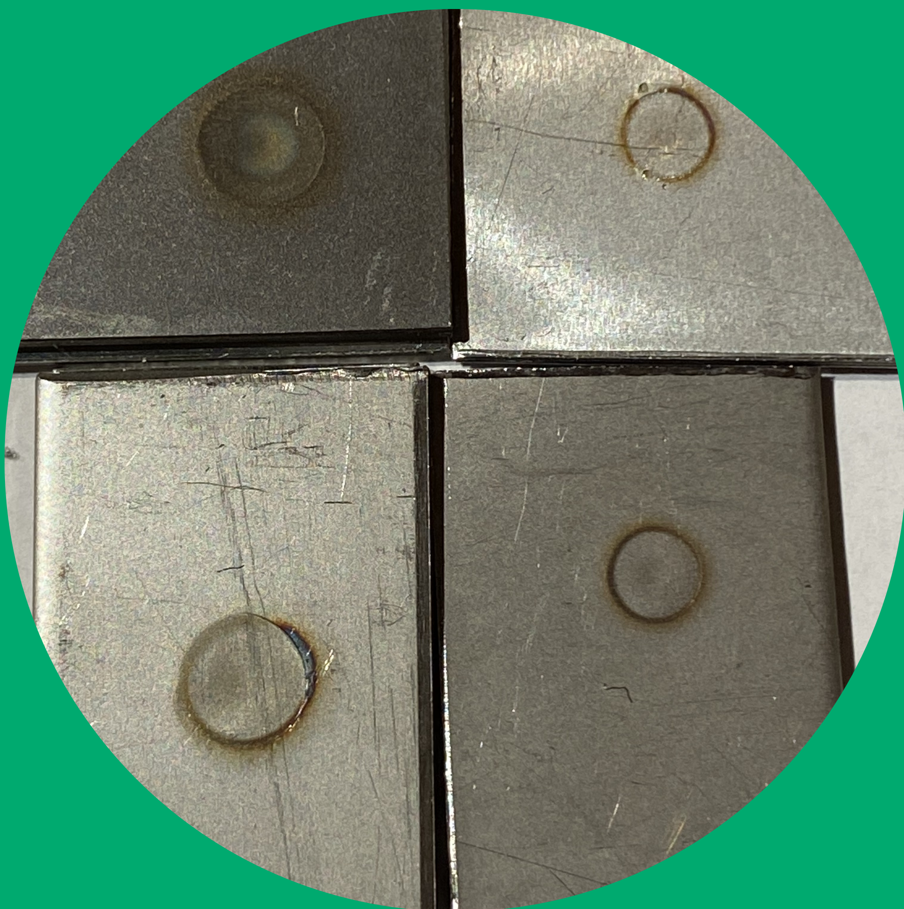
Department of Mechanical Engineering

Corrosion fatigue of spot-welded austenitic stainless steels in 3.5 % sodium chloride solution

Mervi Somervuori



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Mervi Somervuori

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Abstract

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Abstract

Corrosion fatigue performance and corrosion properties of spot-welded and weld-bonded austenitic stainless steels EN 1.4301 and EN 1.4318, in grades 2B or 2F and 2H, and some dissimilar steel joints were investigated in 3.5% sodium chloride solution.

The corrosive environment and elevated temperature at 50 °C reduced significantly the fatigue strength of both spot-welded and weld-bonded test specimens of austenitic stainless steels. The fatigue strength of the weld-bonded specimens is higher than that of the spot-welded specimens both in the air and the corrosive environment, but the difference is smaller in the corrosive environment than in the air. In the air, the spot-welded specimens of the 2B grade steels exhibited better fatigue strength than the 2H grades of the same steels, but in the corrosive environment, the spot-welded specimens had no distinctive difference in their corrosion fatigue life in the corrosive environment. Both in the air and in the corrosive environment the fatigue cracks in the spot-welded specimens initiated from either side of the recrystallized zone in the HAZ outside the spot-weld nugget.

Fatigue resistance of the spot-welded joints was found to be strongly dependent on the thickness of the sheet. However, when the effect of sheet thickness was eliminated by the line-load range analysis, the steel thickness had no significant effect on the fatigue life of the steel. The fatigue strength of the dissimilar metal joints was between the fatigue strength of the non-stainless steel and stainless steel.

The local corrosion in the crevice was assumed to influence the fatigue crack initiation. Pre-exposure in the corrosive environment did not affect the fatigue life of the spot-welded specimens because the fatigue cracks initiated not at the heat-tinted area where the crevice corrosion was found but at the outer edge of the corona bond area of the spot weld. The results of the surface analysis show that under the colored oxide film is a chromium-depleted layer that is the reason to the reduced corrosion resistance at the heat-tinted areas.

Keywords spot weld, corrosion fatigue, austenitic stainless steel, NaCl solution, weld-bonded joint, dissimilar metal joint

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Tekijä
Mervi Somervuori

Väitöskirjan nimi
Austeniittisen ruostumattoman teräksen pistehitsien korroosioväsyminen in 3,5 %:ssa natriumkloridiliuoksessa

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Tiivistelmä

Piste-ja liimapistehitsattujen austeniittisten ruostumattomien terästen EN 1.4301 and EN 1.4318 (grade 2B tai 2F ja 2H) sekä joidenkin eripariliitosten korroosioväsymistä ja korroosiokäyttäytymistä tutkittiin 3,5 % natriumkloridiliuoksessa.

Korroosioympäristö ja korotettu 50 °C lämpötila alensivat merkittävästi sekä pistehitsattujen että liimapistehitsattujen austeniittisesta ruostumattomasta teräksestä valmistettujen koekappaleiden väsymiskestävyyttä. Liimapistehitsattujen näytteiden väsymiskestävyys oli huomattavasti parempi kuin pistehitsattujen näytteiden sekä ilmassa että korroosioympäristössä, mutta korroosioympäristössä tulosten välinen ero oli huomattavasti pienempi kuin ilmassa. Pistehitsaamalla 2B-teräksistä valmistettujen koekappaleiden väsymiskestävyys oli ilmassa parempi kuin 2H-terästen, mutta korroosioympäristössä väsymiskestävyydessä ei ollut juurikaan eroa. Sekä ilmassa että korroosioympäristössä väsymissäröt ydintyivät pistehitsin ytimen ulkopuolelta, jommalta kummalta puolelta lämpövyöhykkeen (HAZ) rekristallisoitunutta aluetta.

Pistehitsien väsymiskestävyys oli voimakkaasti riippuvainen teräksen paksuudesta. Kun levyn paksuuden vaikutus eliminoitiin ns. line-load range -analyysillä, levyn paksuudella ei ollut vaikutusta teräksen väsymiskestävyyteen.

Teräslevyjen välisessä raossa tapahtuvan paikallisen korroosion oletettiin vaikuttavan väsymissärön ydintymiseen. Pistehitsatun koekappaleen ennakkoaltistus korroosio-ympäristössä ei kuitenkaan vaikuttanut kappaleen väsymiskestävyyteen, sillä väsymissäröt ydintyivät koronavyöhykkeen ulkopuolelta, eivät päästövärejä sisältävältä alueelta, jossa esiintyi rakokorroosiota. Pinta-analyysitulokset osoittivat, että värillisten oksidivyöhykkeiden huonon korroosionkestävyyden syynä oli paksun oksidikerroksen alle muodostunut kromiköyhä vyöhyke.

Avainsanat pistehitsi, korroosioväsyminen, austeniittinen ruostumaton teräs, NaCl-liuos, liimapistehitsi, eripariliitos

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Preface

The research work was carried out in the Laboratory of Engineering Materials of Aalto University (at the time Helsinki University of Technology) in years 2001-2004. The study was part of the 5^{th} Framework project “Weight reduction for safer, affordable passenger cars by using extra formable high strength austenitic steel”, G5RD-CT-2001-00454, financed by the European Commission.

I want to express my gratitude to my supervisors, adjunct professor Dr. Iikka Virkkunen and emeritus professor Dr. Hannu Hänninen, for their kind support, valuable advice and comments as well as their encouragement to finalize the project.

The co-operation with my co-authors and colleagues during the project is acknowledged. I want to express my gratitude to the whole Light&Safe project team, especially to my team mates Lic. Tech. Marko Alenius and PhD Juho Talonen for their help and the fruitful co-operation during the research work and in writing the articles.

I express my gratitude to the personnel of the Laboratory of Engineering Materials who helped with the research work, especially to MSc. Tapio Saukkonen for helping with SEM/EDX.

I am very grateful for all my friends, colleagues both at work and in volunteer work, as well as all others who have encouraged me to finish this project.

I am thankful to my dear family and my parents for all the support they have given to me during the process. All advice and valuable discussions with my father Dr. Tero Hakkarainen are highly acknowledged.

