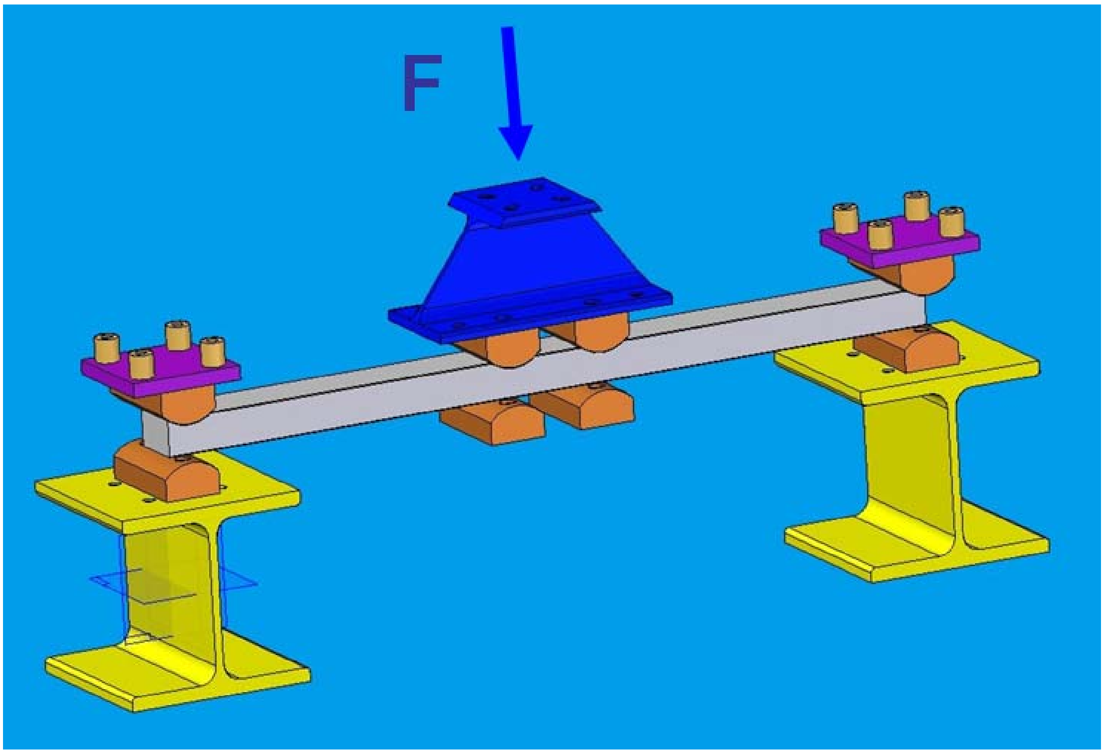
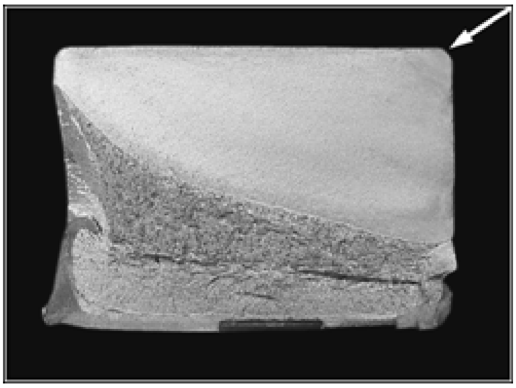
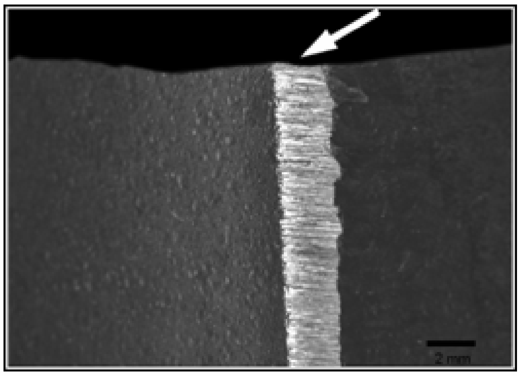


Figure 25. Test rig for four points bending of gas cut beams.

Most of the defects leading to failure occurred on the edge, so the quality of the edge controls the fatigue life. Often surface roughness, effects of shot peen and thermal stresses are measured on the surface away from the edge. In such cases these parameters do not affect fatigue life if no improvements of the corners are performed. In 31 of 32 test specimens, the fatigue crack propagate from the corner, regardless if the corner were grinded or not. The typical start points were the transition from surface groove and grinding, mill scale, grinding grooves and gashes, se Figure 26. This rise the question; why put efforts in getting good surface when the crack starts to propagate from the corner?



a)



b)

Figure 26. Typical start location for the fatigue crack. a) fracture surface, b) grinding grooves perpendicular to the length direction..

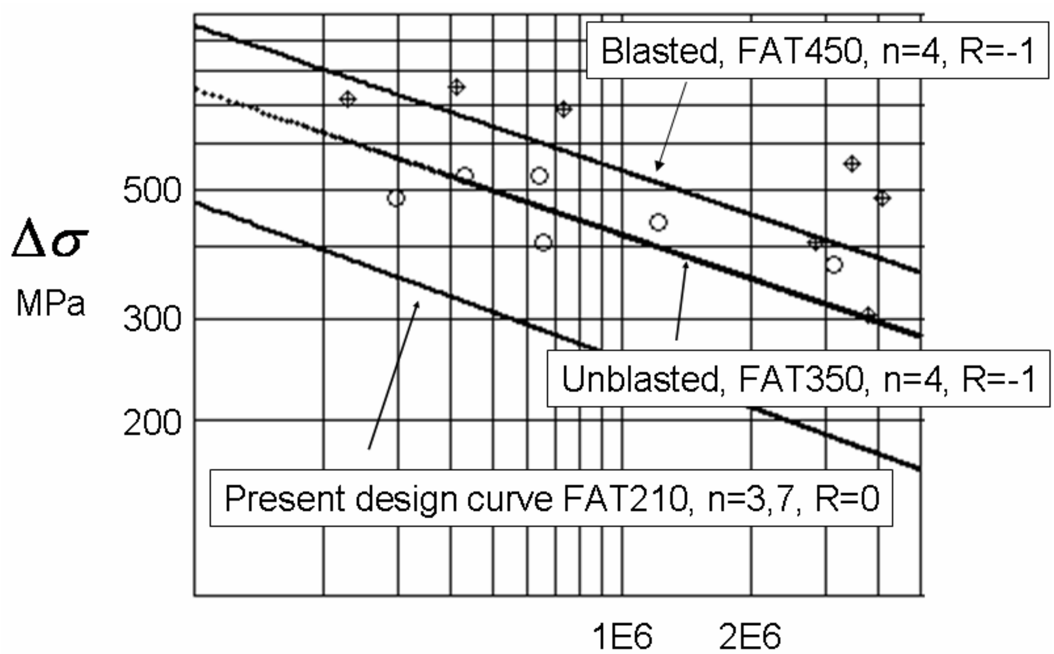


Figure 27. SN-curves for blasted and un-blasted beams in bending compared to present design-curve.

The test results for R=-1 and bending in thick medium grade gas cut steel plates, 60 mm, with at least 2 mm grinding of the corner are presented in Figure 27. The test results are compared with present design curve (for R = 0). The test also contained test series with completely reserved variable amplitude (VA) loading which showed that there is little or no benefit from blasting with the applied spectra. This observation can be explained by the relaxation of residual stresses which occur during the small number of large compression cycles.

WP3 INVESTIGATION OF THINNESS EFFECT

Current design codes of welded structures contain a "thickness effect" penalty where thicker sections are assumed to have reduced fatigue resistance. The thickness effect reduces the design fatigue strength starting with thickness from about 15 mm or greater. Investigations in previous projects have shown that there is an increase in fatigue strength for thinner sections thus supporting the use of higher strength material. In this WP numerical analysis and fatigue testing of test specimen are performed.

Extensive fatigue testing and fracture mechanics calculations have been made on this topic with focus on thick sections during the last twenty years. The results are implemented in current design codes of welded structures that today comprise mandatory equations that reduce fatigue strength for thick sections. An illustrating example taken from a British Standard on fatigue assessment, BS 7910 is that the reduction in fatigue strength for a fillet welded joint, as the thickness is increased from the reference thickness of 16mm to 32 mm, is 30%.

There are published results for thin welded joints, i.e. 3-12 mm sheet thickness that show increased fatigue strength with decreasing sheet thickness. This is referred as the “Thinness Effect”. The amount on published reports is however less than for the above mentioned thick welded joints. The Swedish regulation of building code, BSK and the SSAB Tunnplåt AB handbook are until now the only standards/recommendations that allow higher fatigue stresses for thin sheet welded joints. High strength steels are often used to reduce weight in fatigue sustained vehicles and components and as a result of weight and thickness reduction, fatigue stresses might be crucial. Therefore it is interesting if higher fatigue stresses can be allowed in thin walled structures.

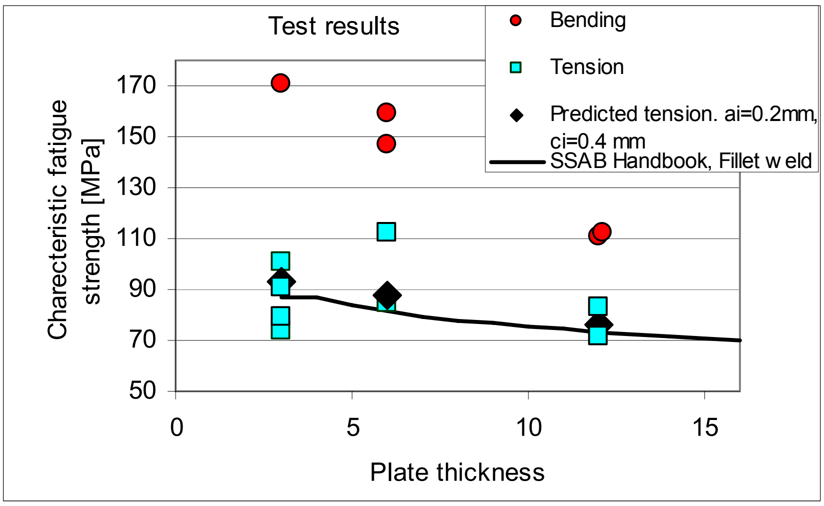


Figure 28. Fatigue test results from welded test pieces with different plate thickness

In this work package, WP3, approximately 150 non-load carrying cruciform fillet welded joints specimens, with thicknesses of 3 mm, 6 mm and 12 mm have been fatigue tested under constant amplitude load. Local geometry of the joints, i.e. weld toe angle, weld toe radius and leg length of the weld and also angular distortion of the specimen has been measured in order to have an indication of the influence of local and global geometry on the fatigue strength. The fatigue test result, see Figure 28, show clearly an increase in fatigue strength at least down to 6 mm sheet thickness. This was also predicted successfully with linear elastic fracture mechanics.

he main conclusion from WP 3, is that the test results support the existing design bonus in the SSAB Sheet Steel Handbook that allow higher fatigue stresses for fillet welds down to 4 mm sheet thickness. Fracture mechanics calculations show the same trend as the test results. Joints of 3 mm thickness are more sensitive to weld defects than joints with greater thickness. Hence it is important to consider the weld quality if a design bonus is to be applied.

WP4 RESIDUAL STRESS PREDICTION

In welded joints residual stresses significantly influence the life. The design rules are, in some cases, overly conservative. Especially in those cases where fatigue failure initiates from the weld root side, knowledge about the residual stress field may improve the fatigue assessment. In the previous Nordic project, FE-Design 2000, many of the case studies were related to root problems. The actual residual stress distribution was known in only one of the four cases. In this WP the aim is to develop procedures and also predict and measure residual stress distributions.

The Swedish research contribution within WP4 was carried out at KTH and Volvo CE. The results have been presented at international conferences and published in scientific journal. An abstract of the research work is presented below.

Application to tubular joint structures and influence on fatigue life

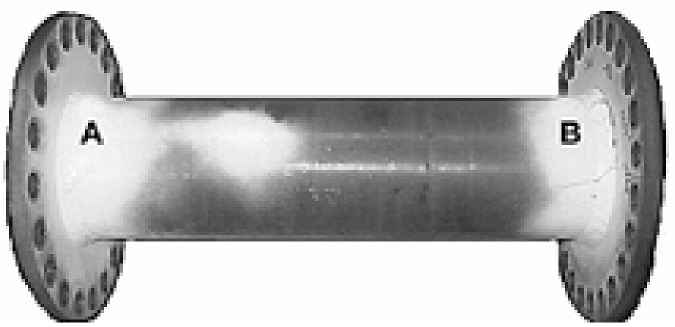


Figure 29. Welded tubular joint structure.

One of the objectives is to investigate the residual stresses, their effect on the fatigue strength and their relaxation under external loading near the weld root and the weld toe for multi-pass welding. For this purpose two different tubular structure configurations were studied; a three-pass single-U weld groove for maximum weld penetration and a two-pass fillet (no groove) welded tube-to-plates for minimum weld penetration. Figure 29 shows the tubular joint structures

2D axi-symmetric and 3D finite element models were developed to calculate the temperature distribution, HAZ, penetration depth and the residual stress distribution for the sequentially coupled thermo-mechanical analysis. Figure 30 shows the two different weld grooves for the tubular joints structures studied.

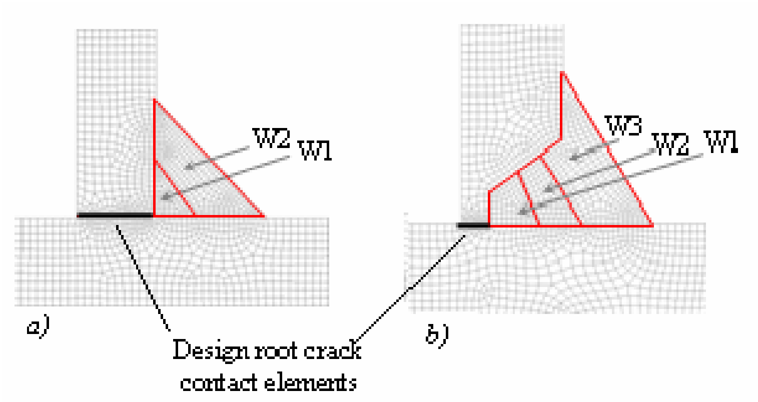


Figure 30. Axi-symmetric finite elements mesh: a) No groove and two passes
b) Single-U weld groove and three passes

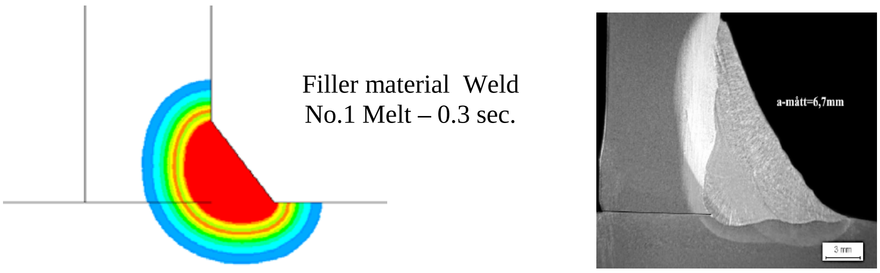


Figure 31. Thermal analysis: Numerically and experimentally weld penetration profile;

The thermal analysis and the moving heat source were verified with temperature measurements and by comparison of the weld penetration profile with micro samples. The temperature distribution during the welding showed good agreement with the numerically obtained when using a simplified moving heat source, see Figure 31 and 32..

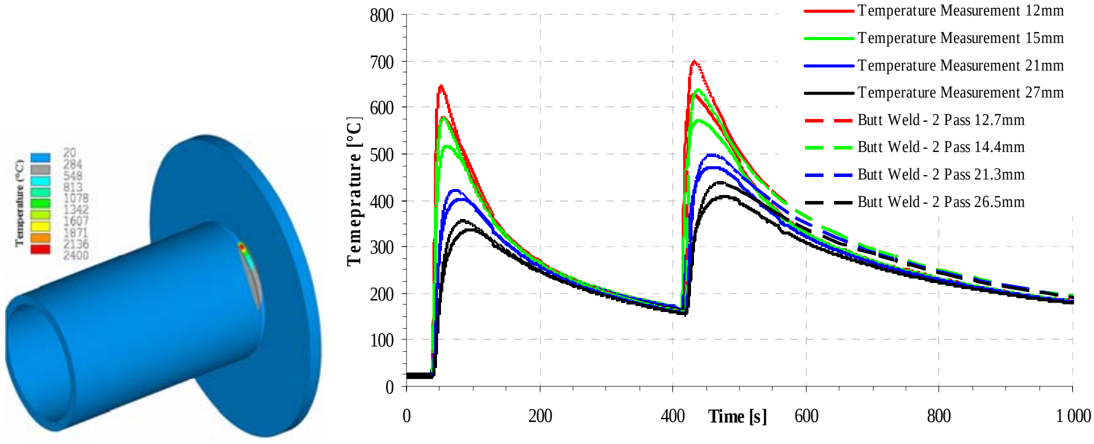
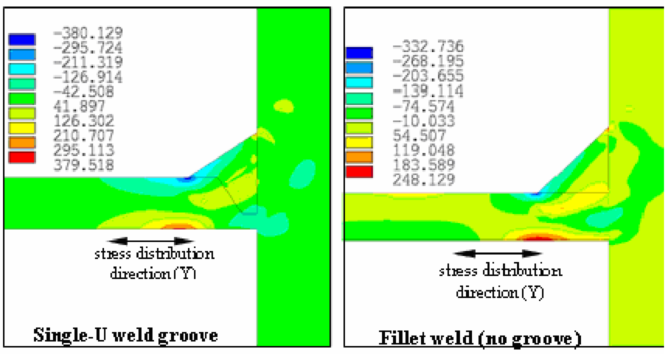
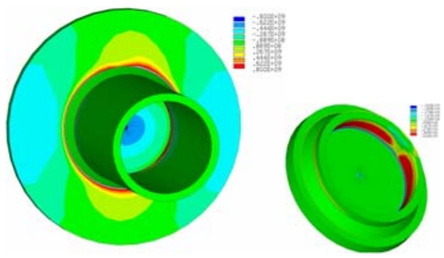


Figure 32. Thermal analysis: a 3D moving heat source, predicted and measured temperatures

The computed residual stresses were verified with hole drilling measurements and X-ray diffraction technique. The computed residual stresses are in qualitative good agreement with the experimental obtained.



a)



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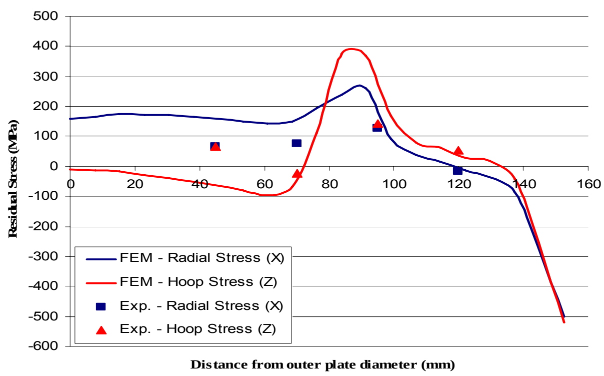
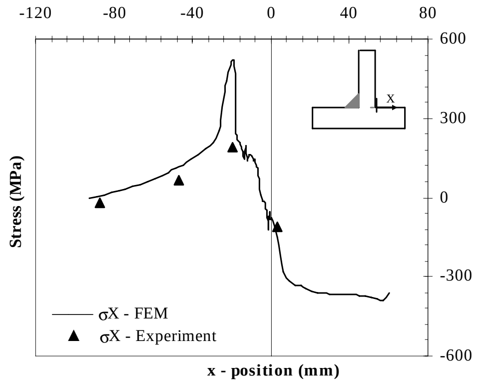


c)



d)

Figure 33. Residual stresses: a) residual stress profiles showing compressive residual stresses at weld root ; b) 3D welding residual stresses; c) Comparison numerically (3D) and hole drilling; d) comparison numerically (2D) and hole drilling.

The weld root is, from a fatigue resistance point of view, under favourable compressive residual stresses. Figure 33 illustrates the residual stress distributions.

The welded tubular joint structures configurations where produced in series in order to conduct fatigue tests to study failure from the weld root and weld toe. One objective of the fatigue tests was to quantify the influence of the weld penetration depth on the fatigue resistance. Another important objective was to study the effects of residual stresses on fatigue resistance. For that reason some of the tubular structures were stress relieved before testing in order to study the influence of residual stresses, some were pre-stressed with constant internal pressure in order to enable root cracking and some were tested as welded.