Espoo 26.1.2021 Mervi Somervuori

Contents

List of Symbols and Abbreviations

2B	cold-rolled, soft annealed, pickled, and skin pass rolled
2F	cold-rolled, soft annealed, pickled, and skin pass rolled on roughened rolls
2H	hard cold-rolled, cold-rolling reduction 5%
2H/C850	hard cold-rolled, cold-rolling reduction 5%
2H/C1150	cold rolled, high strength condition
3D	three dimensional
° C	degrees Celsius
$CaCl_2$	calcium chloride
A_{80}	percentage elongation after fracture using a specimen with gauge length L_o = 80 mm
EDX	Energy Dispersive X-ray Spectroscopy
FE model	Finite Element Model
GD-OES	Glow Discharge Optical Emission Spectroscopy
HAZ	heat-affected zone
Hz	hertz
I_{2cc}	short-circuit current
kA	kiloampere
kN	kilonewton
kVA	kilovolt ampere
mol	mole
mol Cl/ l	mole of chlorides per litre
MnS	manganese sulfide
$MgCl_2$	magnesium chloride
MPa	megapascal
ms	millisecond
N	number of cycles
NaCl	sodium chloride
$R_{p0.2}$	yield strength
R_m	tensile strength
S-N curve	stress versus number of cycles to failure curve

SCC	stress-corrosion cracking
SEM	Scanning Electron Microscopy
t	thickness (of the sheet)
X-ray	Röntgen radiation

Original Features

In this study, the corrosion-fatigue performance of spot-welded and weld-bonded austenitic stainless steels was evaluated, and the factors affecting the fatigue strength of the welded joints in a wet, corrosive environment and the corrosion-fatigue crack initiation were clarified. The main findings are summarised in this chapter.

The corrosive environment of 3.5 % NaCl solution at elevated temperature 50 °C reduces remarkably the fatigue strength of both spot-welded and weld-bonded specimens. The weld-bonded joints perform better than the spot welded, but the difference is minor in the corrosive environment than in the air. Adding an adhesive and using weld-bonding instead of spot welding is a way to improve the fatigue resistance of the joint both in the air and in a corrosive environment.

The spot-welded specimens of annealed 2B grade steels have better corrosion fatigue resistance than those of the cold-worked 2H grade steels of the same thickness despite the better fatigue resistance of the 2H base material. Residual stresses around the spot welds are close to the yield strength of the steel. They are high enough to cause stress-corrosion cracking in the absence of external load in a very aggressive environment. The high residual stresses around the spot weld are assumed to be the reason for the reduced fatigue resistance of the spot-welded high strength steels and may also affect the pitting susceptibility of the spot welds.

The sheet thickness has a remarkable effect on the fatigue resistance of the spot weld both in the air and in the corrosive environment. When the thickness of the steel was eliminated by the line-load range analysis the fatigue resistance of the same steel with different thickness was at the same level. The fatigue strength of the dissimilar metal joints was between the fatigue strength of the non-stainless and stainless steel.

The initiation of the corrosion-fatigue cracks was initially presumed to be affected by localized corrosion in the crevice at the heat-tinted area around the spot weld. A chromium-depleted layer was found under the yellow heat-tinted oxide film, which explains the reduced corrosion resistance of the heat-tinted area. However, the corrosion-fatigue cracks did not initiate at the area where coloured heat-tinted oxides were, and crevice corrosion occurred in the immersion tests. In all spot welds, the cracks initiated at the outer edge of the corona bond area in the recrystallized microstructure at the notch.

List of Publications

The doctoral dissertation consists of a summary and of the following publications which are referred to in the text by Roman numerals:

I Somervuori, M. E., Johansson, L.-S., Heinonen, M. H., Van Hoecke, D. H. D., Akdut, N., Hänninen, H. E., Characterisation and corrosion of spot welds of austenitic stainless steels, Materials and Corrosion, Vol.55, Issue 5 (2004), p. 421-436.

II Somervuori, M. E., Alenius, M. T., Hänninen, H. E., Karppi, R., Corrosion fatigue of spot-welded austenitic stainless steels in 3.5% NaCl solution, Materials and Corrosion, Vol.55, Issue 12 (2004), p. 921-929.

III Somervuori, M. E., Alenius, M. T., Kosonen, T., Karppi, R., Hänninen, H. E., Corrosion fatigue of weld-bonded austenitic stainless steels in 3.5% NaCl solution, Materials and Corrosion, Vol.57, Issue 7 (2006), p. 562-567.

IV Alenius, M. T., Somervuori, M. E., Hänninen, H. E., Mechanical and corrosion properties of spot-welded high-strength austenitic stainless steel EN 1.4318, Materials and Corrosion, Vol.59, Issue 4 (2008), p. 296-302.

V Alenius, M., Pohjanne, P., Somervuori, M., Hänninen, H., Exploring the mechanical properties of spot-welded dissimilar joints for stainless and galvanized steel, Welding Journal, Vol.85, Issue 12 (2006), p. 305-s-313-s.

Authors Contributions

Publication I: “Characterisation and corrosion of spot welds of austenitic stainless steels”

The author was responsible for the planning and performing the study as well as analyzing the results and writing the article. The author planned and performed the electrochemical measurements and immersion tests, analyzed the results and carried out light optical microscopy, SEM and EDX.

All co-authors commented the manuscript. L-S Johansson was responsible of the XPS results and wrote the parts concerning the method and the results. M. Heinonen was responsible for of AES results, D. van Hoecke and N. Akdut of the GD-OES results. H. Hänninen was the project manager and the supervising professor.

Publication II. “Corrosion fatigue of spot-welded austenitic stainless steels in 3.5% NaCl solution”

The author was responsible for planning the study, the corrosion fatigue experiments and the test arrangement, including the cell and test specimen design, and using of the Taguchi Method® as well as analyzing the results and studying the specimens. The author wrote the first draft of the article and the co-authors commented it. M. Alenius produced the spot welds and helped with the results and figures. R. Karppi was responsible for the air fatigue tests performed at VTT and H. Hänninen was the project manager and the supervising professor.

Publication III: Corrosion fatigue of weld-bonded austenitic stainless steels in 3.5% NaCl solution”

The corrosion fatigue tests were planned and performed according to the test procedure developed by the author who was responsible for writing the article. The experimental results were analyzed and the test specimens inspected by the author.

All co-authors commented the manuscript. M. Alenius performed the joints and participated actively on the writing process. T. Kosonen was responsible of the air-fatigue tests of weld-bonded joints and R. Karppi of the air-fatigue tests of spot welds at VTT and commented the article. H. Hänninen was the project manager and the supervising professor.

Publication IV: "Mechanical and corrosion properties of spot-welded high-strength austenitic stainless steel EN 1.4318"

The corrosion fatigue measurements were planned together with the author and performed according to the test procedure developed by the author who also participated to analyzing the results and writing the article. The author was responsible for planning the corrosion research of the spot welds, performed the electrochemical measurements, studied the test specimens and analyzed the results of the measurements.

M. Alenius is the main author of the article and he was responsible of producing the welds and the mechanical testing of the spot welds. H. Hänninen was the project manager and the supervising professor and commented the article.

Publication V: "Exploring the mechanical properties of spot-welded dissimilar joints for stainless and galvanized steel"

The corrosion fatigue measurements were planned and performed using the testing procedure and the corrosion cell developed by the author.

M. Alenius is the main author of the article and he was responsible of producing the welds and the mechanical testing of the spot welds. All co-authors participated in writing the article. P. Pohjanne was responsible for the testing performed at VTT and H. Hänninen was the project manager and the supervising professor.

1 Introduction

This study was part of a larger research project, where austenitic stainless steels were studied for automotive applications [1]. In the automotive industry, design and materials selection are closely related and have to be done together. The demand for higher fuel economy with using lighter structures forces the automotive industry to search for new material solutions and joining techniques. By using corrosion-resistant materials, the manufacturing costs can be reduced by avoiding protective painting.

Austenitic stainless steels are used mainly because of their corrosion resistance. However, they also have excellent mechanical properties, formability and weldability, which makes them potential materials for passenger cars. Weight savings can be achieved by replacing the conventional carbon steels with thinner high-strength stainless steels. However, the excellent mechanical and fatigue properties of stainless steels are not usually retained in resistance spot-welded structures tested in the air [2, 3] or in a corrosive environment [3, 4]. There is, still at present, only a small amount of information available obtained in the field, even it is vital to understand the corrosion-fatigue behaviour and mechanisms of spot welds to maintain the high performance of the welded structure.

Resistance spot welding is a standard method of joining automotive parts, and it can also be used for stainless steel parts. Weld bonding is a hybrid-joining technique used for many different materials. In automotive applications, stainless steel may need to be joined with non-stainless steel, and therefore, corrosion fatigue testing of dissimilar metal joints was included in this investigation.