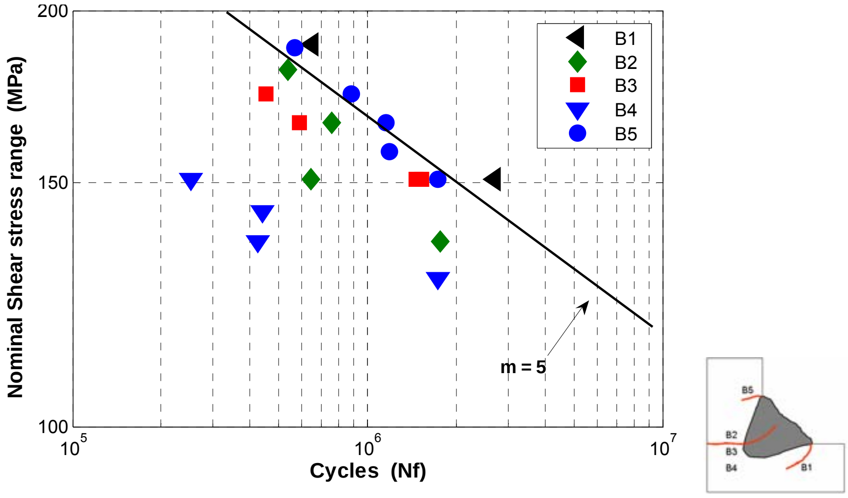


Figure 34. Fatigue test result and crack paths.

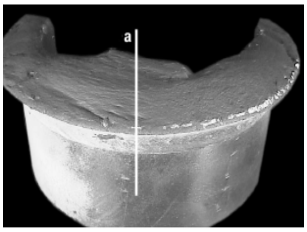
Figure 34-35 and Table 3 summarize the fatigue test results of the tubular joint structures. It is shown that the compressive residual stresses at weld root side for the both tubular joint configurations increase the fatigue strength and keeps the root crack closed. Root cracking is only observed when internal pressure is applied. The stress relieving shows little or no increase in fatigue strength as compared with the weld condition.

Table 3. Fatigue test matrix of welded tubular joints.

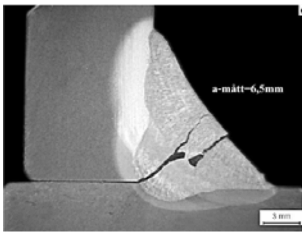
	B1*	**B2***	**B3***	**B4****	**B5*** *(Stress relief)*
$P_{internl}$ (MPa)	0	25	15	0	0
$FAT_{50\%}$	155	137	132	108	146
FAT accord. to IIW	**142**	**123**	**116**	**83**	**142**
Failure	Toe	Root	Root	Root	Toe

*) Single-U weld groove
**) Fillet weld (no groove)

a)



b)



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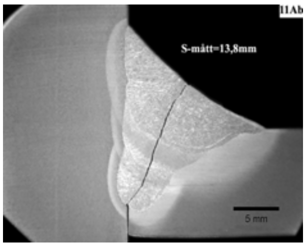


d)

e)

Figure 35 Fatigue crack paths for tubular joint structures: a) and b) batch B1 toe cracking; c) batch B4 – root cracking; d) batch B2 and B3 – root cracking; e) batch B5 (stress relieved) – weld toe

Residual stress relaxation due to the applied external loading was studied numerically by cycling the 3D FE model for 20 cycles (±220 MPa). The objective is to simulate the change in residual stresses in the vicinity of the weld toes and weld root. Figure 36 shows the residual stresses after loading. The analysis shows a small amount of relaxation of the residual stress due to the small amplitude of the fatigue loading.

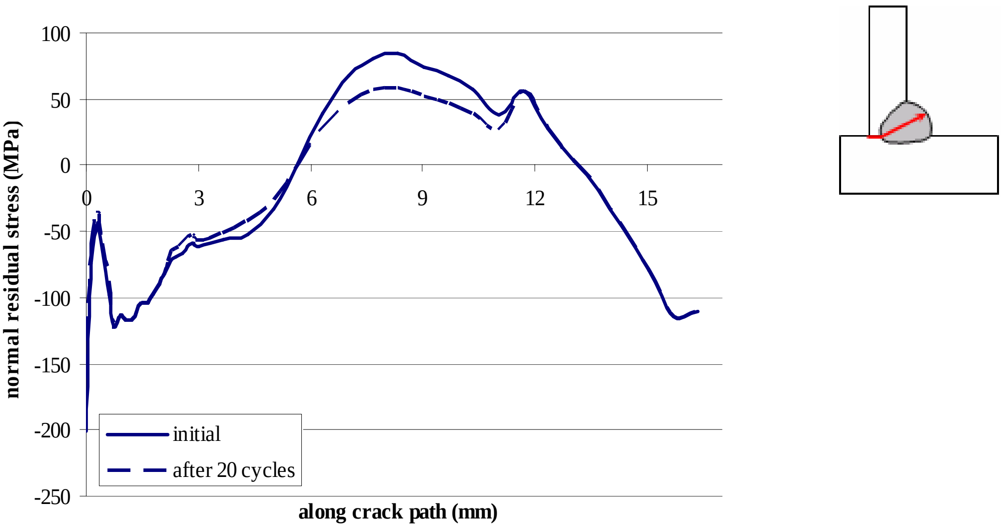


Figure 36**.** Residual stress responses along the observed fatigue weld root crack trough the weld throat at selected fatigue loading cycles.

Residual stress management in manufacturing of ship engines

Two projects within WP4 and 5 have been carried as a Danish joint project with MAN Diesel A/S and DTU as partners. In welded steel structures, a stress relieving by post-weld heat treatment is in some cases carried out to increase the fatigue life. The purpose is to remove harmful tensile residual stresses due to the welding. This has also traditionally been done for the welded structures for diesel engines. Due to the large size of the components in question, this is a costly process. However, theoretical estimates of the residual stresses indicated that favourable compressive residual stresses from the welding would develop at the critical areas with respect to fatigue crack initiation for the actual structures. Laboratory fatigue tests demonstrated this to be the case. As-welded test specimens were found to have significantly higher fatigue strength than did stress relieved specimens. Thus, a costly stress relieving could be avoided and at the same time a longer fatigue life was obtained.

The overall objective of this study was to develop a finite element based simulation tool for better understanding of the influence of welding induced residual stresses on fatigue. Software for setting up the input deck to the FE analysis is presented as developed based on the capability of the general-purpose finite element software packages ABAQUS, see Figure 37.

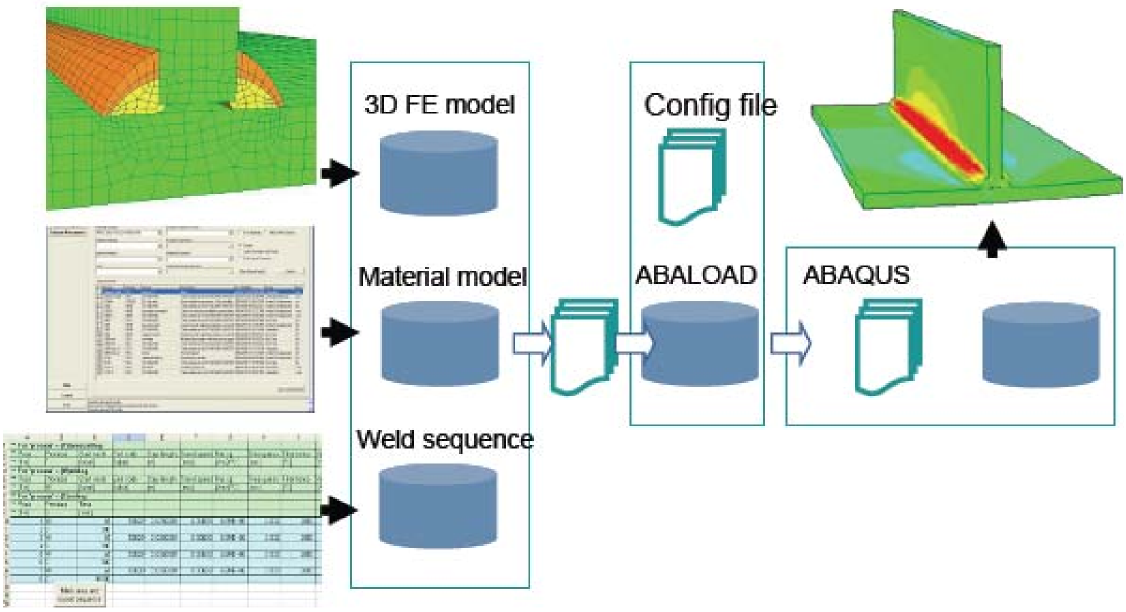


Figure 37. Principle of the numerical tool developed in the project.

An experimental setup with a K-butt weld application is investigated as it combines verification of the FEA tool with a relevant structural detail for the product of MAN

Diesel. With the developed tool the complex modelling setup with multi-pass welds including specific weld sequences, weld directions, addition of weld filler material and travel speed of each pass etc. is made as a sequential thermal and mechanical/structural analysis, see Figure 38..

As for the results of the thermal analysis the numerical obtained weld pool profiles are compared with micro-samples. The residual stress fields from the structural analysis are compared to residual stress measurements through measuring of residual strains by “the hole drilling strain gauge method”, se Figure 39. The structure is cut-up for subsequent fatigue assessment, and the redistribution of residual stress by this is also modelled numerically and evaluated against measurements.

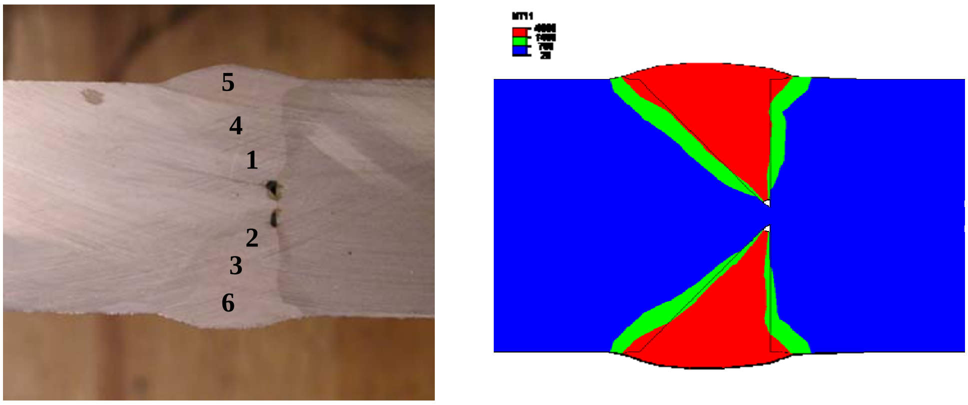


Figure 38 Micro-sample compared with numerical obtained weld pool profile.

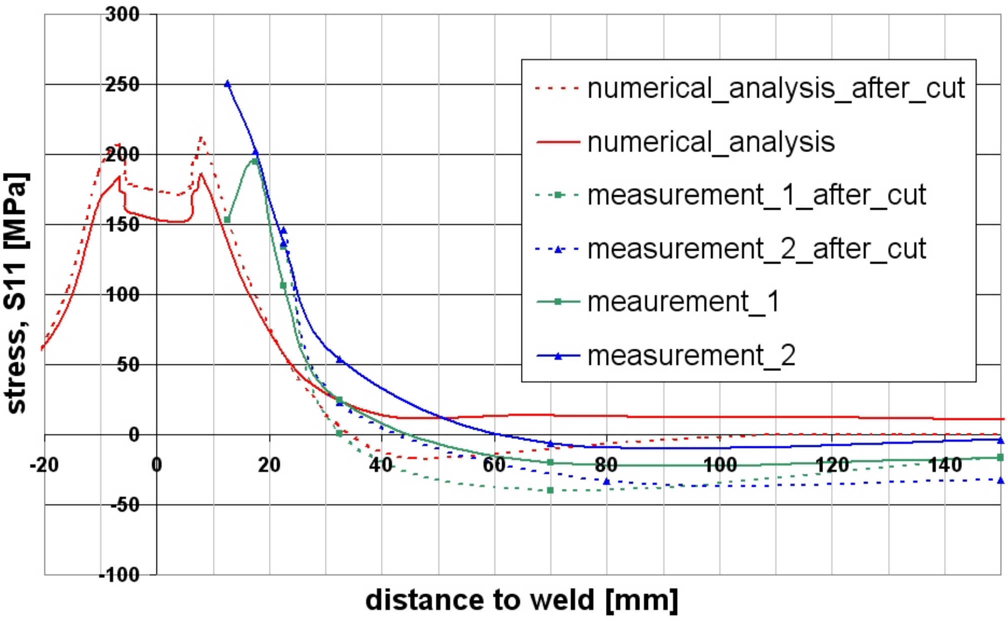
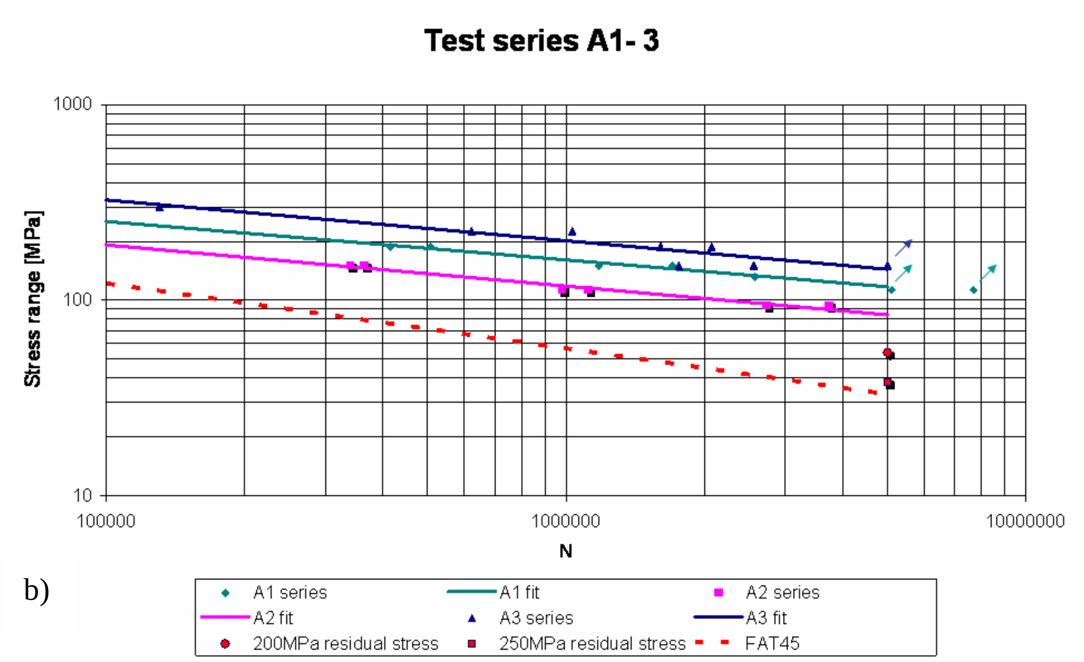


Figure 39. Residual stresses transverse to the weld, dotted lines are residual stress on plates after cutting for fatigue tests in strips of 750 mm x 70 mm x 25 mm.

The structural detail with the K-butt weld is subjected to constant amplitude loading. Experimental fatigue tests are carried out on as-welded and PWHT parts and compared to IIW FAT45 recommendations, see Figure 40.

a)



b)

Figure 40.a): Specimens after failure and the test rig prepared with new specimen.
b): Results from fatigue tests. IIW FAT45 curve is shown for reference.

The achieved results and improved understanding influence many empirical best-practice recommendations for production and repair in MAN Diesel, and may contribute to improvement of these in the future. FE simulations of welding induced stresses are still quite demanding with respect to computational capacity. However, this study has shown that many process related factors influence the welding induced residual stresses and, thereby, fatigue resistance. These factors can be investigated with moderate model sizes and calculation times and can provide qualitative information on the prevalent stress distribution and, to some extent, quantitative values.

WP5 POST-WELD IMPROVEMENT TECHNIQUES FOR PRODUCTION ENVIRONMENTS

In contrast to machined components, the fatigue strength of welded joints in the as-welded condition does not increase proportionally with steel tensile strength. Weight savings using high tensile steels are therefore realised only when static strength rather than fatigue are dominating the design. In fatigue situations, post weld treatments have proven effective for common structural steels. Among methods suitable for industrial application are TIG dressing, grinding and hammer peening, as well as the recently developed ultrasonic impact treatment (UIT), and use of low temperature transformation (LTT) welding wire. The use of improved welds may therefore facilitate the use of high strength steel in structures, thus making these structures lighter and less energy consuming. Robotised application of improvement methods will increase productivity and this aspect will be investigated in the project.

Introduction

The main objectives of WP5 were to develop guidance for the implementation of weld improvement techniques into fabrication processes. Q-FAB is coordinated with the International Institute of Welding (IIW) round robin testing program on improvement methods which started in January 2004. To further the introduction of improvement techniques in design guidance a cooperation with FITNET, see www.eurofitnet.org, was established in 2004, see section 3.

Fatigue test programs

In the first phase of the fatigue testing program in 2004 and early 2005 the specimen used was the one shown in Fig. 1a). A total of approximately 50 specimens with strength of 355, 700 and 900 MPa were tested in Phase 1. The majority of the test results were reported in a MS thesis. In the next phase the specimen in Figure 41 was used, and the material was 700 MPa and 1100 MPa steel in 5 mm plate thickness. The test results were reported in another MS thesis In this program the following weld conditions were used:

1. As welded, for reference
2. Ground
3. Ultrasonic impact treatment (UIT)
4. Grinding plus UIT
5. Low transformation temperature (LTT) weld material.

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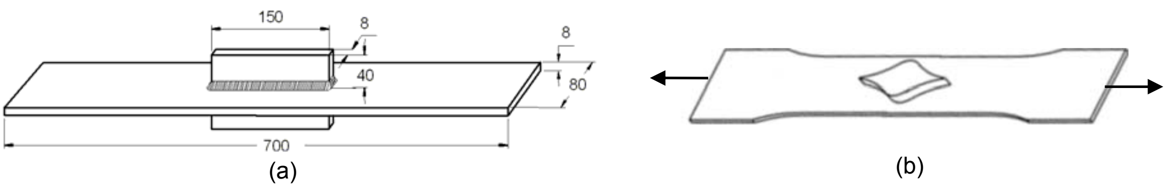


Figure 41. Specimens for Q-FAB and IIW fatigue testing

Summary of test results.

The specimen shown in Fig. 41b) was chosen because it represents a typical detail in a light weight structure. The shape of the cover plate with elongated ends is optimized to lower the stress concentration factor. With a length of the cover plate of 150 mm length this detail is a category 71 detail (or FAT 71) in the IIW design recommendations for welded structures, while the corresponding class is in the DNV and Norsok systems is F1 (or FAT 63). In most design codes in which this detail is categorized the plate is rectangular or circular in shape. Since the stress concentration factor for the shape in Fig. 1b) is assumed less than that for a rectangular or circular plate of the same length, FAT 71 is used for comparison. Figure 42 shows a comparison of the four types of weld treatment.

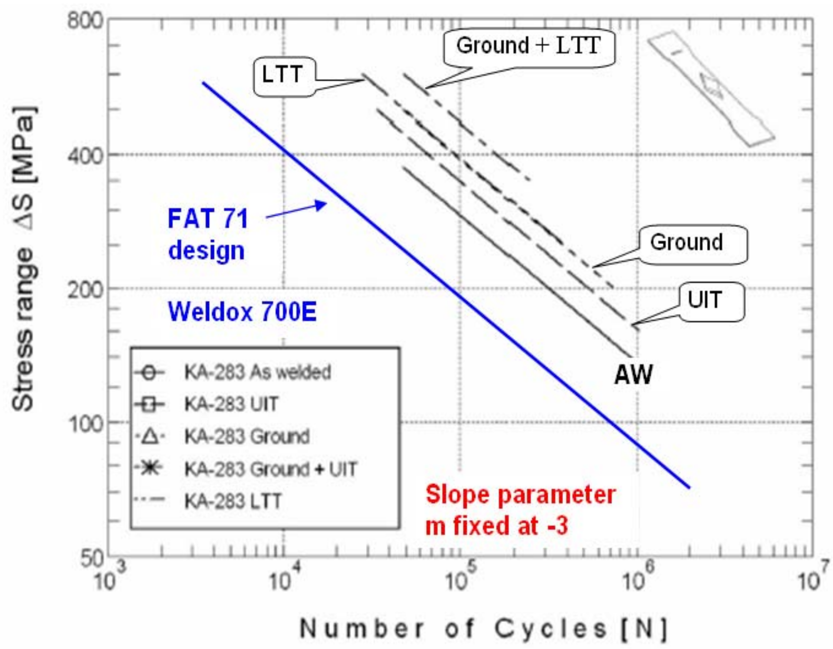


Figure 42. Comparison of improvement methods, Weldox 700E base material.. All slopes fixed at m = 3 in regression analysis.