The main corrosive agents for the cars are de-icing salts and the marine atmosphere that can induce localized corrosion, e.g. pitting and crevice corrosion. In critical areas, for example, spot welds, the localized corrosion can dramatically affect the durability of the construction.

Stainless steels are used widely in different structures because of their excellent mechanical properties and corrosion resistance. However, steel structures usually have joints, and the durability of the joints is affected by environmental factors. Failure can usually be avoided by following the recommendations for fatigue design, but those do not apply to corrosive conditions. In a corrosive environment, local corrosion of stainless steel can be detrimental to the durability of the whole structure and, therefore, corrosion risks have to be taken into account during the design. The excellent mechanical and corrosion properties of the base material do not guarantee high performance in a structure containing spot welds or weld bonds in a corrosive environment.

Consequently, a better understanding of the corrosion fatigue properties of spot-welded and weld-bonded joints is needed. In this study, corrosion fatigue properties of spot welded and weld-bonded austenitic stainless steels have been studied widely to understand all phenomena related to the durability of structures containing spot welds and weld bonds. However, there is still very little information published on corrosion fatigue of spot-welded or weld-bonded stainless steels.

Localized corrosion in the crevice between the steel sheets at the heat-tinted areas of the spot weld was believed to affect the crack initiation in corrosion fatigue of spot welds primarily. The corrosion resistance of welded stainless steel structures can often be restored by removing the heat-tinted oxides on the surface by a post-weld pickling treatment. However, in spot welds, pickling of the surface may be possible, but removing the heat tints from the crevice is not feasible. The pickling acid cannot be removed from the crevice between the steels, and the residual acid causes severe corrosion damage.

The purpose of the corrosion experiments is to estimate the performance of the material or structure for a more extended period of use. Therefore the corrosion reactions are generally accelerated in some way, for example, by using higher temperature or a more corrosive environment. In fatigue experiments, higher loads than in the actual structure are used to accelerate the fracture and reduce the time needed for the tests.

This study aimed to enlarge the knowledge on corrosion fatigue performance of spot-welded joints in austenitic stainless steel and study the role of heat-tinted oxides on crack initiation in a corrosion fatigue failure. The effects of cold work and the role of adhesive on corrosion fatigue life of spot welds were clarified.

1.1 Corrosion fatigue of spot welds and weld-bonded joints

The fatigue strength of metals is known to be dependent on the surrounding environment. However, corrosion fatigue of resistance spot-welded stainless steels has been studied only in a few investigations [3, 4].

The role of adhesive on corrosion fatigue of weld-bonded joints has not been studied for stainless steels but for other metals, for example, high-strength steels [5, 6]. LeBozec et al. [7] used cyclic atmospheric tests to study the corrosion and mechanical performance of joined steels. They found that the strength loss of spot welds was connected to the corrosion of the overlap area of the joint.

In fatigue testing in the air, the testing frequency plays no significant role in fatigue performance. But in a corrosive environment, the testing frequency is an essential factor because the corrosion reactions are time-dependent. The load frequency in corrosion fatigue experiments is usually below 0.1 Hz and the experiments require very long time. However, in automotive applications the typical cyclic loads are higher, about 10 Hz [8]. Therefore a higher testing frequency used in this investigation is well-grounded.

Linder et al. [4] found that in 3 % NaCl solution fatigue strength of spot-welded stainless steels can be reduced by 30 - 40 % as compared to the fatigue strength of similar specimen tested in air. In air, the joints fatigue loaded with the same parameters as in the corrosive environment exhibited runouts without any cracks visible on metallographic studies. Consequently, the lower fatigue strength was attributed to enhanced crack initiation in the corrosive environment. They also found that pitting corrosion and environmental enhancement of the fast crack growth rate are possible mechanisms for the environmental influence on fatigue strength. On the other hand, pre-exposure of unloaded duplex stainless steel specimens did not cause a significant reduction in the fatigue strength compared to the non-pre-exposed specimens. This indicates that the pitting might not be the reason for the reduced fatigue strength in the corrosive environment. The fatigue strength of both the spot-welded austenitic and duplex stainless steel specimens was at the same level in the corrosive environment, although the corrosion resistance of the duplex stainless steel base material is better in that environment.

Vucko et al. [5] found that in general, the damaging effect of corrosion is increased by the simultaneous fatigue loading compared to pure corrosion tests, particularly with adhesive materials. They studied the interaction between corrosion and fatigue on spot-welded, weld-bonded and adhesive-bonded HSLA-steel specimens tested for automotive applications. They fatigued the lap shear joints in air and a corrosive environment using both altering and simultaneous exposure. The adhesive-jointed and weld-bonded specimens performed better than the spot-welded ones. However, the fatigue life of the spot-welded specimens exposed to altering corrosion and fatigue was close to that in the air. For samples exposed simultaneously to the corrosion environment and the cyclic loading, the fatigue life was decreased at high loads but increased at low loads. They assumed that corrosion products caused a local stress effect leading to a reduction of the local effective-stress amplitude. Those effects are strongly linked to the opening of the gap near the spot weld at high load amplitudes. At low amplitudes, corrosion might reduce the local stress at the notch root of the spot weld.

1.2 Factors affecting fatigue strength of spot welds

The sheet thickness, the weld size and the loading mode have been found to have a significant influence to the fatigue strength of spot-welded carbon steel [9,10]. Similar findings have been obtained for stainless steels [2, 3, 11]. In contrast, the steel strength level was found to have only a minor effect on the fatigue strength of the spot-welded carbon steel [9], but it can have a remarkable impact on spot-welded stainless steel joints [12].

In the investigation of Söderlund [12] a spot-welded specimen made of solution-annealed steel had a 25 % longer fatigue life than a similar specimen made of cold-stretched austenitic stainless steel. The sheet thickness was reduced in the cold stretching, which may have affected the fatigue life of the joint.

Linder et al. [2] found that the shear-loaded joints of stainless steel have higher fatigue strength than the peel-loaded of equal sheet thickness. They also found that the fatigue strength of spot-welded specimens decreases with decreasing sheet thickness. That is more accentuated for peel-loaded specimens compared to shear-loaded specimens. The influence of the sheet thickness is due to the bending resistance of the sheets, because bending may induce very high local stresses just outside the spot weld.

Triyono et al. [11] studied fatigue behaviour of resistance spot-welded austenitic stainless steels with unequal sheet thickness. They used the same welding parameters for the equal and unequal thick steels, i.e. the nugget was not the same in every joint. Although the nugget diameter was smaller for the unequal thickness steel joints than for the specimens of equal thickness steels, the fatigue strength was higher. The failure mode was plug failure of the thinner sheet. They concluded that the joint stiffness is the controlling factor of the fatigue strength of resistance spot-welded unequal sheet thickness austenitic stainless steel.

Linder et al. [2] fatigued spot-welded specimens with different geometry and found that the fatigue strength of the shear-loaded specimens was higher than that of the peel-loaded joints. Also, peeling forces, combined with shear stress, reduced the fatigue strength of the spot weld. In the air the fracture paths of the peel-loaded and shear-loaded spot-welded stainless steel specimens are different. The fatigue strength of the peel-loaded samples is inferior to that of the shear-loaded samples. In the shear-loaded samples, the fatigue crack initiation occurs at the weld edge between the sheets at a certain angle (about 70-80°) to the load direction. After crack initiation, the fatigue crack propagation occurs in the base material through the sheet thickness at some distance away from the HAZ.

Melander et al. [6] studied the effect of the arctic, room temperature and tropical environments to the weld-bonded high-strength steels. The fatigue strengths of the peel-loaded weld-bonded specimens were 2 - 3 times higher than those of the spot-welded specimens.

Long et al. [13] studied the relationship between microstructure, residual stress and fatigue behaviour of carbon steel. Post heating of the spot weld decreased the strength of the spot-welded joint by releasing the residual stresses and reduced the fatigue life of the specimen.

1.3 Weld bonding

Weld bonding is a hybrid method where conventional resistance spot welding is used together with an adhesive. It is credited by combining the advantages of spot welding and adhesive bonding and largely eliminating their respective disadvantages. Spot-welded joints can exhibit low fatigue strength and crevice corrosion between the sheets. On the other hand, limited thermal resistance, sensitivity to peeling forces and ageing behaviour are disadvantages of adhesive-bonded joints [14]. The long-term durability of the adhesive-bonded joints remains unpredictable, which limits the use of adhesive bonding in the structures. Advantages of weld bonding include good appearance, high static strength, improved fatigue strength, improved corrosion resistance, good acoustic properties and a large area of force transfer.

Weld bonding is a relatively new method for joining stainless steels. The fatigue resistance of weld-bonded stainless steel lap joints has been studied only in a few investigations [15, 16, 17]. However, more studies can be found on the weld-bonding of carbon steel [14, 15, 18, 19, 20, 21, 22].