The specimen shown in Fig. 41b) was chosen because it represents a typical detail in a light weight structure. The shape of the cover plate with elongated ends is optimized to lower the stress concentration factor. With a length of the cover plate of 150 mm length this detail is a category 71 detail (or FAT 71) in the IIW design recommendations for welded structures, while the corresponding class is in the DNV and Norsok systems is F1 (or FAT 63). In most design codes in which this detail is categorized the plate is

rectangular or circular in shape. Since the stress concentration factor for the shape in Fig. 1b) is assumed less than that for a rectangular or circular plate of the same length, FAT 71 is used for comparison. Figure 42 shows a comparison of the four types of weld treatment.

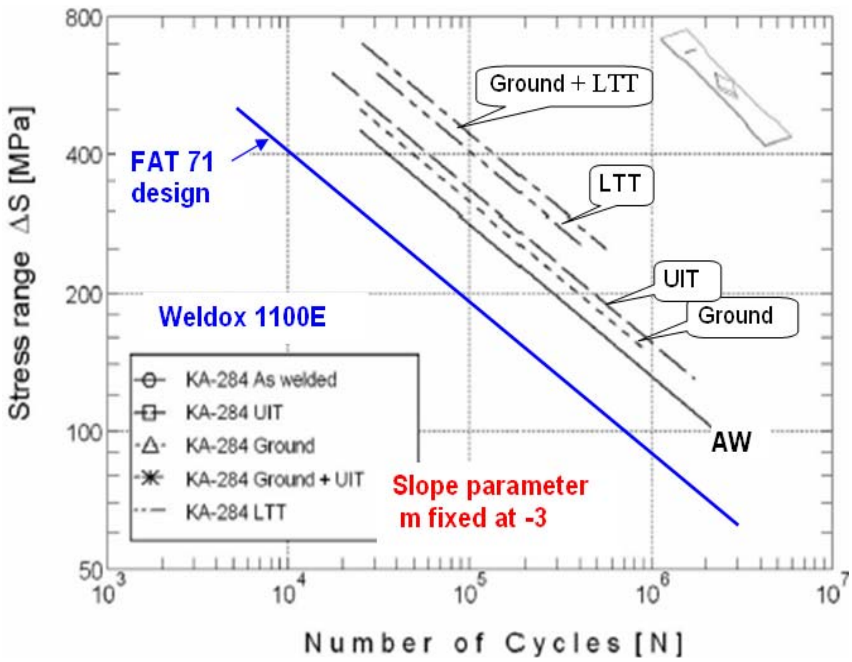


Figure 43. Comparison of improvement methods for Weldox 1100 base material. All slopes fixed at m = 3 in regression analysis.

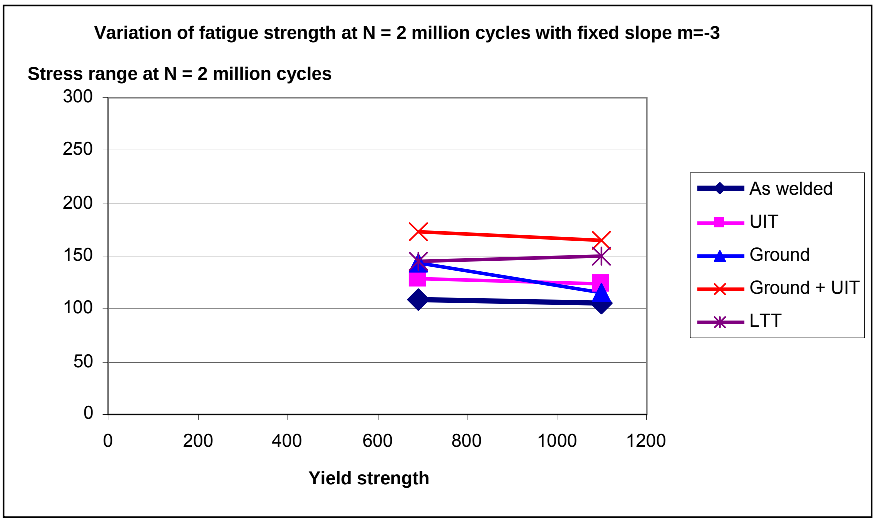


Figure 44. Variation of fatigue strength at 2million cycles with yield strength, mean line data for a fixed slope, m = 3.

The results for improved welds in Figure 43 are generally slightly lower than the results for Weldox 700 material shown in Figure. 42. A comparison of the FAT values in Fig. 43 indicates equal or even lower results for some improvement techniques when applied to Weldox 1100 material. The test results with different steel grades are plotted in Figure 44.

This contrasts with previously obtained relationships between the long life fatigue strength and base material strength for improved joints, which generally shows an increase in fatigues strength with higher yield or ultimate strength. Some older results obtained are shown for comparison in Figure 45.

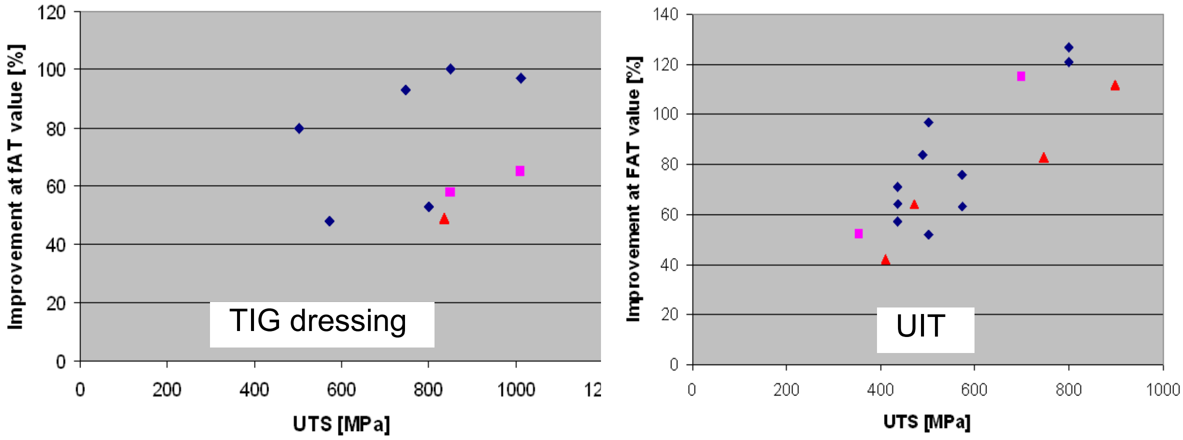


Figure 45. Variation in fatigue strength at 2million cycles with ultimate tensile strength, typical data obtained for the specimen in Fig. 41

Possible reasons for the trends in the data in Fig. 44 are:

1. Higher notch sensitivity for the 1100 MPa YS steel compared with lower grades of steel.
2. Indications of larger defects in ground and LLT-welded specimens 1100 MPa YS.

The defects are being examined, and tests on un-welded specimens in 1100 YS steel with various surface conditions are under preparation to assess notch sensitivity.

Robotized TIG dressing.

A series of robotic TIG-dressing tests was carried out in order to develop suitable dressing parameters. The main aim was to provide a smooth transition between the base material and the weld face, without risk of undercuts. Another important aspect was the robustness of the process, i.e. the ability to cope with deviations along the weld. During the optimization process the main focus was on quality and robustness, not productivity. The test set-up is shown in Fig. 46

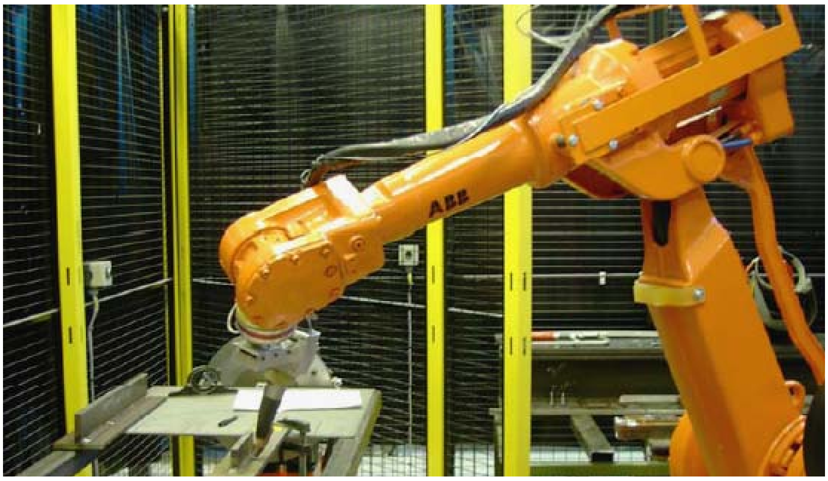


Figure 46. Robotized TIG-dressing

Procedures

All test specimens were treated with thorough wire brushing or light grinding prior to dressing. Removing all traces of mill scale and other possible contaminants in the vicinity of the weld toe was found to have a strong influence on the achieved quality of the TIG-dressed welds. Poorly cleaned welds had pores and undercuts.

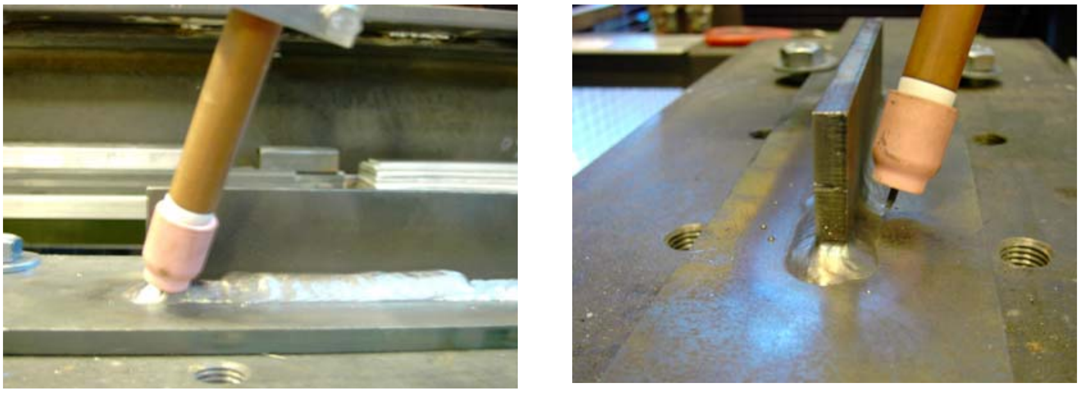


Figure 47. Robotized TIG-dressing - optimized torch angles and electrode position

In order to increase the arc energy, providing a wider melting profile, a mixture of 70% argon and 30% helium was selected as shielding gas. This makes the process less vulnerable to a varying weld toe position. It was also found that the sideways angle (transverse to the welding direction) was an important parameter regarding the creation of detrimental undercuts. Reducing the angle from an initial 35^o to 15^o had a considerable positive effect. The angle in welding direction was not found to be equally important, and 15^o from vertical (forehand) was selected. Optimized TIG-dressing positions are shown in Fig. 47.

The diameter of the welding arc, and hence the width of the melting zone, increases when the arc length is enlarged. As a consequence, a long arc makes the process more robust with respect to the ability to cope with irregularities along the weld toe. On this basis an electrode stand-off length of 5mm was selected. The best nominal torch position was found to be pointing to the weld toe as shown in Fig. A. Due to the irregularities along the weld the true electrode position varied between approximately ± 2mm from the weld toe. All parameters are within the range given in the IIW recommendations.

Test results

The test results obtained for robotized TIG-dressing of S700 steel specimens indicate the same order of improvement as obtained in earlier tests in which specimens were treated by manual TIG dressing procedures, se Figure 48. All results to this point lie above the IIW recommended FAT 100 curve. From the six valid S700 tests performed up to now three have failed from the weld toe, two from the weld root and one from a defect on the weld flank. Thus, further improvements might again be achievable if the original welds are of higher quality.

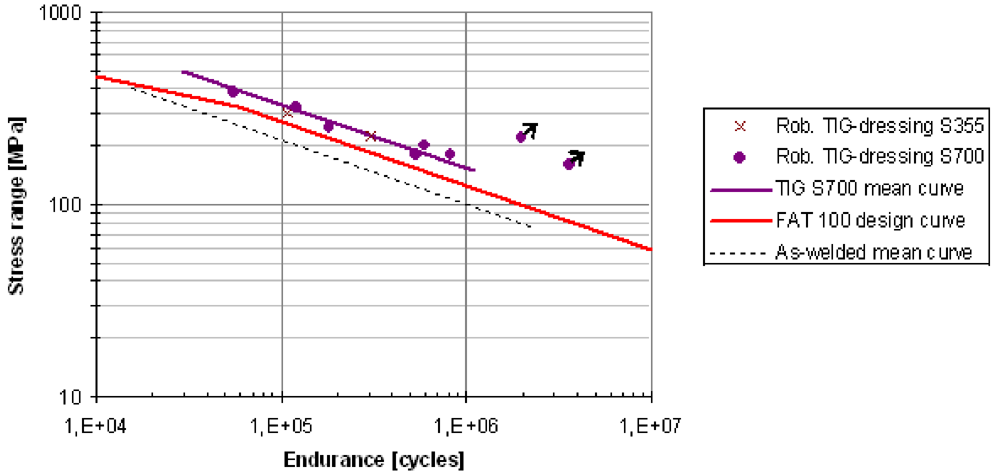


Figure 48. Fatigue test results from robotized TIG-dressing, compared with conventional TIG-dressing.

Quality control and quality assurance activities for improved welds

The IIW guidelines for improvement procedures that are the basis for the IMPRESS project have been developed further in the project. The latest revision includes new guidance for peened joints because lap type defects of the type shown in Figures 49-50 have been found to give a considerable reduction in effectiveness of peening methods. For this reason it is now recommended that all peened joints are checked by magnetic particle inspection (MPI).

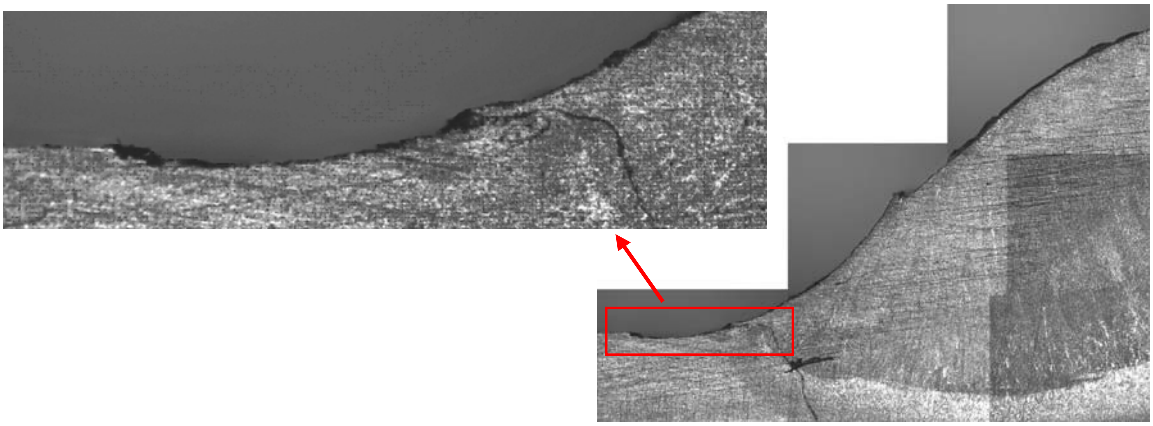


Figure 49. Fatigue crack growth from lap type defect which is typical for hammer peened and UIT joints.

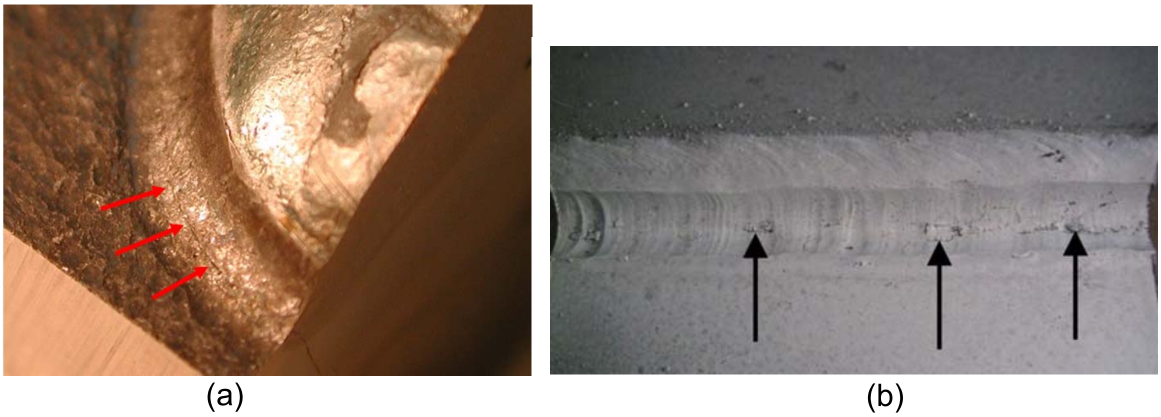


Figure 50. Lap type defects; a) visible at surface; b) MPI indications of lap defects.

Weld geometry measurements of improved welds

For weld improvement techniques that use geometry modification, e.g. weld toe grinding or TIG dressing, the shape at the weld toe is an important quality criterion. In particular, the weld toe radius is the single most important parameter for its influence on the stress concentration factor for the weld. In structures that are susceptible to fatigue cracking, e.g. construction equipment, inspection programs have been established to find welds with small toe radii or very steep weld angles. Visual inspection is subjective and depends on the judgment of the inspector. There are a number of 3-D scanning systems available to which can be linked to a definition of the geometry that is independent of the operator. Sometimes very expensive laser based equipment are used.

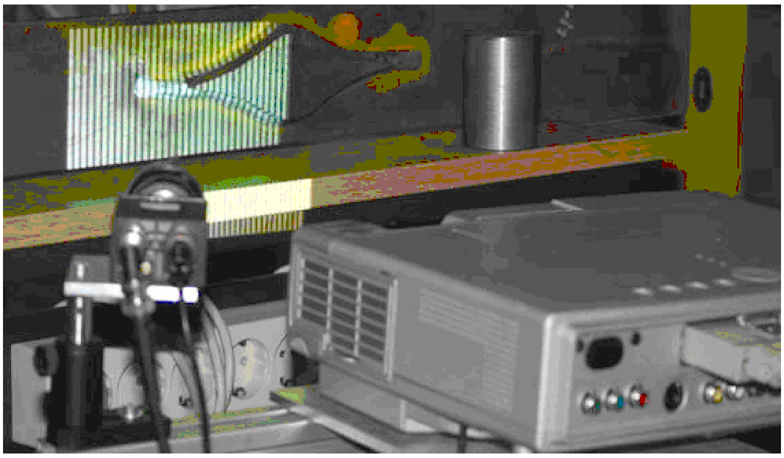
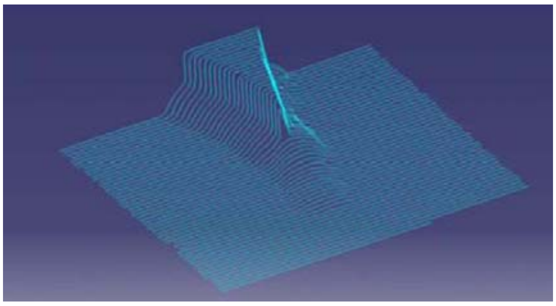
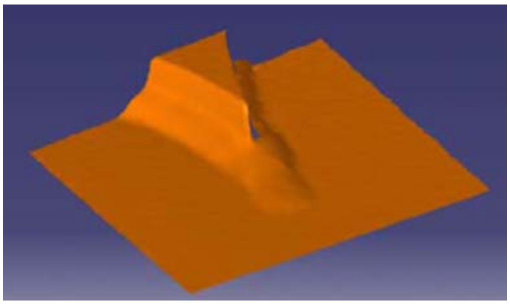


Figure 51. Structured light measurement set-up for specimen in Figure 41.