In air, the fatigue strength of weld-bonded joints is higher than that of the comparable spot-welded joints [15, 17, 19, 20, 21]. Holubka et al. [22] found that the failure of the adhesive joint was accelerated when the joint was exposed to the corrosive environment during the cyclic fatigue loading. The fatigue properties of a simple overlap adhesive joint reduced by three to four orders of magnitude when the joint was pre-exposed to a corrosive environment before fatigue testing. In the corrosive environment, swelling of the adhesive by water and corrosion products caused degradation of the properties of the adhesive and led to failure.

Corrosive environment reduces the fatigue resistance of spot-welded stainless steels [4]. However, the influence of a corrosive environment on the fatigue strength of weld-bonded stainless steels has not been studied thus far.

Ghosh et al. [15] compared the fatigue properties of weld-bonded and spot-welded samples. They used the same welding parameters for both so that the weld nugget of the weld-bonded specimens was smaller than that of the spot-welded specimens. Their fatigue results show that the optimum load-carrying capacity of the weld bond is significantly higher than that of the conventional spot weld. Using ground surfaces may influence on the performance of the adhesive because the adhesion of the adhesive can be improved by using surface preparation instead of as-received samples [17].

Kang et al. [23] developed a structural stress method where structural stress-based S-N curve was developed and applied to predict the fatigue life of joints containing adhesive.

1.4 Stress distributions of the joints

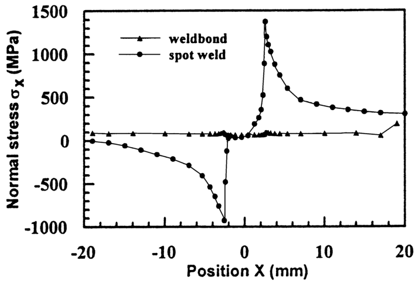
The stress distributions at the spot-welded and weld-bonded joints have been modelled in several investigations [14, 17, 18, 21, 22, 24, 25, 26].

Al-Bahkali et al. [24] studied elastic-plastic stress distributions in weld-bonded lap joints under axial loading. They made 3D FE models for spot-welded, weld-bonded and adhesive-bonded joints. There was a good agreement between the FE models and experimental results as well as data found in the literature. The weld-bonded joints showed the highest load-carrying capacity with the best performance and uniform stress distributions without stress concentration peaks.

Khanna et al. [27] studied residual stresses in spot welds of carbon steel and fatigued spot welds for a relatively small number of cycles (1000 – 10 000 cycles). The residual stresses at the weld centre dropped by about 30 % but increased at the edges by as much as 100 %.

Al-Samhan et al. [25] and Chang et al. [21] investigated the structures and hardness distributions in the weld-bonded lap joints and established computational models for single-spot weld-bonded lap joints. The stress distributions in spot-welded, weld-bonded and adhesive-bonded joints were computed using the model. The stress distributions of spot welds and weld-bonded joints determined by Chang et al. [21] are presented in Fig. 1. A spot-welded sample has high normal stress and shear stress at the periphery of the weld spot. In the weld-bonded sample, the stresses are reduced at the periphery of the weld spot, and small stresses are present at the edge of the lap region. In the adhesive-bonded joints, stresses are distributed uniformly, but small stress concentration is found at the edge of the lap region. That means that adding adhesive to the spot-welding process reduces high stresses in the weld spot and decreases the stress concentration. The results of the numerical analyses are in accordance with the experimental data. In fatigue tests, the weld-bonded specimens performed significantly better than the spot-welded specimens, but they were only slightly inferior to the adhesive-bonded specimens. Application of an adhesive improves the fatigue performance of the spot-welded joints but the presence of a weld spot in an adhesive bond has adverse effects on the fatigue performance of the joint.

Al-Samhan et al. [25] found that the primary principal stress developed in the spot-welded joint is nearly five to six times as high as the principal stress associated with the weld-bonded joints.



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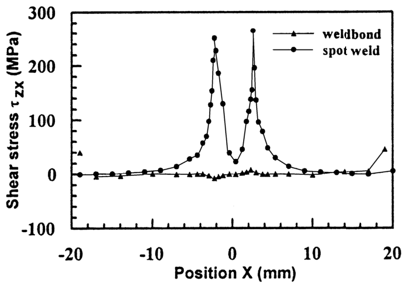


(b)

Figure. 1. Stresses in spot-welded and weld-bonded joints. The nugget diameter is 5 mm, and the overlap is 40 mm. (a) Normal stress. The stress peaks of the spot-welded sample are located just outside of the weld nugget at X = ± 2.5 mm. The tensile stress concentration of the spot weld on the right is located at the loaded end of the sample and the compressive normal stress at the free end of the sample. For the weld-bonded specimen, the distribution of σ_x is almost uniform, and no stress concentration exists in the weld-bonded area. The maximum value of σ_x is located at the right edge of the lap region. (b) Shear stress. Shear stresses are concentrated at the right and left edges of the spot weld. The stress distribution in the lap region of the weld-bonded sample is approximately uniform but increases near to the two edges of the lap region. [21]

1.5 Corrosion fatigue of dissimilar metal joints

There are several investigations made on mechanical properties of the spot-welded dissimilar metal joints between stainless steel and carbon steel [28, 29] but only some results on fatigue in the air [30] or in a corrosive environment [31].

Jamasri et al. [31] studied corrosion fatigue of resistance spot-welded specimens between carbon steel and austenitic stainless steel. In natural seawater, the fatigue strength of the joints was lower than in the air. The carbon steel was 3.0 mm and the stainless steel 1.0 mm thick. Both in air and corrosive environment, the failure was a pull-out fracture of the thinner sheet - the fatigue crack initiated as nugget cracks due to excessive sheet separation. After initiation, the crack propagation occurred through the thickness of the thinner sheet in the heat-affected zone. They attributed the weakening of the corrosion fatigue strength to the hydrogen-enhanced plasticity mechanism that tends to ease the generation and mobility of dislocations. Triyono et al. [32] found that the fatigue strength of plug-welded dissimilar steel joints reduced to a half in a corrosive environment.

Vural et al. [30] found that in fatigue testing of spot-welded dissimilar metal joints in air, the fatigue life increases when the load range decreases. The fatigue limit of dissimilar metal joints between carbon steel and stainless steel was lower than the fatigue limit of the spot welds of the similar steel joints. However, the measured crack growth rate of spot-welded galvanized steel to stainless steel was slower than that for the base materials found in the literature.

1.6 Pitting corrosion of heat-tinted areas

The corrosion properties of stainless steels depend on the passive oxide film forming on the steel surface. The corrosion resistance of an oxide film formed on a clean surface in the air is excellent. In spot welding of stainless steel, coloured heat-tint oxides are formed around the spot weld both on the outside surface and in the crevice. The corrosion resistance of these heat-tint oxide layers is known to be reduced compared to that of the base material [33, 34, 35, 36, 37, 38, 39, 40]. Factors affecting the pitting susceptibility of the steel are thickness, composition and structure of the oxide film and the amount of chromium depletion under the film.

Heat-tint oxide layers on spot-welded and induction-heated samples and their pitting corrosion have been studied in Publ. I. The results concur with the results in the literature. Because spot welding is affecting the corrosion resistance of the structure, spot welds of austenitic stainless steels have been studied further.

Martín et al. [41] have studied the effect of welding parameters on pitting corrosion behaviour of spot-welded austenitic stainless steels. De Tiedra et al. [42] used electrochemical potentiokinetic reactivation tests to study the degree of sensitization in resistance spot welded joints of austenitic stainless steel.

Hafez [43] has studied the effect of the shielding gas and the heat input during welding on pitting corrosion of spot welds of AISI 304L steel. He concluded that the spot-welded nuggets with high heat input have a lower pitting corrosion resistance than that of other nuggets in 3.5% NaCl solution.

2 Experimental procedures

A corrosion fatigue test arrangement designed especially for this study was used because there is no standardised method for corrosion fatigue testing of spot welds. The corrosion cell was designed to be around the test specimen situated in the loading machine. The test arrangement was kept as simple as possible, and therefore only single spot welds were used in the specimens.

2.1 Test materials and joints

The studied materials were austenitic stainless steels EN 1.4301 and EN 1.4318. For dissimilar metal joints also galvanized carbon steel was used. Both stainless steels were tested in 2B/2F and 2H/C850 conditions. The 2B is cold rolled, soft annealed, pickled, and skin pass rolled. The 2F is cold-rolled, soft annealed, pickled and skin pass rolled on roughened rolls. 2H is hard cold rolled and the cold-rolling reduction of the EN 1.4318 2H/C850 steels was 5 %. The steel EN 1.4318 was also tested in cold-rolled, high-strength condition (2H/C1150).

The thicknesses of the austenitic stainless steels were 1.0 mm, 1.9 mm and 1.2 mm. The thicknesses of the galvanized carbon steel used was 1.50 mm. The chemical compositions of all investigated steels are presented in Table 1, and the mechanical properties of the test materials provided by the manufacturers are presented in Table 2. More information about the mechanical properties of the high-strength steel EN 1.4318 2H/C1150 can be found in Publication IV.

2.1.1 Spot welds and weld bonds

In all experiments, single-spot lap-jointed samples were used. The welds were made by a spot-welding machine MDFDC (1000 Hz) (I_{2CC} = 27 000 A, 50 % kVA = 90 kVA). The electrodes were CuNi2Be type and the diameter was 6 mm. The spot-welding parameters were defined so that the desired nugget size was achieved. For electrochemical measurements and corrosion fatigue tests, the required minimum nugget size in millimetres was defined by $4\sqrt{t}$ or $5\sqrt{t}$, where t is the thickness of the sheet. For high-strength steel, the welding parameters were selected so that the 5√t nugget size was obtained, but no expulsion occurred.

Table 1. The chemical compositions of the test materials, wt-%, as reported by the manufacturer. (Combined from Publications I-V)

Steel	C	Cr	Cu	Mn	Mo	N	Ni	P	S	Si
EN 1.4301 2B 1.00 mm	0.041	18.2	0.37	1.71	0.32	0.054	8.1	0.031	0.002	0.33
EN 1.4301 2H 1.00 mm	0.052	18.1	0.43	1.77	0.34	0.059	8.1	0.029	0.001	0.33
EN 1.4301 2F 1.95 mm	0.046	18.1	0.23	1.73	0.24	0.050	8.1	0.031	0.002	0.38
EN 1.4301 2H 1.95 mm	0.048	18.0	0.35	1.78	0.35	0.046	8.1	0.031	0.003	0.37
EN 1.4318 2B 1.00 mm	0.019	17.6	0.22	1.61	0.14	0.094	6.6	0.028	0.002	0.48
EN 1.4318 2H/C850 1.00 mm	0.019	17.6	0.22	1.61	0.14	0.094	6.6	0.028	0.002	0.48
EN 1.4318 2B 1.92 mm	0.024	17.5	0.28	1.23	0.17	0.106	6.4	0.027	0.001	0.52
EN 1.4318 2H/C850 1.92 mm	0.024	17.5	0.28	1.23	0.17	0.106	6.4	0.027	0.001	0.52
EN 1.4318 2H/C1150 1.20 mm	0.022	17.6	0.14	1.22	-	0.131	6.4	0.023	0.002	0.59
DX54DZ 1.50 mm	0.0023	-	-	0.16	-	-	0.02	0.01	0.004	0.004

Table 2. Mechanical properties of test materials as reported by the manufacturer. (Combined from Publications I-V)

Steel	Thickness (mm)	$R_{p0.2}$ (MPa)	R_m (MPa)	A_{80} (%)
EN 1.4301 2B	1.00	330	730	64
EN 1.4301 2H	1.00	510	765	51
EN 1.4301 2F	1.95	315	705	63
EN 1.4301 2H	1.95	435	735	58
EN 1.4318 2B	1.00	310	885	46
EN 1.4318 2H/C850	1.00	495	945	36
EN 1.4318 2B	1.92	360	920	42
EN 1.4318 2H/C850	1.92	500	1010	32
EN 1.4318 2H/C1150	1.20	850	1200	20
DX54DZ	1.50	165	294	47

The welding parameters for stainless steel spot welds used in the electrochemical measurements, corrosion experiments and corrosion fatigue tests are presented in Table 3. Because a bigger nugget size means more heat-tinted oxides and less resistance to localized corrosion, 5√t was used in most of the corrosion fatigue experiments.

For analysing the compositions and structures of the coloured oxide layers, larger areas of oxides of a specific colour were needed. The welding parameters for those samples are presented in Publication I. However, some surface analysis methods demand a larger uniform area than could be produced by spot welding. Larger areas of heat-tinted oxides were produced by induction heating. For induction heated samples, a separate 20 x 50 mm sheet was used.

Table 3. Welding parameters for stainless steel spot welds. t is the thickness of the steel. (Combined from Publications I-V)

Steel	Sheet thickness	Nugget size	Nugget diameter	Welding time (ms)	Welding current (kA)	Electrode force (kN)
EN 1.4301 2B	1.0 mm	4√t	4.0 mm	120	6.5	3.8
EN 1.4301 2B	1.0 mm	5√t	5.0 mm	160	7.3	3.8
EN 1.4301 2B	1.95 mm	5√t	7.0 mm	240	10.6	8.2
EN 1.4301 2H	1.0 mm	5√t	5.0 mm	160	6.7	3.8
EN 1.4301 2H	1.95 mm	5√t	7.0 mm	240	9.8	8.2
EN 1.4318 2B	1.0 mm	4√t	4.0 mm	120	6.5	3.8
EN 1.4318 2B	1.0 mm	5√t	5.0 mm	160	7.0	3.8
EN 1.4318 2F	1.92 mm	5√t	6.9 mm	240	10.5	8.2
EN 1.4318 2H /C850	1.0 mm	5√t	5.0 mm	160	6.7	3.8
EN 1.4318 2H /C850	1.92 mm	5√t	6.9 mm	240	9.5 / 9.1*	8.2 / 8.5.*
EN 1.4318 2H /C1150	1.2 mm	5√t	5.5 mm	160	7.1	7.2

* Publ. IV, in tests for comparison to high-strength steel.

The weld-bonded test specimens were similar to the spot-welded specimen. The adhesive was added to the overlapping area before welding. The welding parameters for the weld-bonded specimens are presented in Table 4. The adhesive used in weld bonding was BETAMITE™ 1496V which is a one-component, heat-curing, epoxy-based adhesive, specially developed for the car body shops. According to the manufacturer, it has good rheology performance, excellent adhesion to automotive steels, resistance to degradation and substrate corrosion on environmental ageing. It can be readily pumped at elevated temperatures and is compatible with the electrocoat paint process in an uncured state. [44]

The welding parameters for dissimilar metal joints are presented in Table 5. The nugget size 5√t was determined using the thickness of the thinner sheet.

Table 4. Welding parameters for the weld-bonded specimens. [Publ. III]

Steel	Sheet thickness	Welding time (ms)	Welding current (kA)	Electrode force (kN)
EN 1.4301 2B	1.9 mm	240	9.6	9
EN 1.4301 2H	1.9 mm	240	8.8	9
EN 1.4318 2F	1.9 mm	240	9.1	9
EN 1.4318 2H	1.9 mm	240	8.5	9

Table 5. Welding parameters for the dissimilar joints. [Publ. V]

Steels, sheet thickness (mm)	Welding time (ms)	Welding current (kA)	Electrode force (kN)
EN 1.43018 2H (1.00) – DX54DZ (1.5)	160	8.5	3.8
DX54DZ (1.5) – DX54DZ (1.5)	240	14.0	5.0

2.2 Corrosive environments

The corrosive environments for this investigation were salt solutions because the primary corrosion risks for automotive parts are marine atmosphere and the de-icing salts. The electrochemical measurements and most of the corrosion fatigue tests were performed in 3.5 % (0.6 mol Cl/l) sodium chloride (NaCl) solution, i.e. in seawater. To study the effect of the type of chloride, in some corrosion fatigue experiments, 3.3 % (0.6 mol Cl/l) calcium chloride ($CaCl_2$) was used.

All electrochemical measurements and some of the corrosion fatigue tests were performed at ambient temperature (20 °C), but most of the corrosion fatigue tests were performed at 50 °C. All fatigue tests in the air were performed at 20 °C. The stress-corrosion cracking test was performed in boiling magnesium chloride ($MgCl_2$) solution at 156 °C.

In all electrochemical measurements and corrosion tests, the specimens were tested in as-welded condition without pickling or degreasing treatment. That is consistent with the situation for real automotive parts in use.

2.3 Corrosion-fatigue testing

In corrosion-fatigue and fatigue experiments, the shape of the joined test specimen was chosen to be similar to the specimen used for base materials testing in the project. The test specimen consisted of two specimen halves joined together with one spot weld in the centre of the overlapping area. A schematic picture of the test specimen is in Figure 2. The minimum nugget diameter of the spot weld was $5\sqrt{t}$, where t is the thickness of the steel sheet. The spot-welded and weld-bonded specimens were tested in as-welded condition without any pickling or degreasing treatment.