A system termed Structured Light Measurement (SLM) which was developed by SINTEF is used the IMPRESS project. A pattern of light and dark stripes is projected on to the object. A camera picks up the distorted pattern and a computer program generates point clouds that define the 3-D geometry. Data processing algorithms have been developed which allows the weld angle and weld toe radius to be defined. Approximately 500,000 data points define surface, the resolution is 1/10.000 of the image size, e.g. 10µm for an image size of 10cm, making the system suitable for weld shape measurement. The system can also be used for distortion measurements of large structural components. An example of the set-up is shown in Figure 51, resulting images are shown in Figure 52.



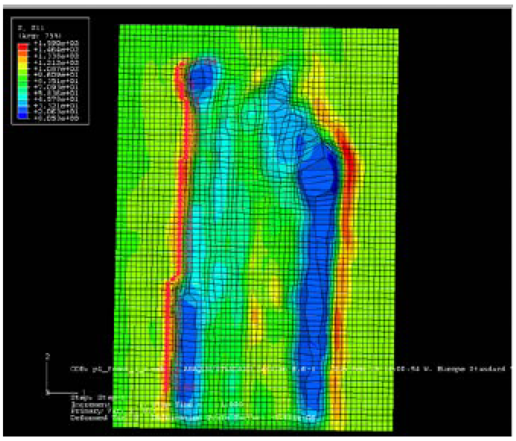
a)



b)

Fig. 52 Visualization of weld in Figure 41; a) As cross sections from which weld toe radii and weld angles are computed; b) As a meshed surface.

The SLM method is being further developed in the IMPRESS project in collaboration between SINTEF, NTNU and Lappeenranta University of Technology in Finland.



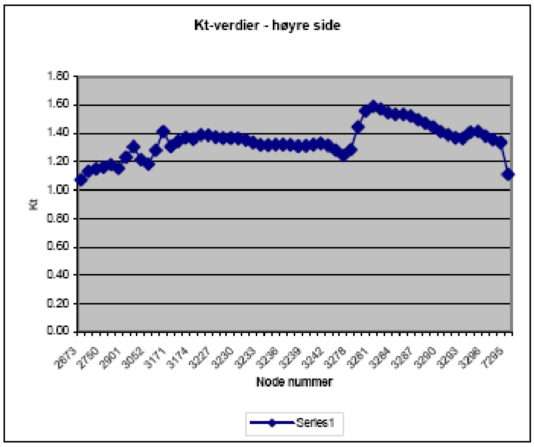


Figure 53. Stress plot derived from a 3D scan by SLM

Figure 54 Example of data obtained from FEA analysis of data from SLM

The SLM method was also used in a project aimed at developing a repair procedure for a floating production, storage and off-loading (FPSO) vessel. In this project a comparative study on of a butt weld in the ship side-shell which had to be made from one side. In this project large plates made with standard weld metal ere compared with welds made with martensitic weld metal that produced low or compressive welding stresses. 3D scanning was used to characterize the weld geometry and thereby quantify any possible contribution from weld geometry changes to the life improvement. The 3D data are imported in Abaqus and a FE analysis is performed. Figure 53 shows an end part of the weld with a stress plot. In Figure 54 the results in terms of the local stress concentration factor along a weld have been plotted

IIW burr grinding at B&W

To improve quality and reduce lead-time in production of large two-stroke diesel engines, several producers have requested that cast iron structures should be substituted for welded steel constructions. Iron castings can only be avoided by the implementation of new easy-to-weld designs, with special focus on the highly stressed transitions between thick and thin plate members. In order to obtain weight reduction corresponding to improved material properties of steel. Burr grinding is an obvious method for improvement of fatigue strength in production of large diesel engine structures. The present investigation compiles results reported in IIW-1629-03 (ex-doc. XIII-1966-03) with new fatigue tests on large-scale burr ground steel S275 specimens with plate thickness of 50mm. All specimens have been subjected to constant amplitude loading, some in pure bending and some in pure membrane loading. 3D linear elastic finite element stress evaluation of burr ground notches have shown almost same endurance limit for pure bending - and membrane loading. This result is important for evaluation of real structures subjected to both bending and membrane loading. Although the number of tests carried out is limited, the results obtained show that burr grinding improves fatigue strength significantly. In some cases, crack initiation moved from the weld toe to the non-ground surface between the ground areas at the weld toes, due to the grinding.

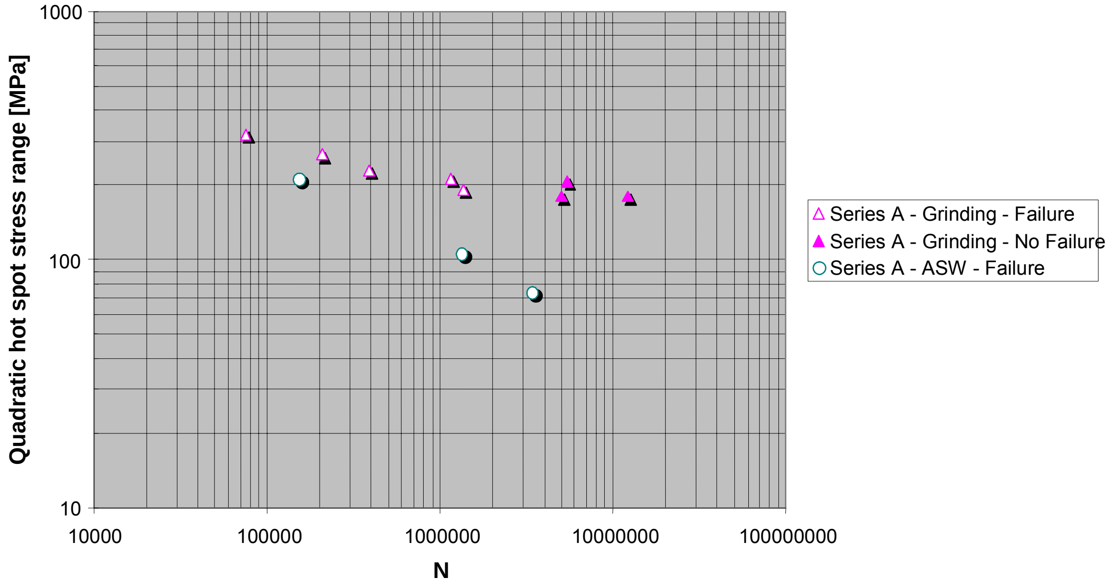


Figure 55. Fatigue test results. Tests as-welded (ASW) and with grinding.

The results obtained in this project showed that a considerable increase in fatigue life may be obtained by grinding the weld toes. In e.g. test series A, (see Figure 55), the fatigue life was increased by a factor ranging from 2.8 to infinity, depending on the stress level. If grinding is used, it will normally be carried out according to international recommendations, e.g. IIW. However, in this project an alternative type of grinding and its effect on the fatigue life was studied, see Figure 56. The first grinding pass was performed with a rotating burr grinder and the second pass with stone. Only visual inspection was undertaken. Although a few undercuts were still visible, no additional grinding was performed prior to laboratory tests.

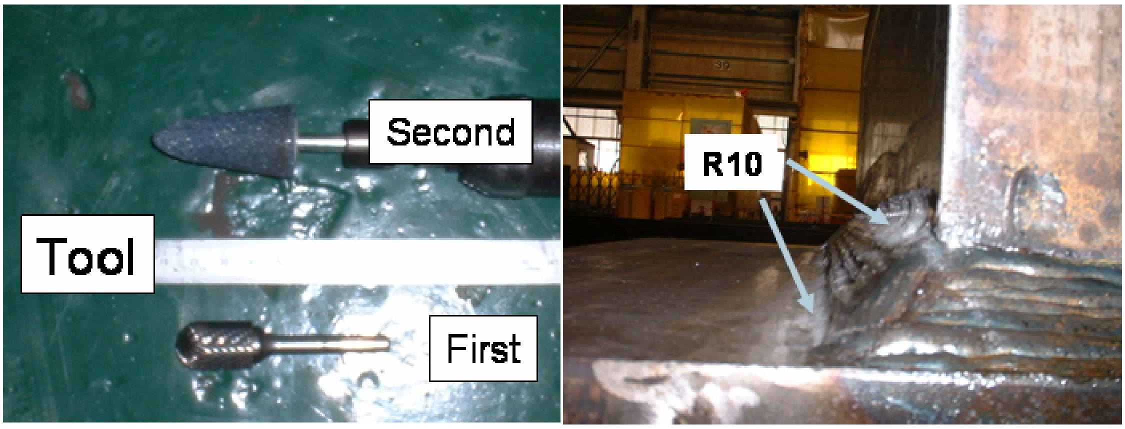


Figure 56. IIW recommended burr grinding, R10. Executed by Mitsui Engineering & Shipbuilding.

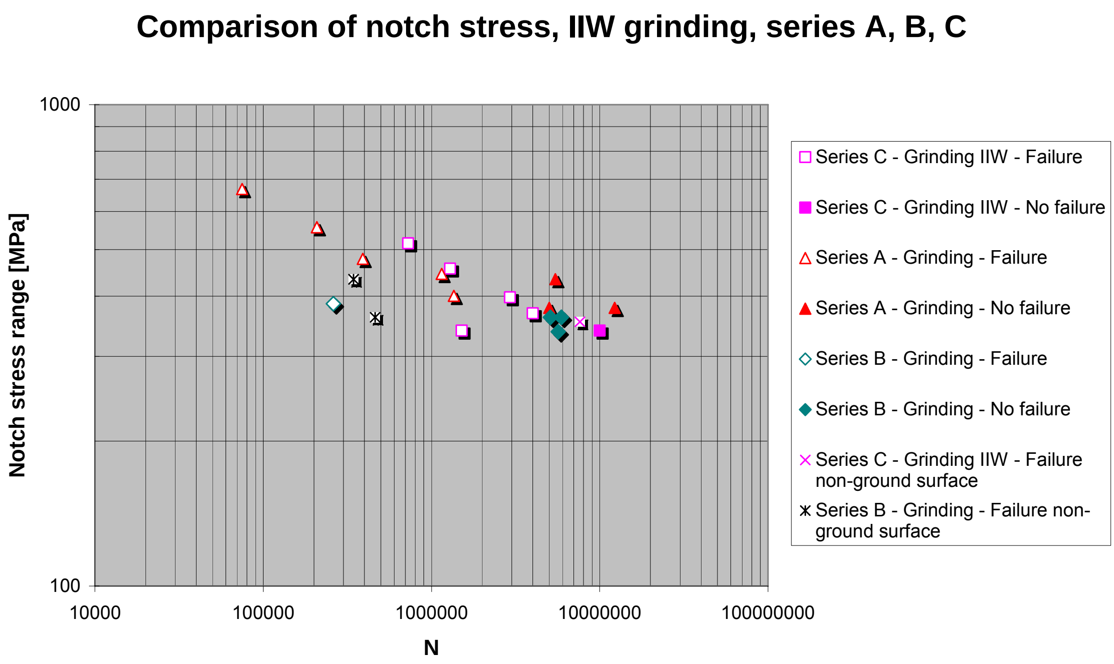


Figure 57. Comparison of notch stress, IIW grinding, test series A, B, C. External load range converted to notch stress range at weld toe by FE calculation.