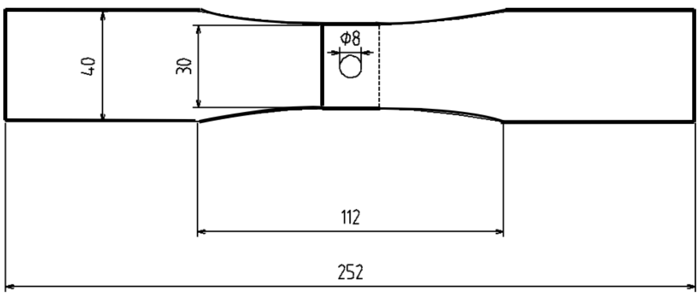


Figure 2. A schematic picture of the fatigue test specimen.

The corrosion cell used in the corrosion fatigue experiments is shown in Figure 3. The cell was located around the test specimen so that the whole experimental part of the specimen was exposed to the electrolyte solution. The immersion test standard ASTM G31-72 [45] defines that amount of solution in an immersion test has to be at least 20 ml/cm^2 to the surface area of the specimen to avoid changes in the corrosivity of the solution during the test. According to that, a total volume of the electrolyte 2 l was chosen. However, the volume of the glass cell was less than that, and therefore, solution circulation was arranged. The solution flew in from the bottom and out from the upper part of the cell. A closed circulation system was used to ensure that the chloride concentration of the solution did not change during the experiment due to the evaporation of water.

The corrosion fatigue testing was executed using a servo-hydraulic testing equipment MTS 810 at Aalto University. During the experiments the load and the specimen stiffness were monitored. Three or four specimens were tested at one load level. The wave form was sinusoidal and the R-value was 0.1. The failure criterion was chosen to be 0.5 mm displacement at the maximum load. The test specimens were lap-shear loaded, but because of bending of the specimen and rotation of the joint, the real loading mode of the spot-welded joint was a mixed shear/peel mode.

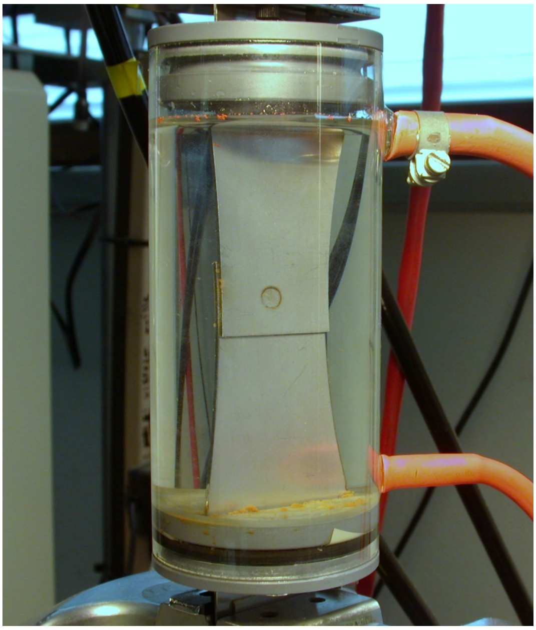


Figure 3. The corrosion cell used in the corrosion-fatigue tests.

To limit the total testing time, most of the corrosion fatigue experiments were performed using a frequency of 15 Hz and a temperature of 50 °C. The 1.9 mm steels were chosen for testing because the heat input in welding is higher and therefore more heat-tinted oxides were formed on the spot weld and around the weld nugget in the crevice.

The fatigue testing in air, used as a reference, was performed at ambient atmosphere. Most of these tests were performed at VTT by two pulsator type machines, Rumul Testronic 8601/40 and Amsler 10 HFP 422. The frequency was 110 Hz and the R-value 0.1, and the failure criterion in these experiments was that the specimen would break off during a few more fatigue cycles. A rapid drop in fatigue frequency during pulsator-type fatigue tests indicates a shortly forthcoming failure of the specimen. To be able to compare the fatigue test results obtained by different methods using different failure criteria, the 2H grade steel specimens were fatigue tested in the air also by using the servo-hydraulic machine at Aalto University. The test arrangement is described in more detail in Publication II.

To compare the fatigue results of steels of different thicknesses, the fatigue results were treated by line-load range analysis presented by Nordberg [46]. In the method, the 'line load' means that the test loads are divided by the width of the joint. Dividing the line load with the thickness of the sheet gives the net-section stress that allows comparing joints of different sheet thickness. The method is described in more detail in Publication IV.

2.3.1 Relative effect of frequency, load, temperature and steel grade

Corrosion reactions demand time, but performing fatigue experiments using a low frequency limit the number of experiments which can be performed by one machine and in a given time. To determine the relative importance of some parameters, i.e. the frequency, the steel grade, temperature, the maximum load and the type of chloride on corrosion-fatigue strength of the spot-welded specimens, the Taguchi Method® [47] was used for 1.0 mm thick stainless steel specimen. Four 1.0 mm steels were tested using two frequencies, two loads, two temperatures and two types of chlorides using the Taguchi array L8 (2-4-4-1) matrix presented in Table 6.

The Taguchi Method® reduces the number of required experiments. Not all combinations will be tested, but the effect of each factor can be calculated from the tests performed according to the chosen matrix. Altering one parameter at the time testing four types of steels with two loads at two frequencies and two temperatures and with two types of chlorides require 64 (4x2x2x2x2) experiments, but by Taguchi Method®, the number of experiments can be reduced to eight (8).

Table 6. The Taguchi L8 (2-4-4-1) matrix used for corrosion-fatigue testing of spot-welded 1.0 mm thick steel specimen.

Test No	Steel grade	Maximum load (kN)	Solution 3.5%	Frequency (Hz)	Temperature (°C)
1	EN 1.4318 2B	1.2	NaCl	15	20
2	EN 1.4318 2B	2.0	$CaCl_2$	0.2	50
3	EN 1.4318 2H	1.2	NaCl	0.2	50
4	EN 1.4318 2H	2.0	$CaCl_2$	15	20
5	EN 1.4301 2B	1.2	$CaCl_2$	15	50
6	EN 1.4301 2B	2.0	NaCl	0.2	20
7	EN 1.4301 2H	1.2	$CaCl_2$	0.2	20
8	EN 1.4301 2H	2.0	NaCl	15	50

2.4 Characterization of the spot welds and the heat-tinted areas

Different surface analysis methods were used to characterize the spot welds and the heat-tinted oxides. The methods are described more detailed in Publication I.

Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDX) were used to study the microstructures of the welds and base materials, local corrosion on the spot welds and around the weld nugget in the crevice, as well as the fracture surfaces and crack initiation sites.

The Glow Discharge Optical Emission Spectroscopy (GD-OES) was used to measure the element distribution as a function of the depth for the base material and a yellow heat-tinted sample of EN 1.4301 2B (1.0 mm) steel.

Residual stresses on and around the spot welds ($5\sqrt{t}$) were measured with an X-ray diffraction stress analyser. The stresses were measured both in the rolling and in the transverse direction from the centre of the spot weld and the heat-tinted area. The diameter of the X-ray beam was 1 mm.

The residual stress distribution at the spot weld area was estimated by Finite Element Analysis (FEA), and the results were compared with the measured values. The residual stresses were modelled with a two-dimensional, linear-elastic model, assuming constant residual stress in the nugget area equal to the yield strength of the material.

2.5 Immersion tests

To investigate the formation of crevice corrosion in the crevice around the spot weld of stainless steel samples, immersion tests were performed. The test solution was 3.5 % NaCl solution and the volume of the solution was 20 ml/cm^2. The immersion times varied from one week to three months.

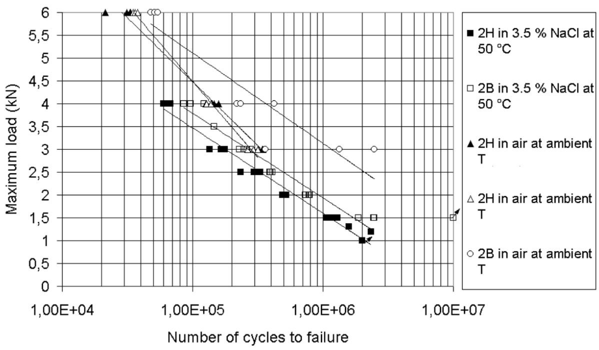
2.6 Stress-corrosion cracking testing

A stress-corrosion cracking test was performed to indicate the directions of the main residual stresses at the spot-weld area and to find out if the stresses are high enough to cause cracking in the absence of external load. The test arrangement was similar to the standard boiling magnesium chloride test ASTM Standard G36-94 [48] and it is described in Publication I.

3 Results

3.1 Corrosion-fatigue testing

The corrosion-fatigue and air-fatigue test results of the spot-welded 1.9 mm thick EN 1.4301 and EN 1.4318 steel specimens are presented in Figures 4a and 4b. Both in air and the corrosive environment, the annealed 2B or 2F grade specimens exhibit better fatigue strength than the 2H grades. Some spot-welded specimens of EN 1.4318 steel were pre-exposed for 50-175 h before the test to 3.5 % NaCl solution at 50 °C. The pre-exposure does not seem to reduce the fatigue strength of the spot-welded sample.



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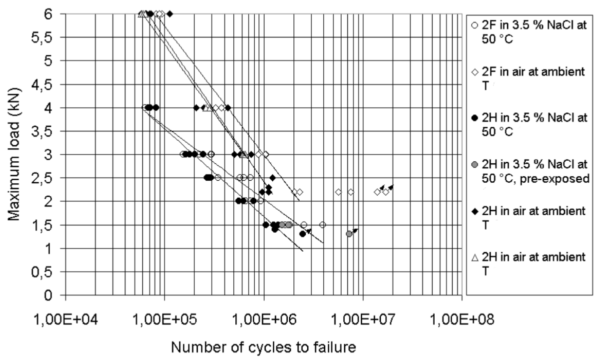

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Figure 4. Corrosion-fatigue and air-fatigue test results of 1.9 mm thick spot-welded steel specimens in the air at ambient temperature and in 3.5 % sodium chloride (NaCl) solution at 50 °C. a) EN 1.4301 and b) 1.4318. The pre-exposed specimens were subjected to the 3.5 % NaCl solution at 50 °C for 50-175 h prior to the test. [Publ. II]

3.1.1 Effect of cold working

The fatigue results of cold-worked 2H steels (1.9 mm) in air and in 3.5 % sodium chloride solution are presented in Fig. 5. In the air, the spot-welded EN 1.4318 2H steel had higher fatigue strength than EN 1.4301 2H steel, but in the corrosive environment, the fatigue strengths of the steels were equal. The air-fatigue results measured by different machines using different frequencies and failure criteria are in good accordance with each other.

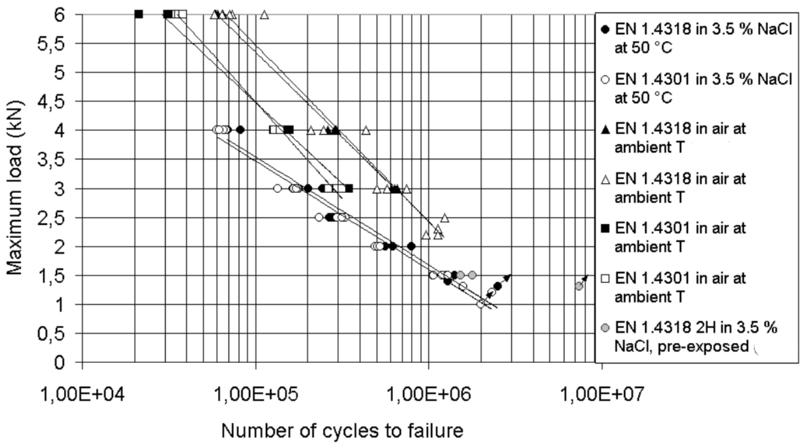
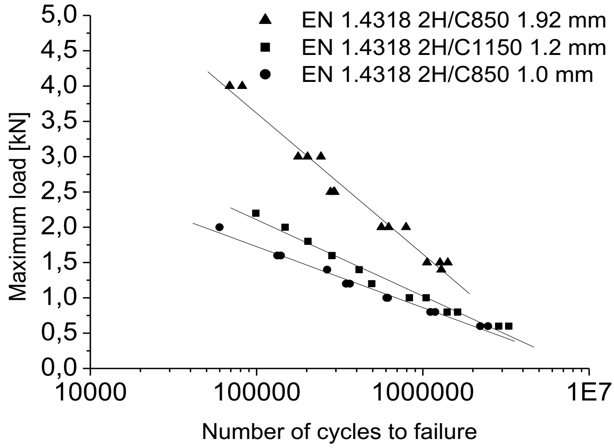


Figure 5. Comparison of corrosion-fatigue and air-fatigue test results of 1.9 mm thick spot-welded 2H steels. The pre-exposed specimens were subjected to the 3.5 % NaCl solution at 50 °C for 50-175 h prior to the test. [Publ. II]

Since high-strength steels are interesting for many applications, also a high-strength EN 1.4318 2H/C1150 steel was tested and the results were compared with those of the EN 1.4318 2H/C850 steels. The corrosion-fatigue test results of the spot-welded joints of the EN 1.4318 2H steels are presented in Fig. 6a. It can be seen that the spot-welded stainless steel EN 1.4318 2H/C850, t = 1.92 mm, exhibited better fatigue endurance than the high-strength stainless steels. The difference became smaller at lower loads. In Figure 6b, the same results are presented after the line-load range analysis, where the test load is divided by the width of the joint and the effect of sheet thickness is eliminated. However, there are no significant differences between stainless steels of different strength levels after line-load range analysis, but steel EN 1.4318 2H/850, t = 1.92 mm, exhibited slightly better fatigue resistance than the other steels.



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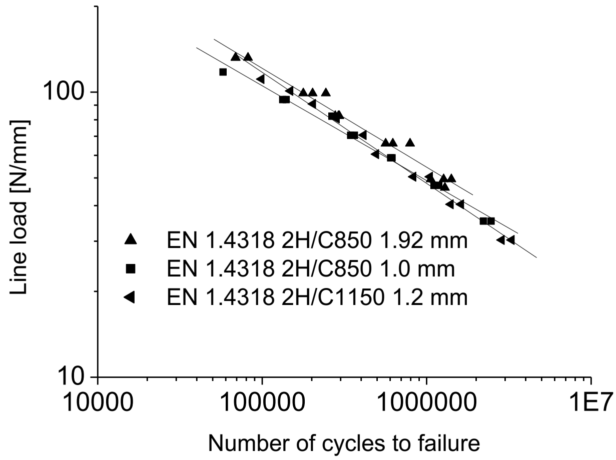

b)

Figure 6. a) Corrosion-fatigue test results of spot-welded high-strength stainless steel joints in 3.5 % NaCl solution at 50 °C and b) line-load range analysis of the data. [Publ. IV]

3.1.2 Effect of the adhesive

The corrosion-fatigue and air-fatigue test results of the weld-bonded EN 1.4301 and EN 1.4318 steel specimens are presented in Fig. 7. As expected, the fatigue strength of both steels is higher in the air than in the corrosive environment. The 2B and 2H grades of EN 1.4301 steel performed equally, and the effect of work hardening by cold rolling is negligible. In the case of EN 1.4318 steel, the 2H grade specimens exhibit, however, significantly lower fatigue strength than the 2F grade specimens. That applies both to fatigue in air and the corrosive environment.

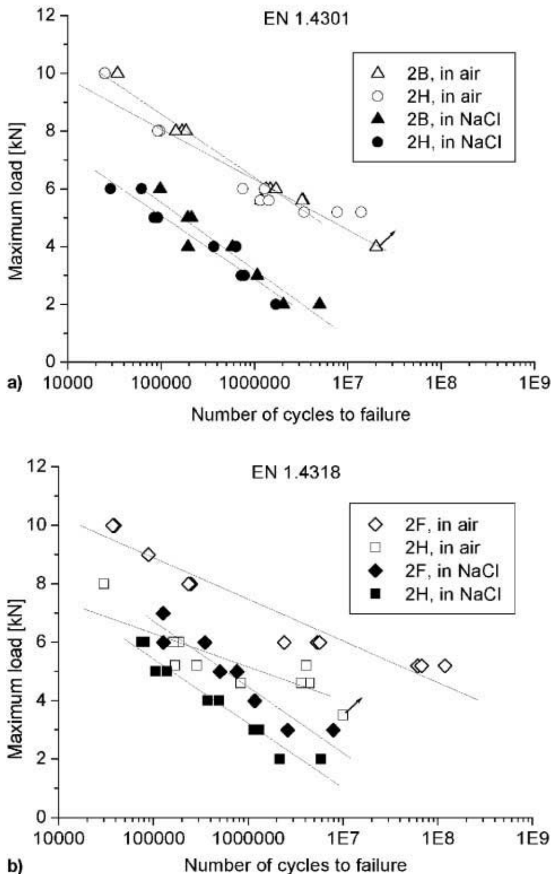

Figure 7. Corrosion-fatigue and air-fatigue test results of weld-bonded a) EN 1.4301 steel and b) EN 1.4318 steel specimens in the air at ambient temperature and in 3.5 % NaCl solution at 50 °C. [Publ. III]

In Fig. 8, the results of the weld-bonded specimens are compared to the results of spot-welded steel specimens. In the air the fatigue strengths of the weld-bonded specimens of EN 1.4301 2B and 2H steels, as well as EN 1.4318 2F steel, are superior to the fatigue strength of the spot-welded specimens. In the case of EN 1.4318 2H steel, the difference is not large at maximum load of 6 kN, but becomes evident at lower loads. However, in 3.5% NaCl solution, the difference between the weld-bonded and spot-welded samples is reduced compared to the difference in the air. The slopes of the corrosion fatigue data curves are almost equal in all cases.