The fatigue tests carried out demonstrated that the alternative type of grinding resulted in fatigue strengths at least as that obtainable by using the international recommendations, Figure 57. The advantage of the alternative type of grinding is that it saves about 30% of the machining time, which for these large structures has a considerable economical impact.

LTT filler material

It is commonly accepted that the fatigue strength in welded joints is independent of the applied nominal mean stress. This is explained by the fact that tensile residual stresses of the magnitude of base material yield strength are present in the vicinity of the weld. There are basically two methods to increase the fatigue strength of welded joints. Either the residual stress situation or the weld geometry can be improved.

During the last 15 years, Low Temperature Transition (LTT) welding filler material has been developed. These consumables are typically alloyed with 10-15 wt% Cr, 0-10% Ni, sometimes also Mo, Cu and C. During cooling of the deposited weld metal, martensite forms at low temperature, typically below 200°C. When martensite forms, a volumetric expansion takes place; hence compressive residual stresses are introduced into the welded joint. Compressive residual stresses are beneficial for fatigue strength in welded joints. This has been shown for joints welded with LTT filler material when tested under constant amplitude load. Improvement of typically 25-100% in fatigue strength at $1 \cdot 10^6$ or $2 \cdot 10^6$ cycles can be found in previously reported work. From Japan LTT filler material has been reported to be successfully used for bridge repair. Minimizing of weld distortion is another interesting possibility with LTT filler material.

There are, however some question marks regarding LTT filler material. One question mark might be the fracture toughness. The fracture toughness is from some sources reported to be satisfying, but in some cases the fracture toughness has been very low.

Another question mark to consider is stress relaxation under spectrum load. In practice, many applications are subjected to spectrum loads rather than constant amplitude loads. Spectrum loads have for joints welded with conventional welding consumables been shown to cause rather rapid stress relaxation if the maximum stress levels are high. It is therefore interesting to investigate if the positive effect on fatigue strength of joints welded with LTT filler material remains under spectrum load.

In order to investigate the effect of spectrum load on joints welded with LTT filler material, a linear spectrum with high mean stress has been used on non-load carrying fillet welds, welded with LTT filler material, see Table 4 and Figure 58. The LTT filler material was in this case ESAB OK 15.55 which is a conventional stainless martensitic filler material that mainly is used for welding martensitic steel pipes an thus not especially developed to maximize the compressive stresses in welded joints. Base material was a cold forming steel, Domex 700 MC with nominal yield strength 700 MPa. For comparison, similar joints welded with conventional filler material are tested under identical conditions. Residual stresses have been measured prior and during testing. Constant amplitude testing has also been performed. Fatigue testing is still ongoing and the test results should therefore be considered as preliminary.

Table 4. Alloy content in used electrodes for the test in Figure 58

		Alloys (w%)						
Series	Consumables	Cu	Si	Mn	Cr	Ni	Mo	Cu
A	OK Autorod 12.51	0.1	0.7	1.1				
B (LTT)	OK Tubrod 15.55	0.01	0.4	1.8	12.5	6.7	2.5	0.5

From the preliminary test results it is concluded that the improvement in fatigue strength for the specific LTT under the specific spectrum load was considerable less compared to improvement achieved under constant amplitude load.

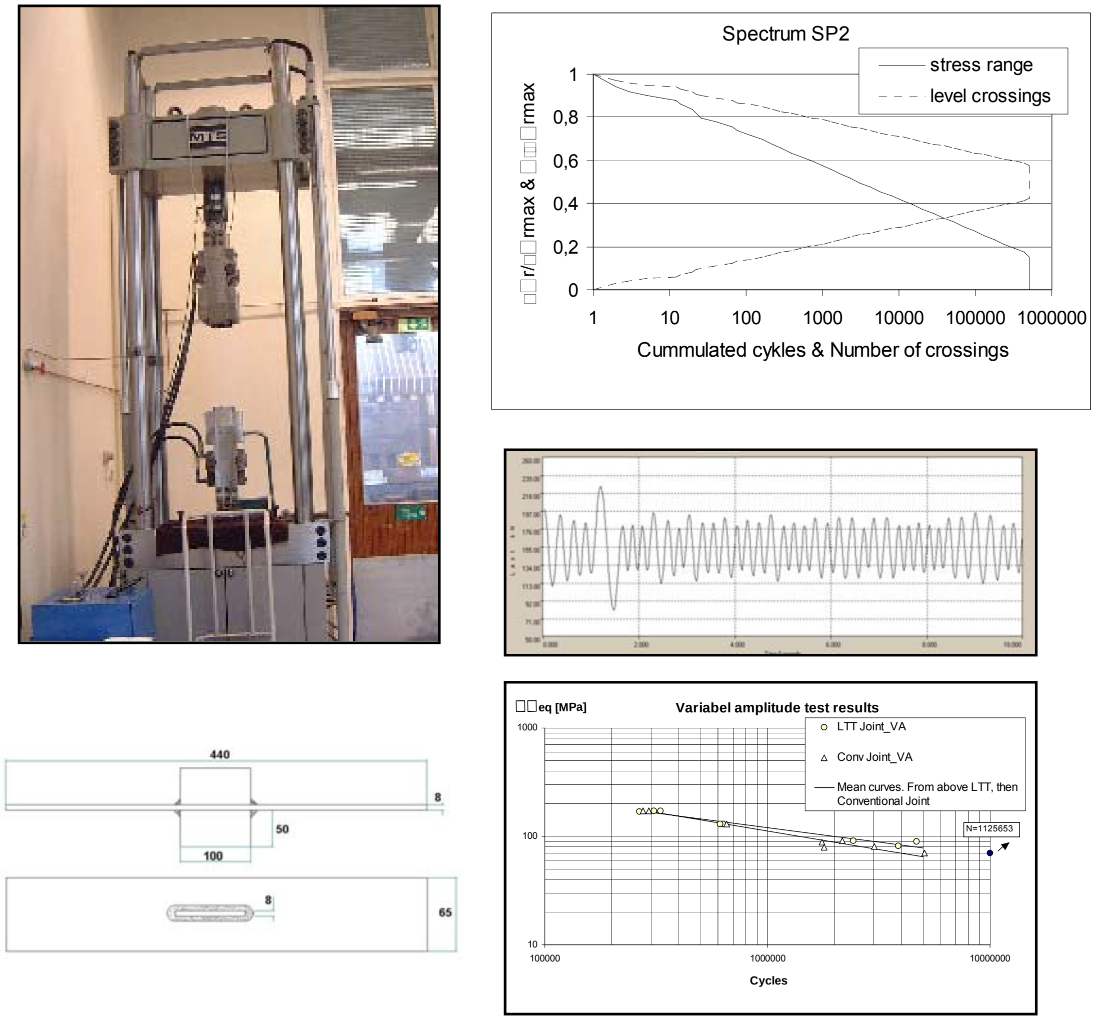


Figure 58. Test rig, specimens, shape of spectrum used, real time signal and preliminary variable amplitude test results expressed as equivalent stress range

Large scale fatigue tests.

Exploratory tests have been performed on 6” pipes with one sided girth welds made with LTT electrodes. A few tests made in another project has indicated that LTT has a potential for substantially improving the fatigue strength in butt welds in pipes made from one side and other welded joints in which the root is not accessible for improvement.

Tests on large scale plate specimens have also been carried out in a study to optimize a repair procedure for a floating production, storage and off-loading (FPSO) vessel

DISCUSSION AND CONCLUSIONS

The results of the project will provide practical guidance of immediate value to industry and exploitation will concentrate on the provision of information in a user-friendly form that is readily applicable. Although the project will address transportation structures, there is no doubt that the results will be applicable to most industries involved with fatigue-loaded welded structures. The following results were achieved within the project:

1. Significant improvement has been achieved in the performance and understanding of fatigue life assessment of welded structures.
2. A draft of a weld quality classification system is under development based on a scientific ground
3. Spatter induced cold laps is still the most frequent defect in MAG-welding an occur also in laser-hybrid (MAG) welding
4. Automated assessment of weld geometry and the determination of weld quality can be unsafe in cases of presence of cold laps
5. A simulation tool for testing the effect of variations and changes in parameters of welds are under development and applied on simple weld geometries
6. Two important methods of weld improvement are investigated, grinding according to IIW and UIT (Ultransonic Impact Treatment). In CA testing the grinding showed an increase in fatigue limit of near 100 % and UIT even more.
7. In case of weld improvement the failure location may shift to root side, design methods must have capacity to assess potential failures.
8. Fatigue test of gas cut edges in thick sections showed fatigue limit higher than current design curves.
9. FE simulations of welding induced stresses are still quite demanding to computational capacity, but this project shows that many process related influences on residual welding induced stresses, and thereby fatigue resistance, can be investigated with moderate model size and calculation time giving a prevalent agreement in qualitative stress distribution and to some extent a quantitative agreement
10. Over 70 technical report is produced within Q-FAB including several PhD- and Licentiate-thesis.

Participating manufacturer will exploit the results of the project but also by the steel manufacturer and consultant firm. The dissemination will not only be by technical reports, PhD theses and presentation of the results at national and international seminars, but perhaps more important, the findings has also led to renewed discussions within the welding community regarding the foundations of existing standards. Steps have been taken towards a consensus on relevant and appropriate scientific basis for future fatigue and integrity correlated standards.

RECOMMENDATIONS FOR FURTHER WORK

While the current project has contributed significantly to the competence of Nordic industrial partners, there are several issues which have gained attention during this project and should receive more research work in the future.

- Simulation tools to better understand those weld process parameters which lead to high quality welds should be further developed
- Non-destructive assessment systems for weld geometry determination should be developed from the currently semi-autonomous state toward being fully automated.
- Several weld improvement techniques for high strength steels show good promise, but currently they are fully manual. Robotised weld improvement methods must be developed.
- Methods and software for more efficient analysis of welding induced residual stresses must be developed.

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