As assumed, the fatigue strengths of the weld bonds of both steel grades are higher in the air than in the corrosive environment. The fatigue strength of the weld-bonded specimens in the corrosive environment was also higher than that of the spot-welded specimens of the same steels.

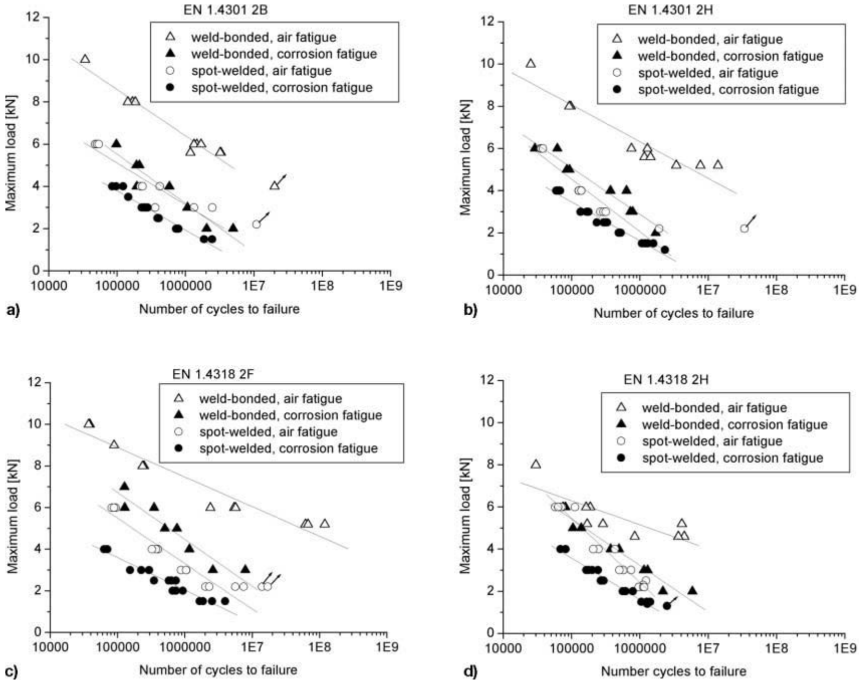

Figure 8. Comparison of the corrosion-fatigue and air fatigue test results of weld-bonded and spot-welded specimens of a) EN 1.4301 2B steel, b) EN 1.4301 2H steel, c) EN 1.4318 2F steel and d) EN 1.4318 2H steel. [Publ. III]

3.1.3 Dissimilar metal joints

The corrosion fatigue results of dissimilar metal joints are presented in Fig. 9. In joining stainless steel to galvanized steel by spot welding, the strength level of the base material seems not to affect the fatigue strength of the spot-welded joint, but the sheet thickness has a significant effect. The fatigue strength of a spot-welded joint increased with the increasing sheet thickness. Also, a bigger nugget size improves the corrosion-fatigue strength. Especially at low loads, dissimilar metal and non-stainless steel joints exhibited higher fatigue strength than 1.0 mm thick stainless steel joints. The fatigue strength of the dissimilar metal joints was found to be between the fatigue strength of the non-stainless and the stainless steel.

In a wet, corrosive environment, the dissimilar metal joints are susceptible to hydrogen embrittlement, but the austenitic stainless steel welds are resistant to it because there is no galvanic contact to zinc.

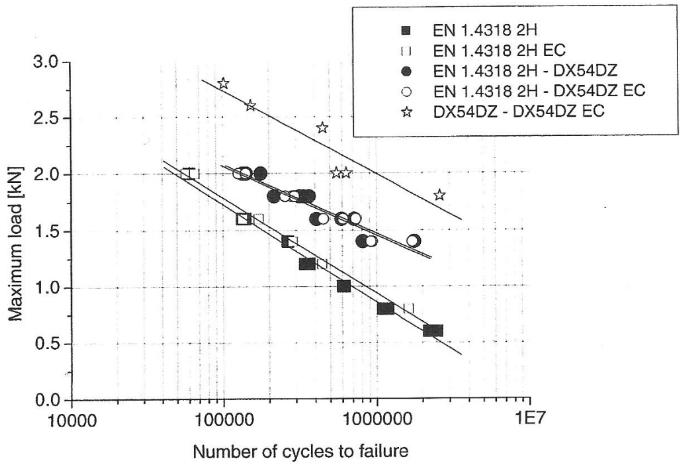

Figure 9. Comparison of the corrosion-fatigue test results of the spot-welded stainless steel, dissimilar metal and non-stainless steel joints. [Publ. V]

3.1.4 Relative effect of different factors on fatigue strength

The results of the test designed by the Taguchi method® using a Taguchi L8 (2-4-4-1) matrix are presented in Fig. 10. They show that increasing the load from 1.2 kN to 2 kN has the strongest effect on the spot-welded steel specimen. Also, the steel grade and surface finish may play a role. The rise of temperature from 20°C to 50°C seems to have less effect than lowering the frequency from 15 Hz to 0.2 Hz. The calcium chloride appears to be only slightly more aggressive than the sodium chloride solution containing the same amount of chloride ions.

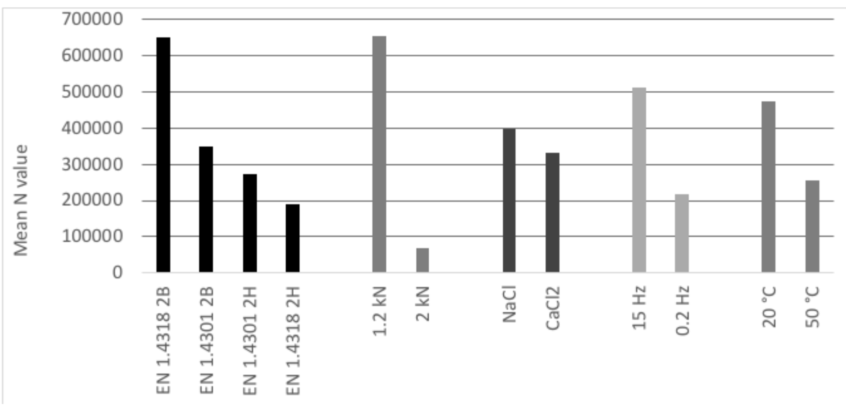

Figure 10. The mean N values of the corrosion-fatigue test results of different steels, loads, chlorides, frequencies and temperatures based on the Taguchi L8 (2-4-4-1) matrix presented in Table 5. [Publ. II]

3.1.5 Crack initiation

In the spot-welded specimens, the corrosion-fatigue cracks initiated from several locations in the crevice around the spot weld. The fracture surface of the spot-welded 1.0 mm steel specimen fatigued at the load level of 2 kN in 3.5 % NaCl solution is presented in Figure 11. The fracture surface is typical for the fatigue of a spot-welded specimen. The fracture surface in the air is presented in Publication II.

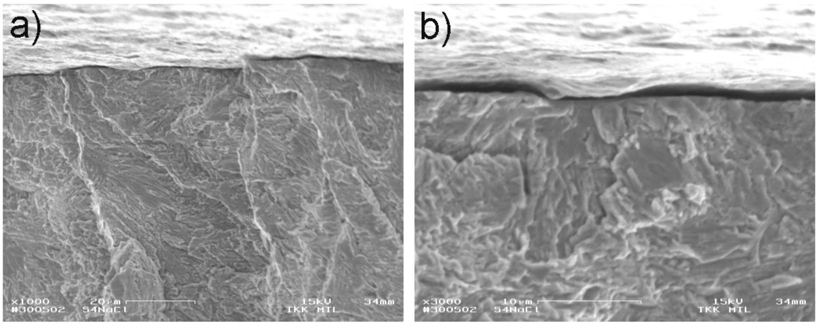

Figure 11. SEM images of the fatigue fracture surface of a spot-welded specimen of EN 1.4301 2B steel (1.0 mm) tested in 3.5 % NaCl at ambient temperature at the load level 2 kN. a) 1000x, b) 3000x. [Publ. II]

Cross-sections of typical fatigue failures of spot-welded and weld-bonded specimens of EN 1.4301 2H steel are presented in Fig. 12. The weld nugget can be recognized as a darker area on the left side of the picture. Outside the nugget, there is the heat-affected zone (HAZ). At the tip of the notch, there is a small recrystallized area with slightly finer grain size and higher hardness than those of the base materials. Hardness measurements are presented in Publication IV. Both in the air and the 3.5 % NaCl solution, the fatigue cracks of stainless steel have initiated at the notch between the sheets just outside the edge of the corona bond of the spot weld. At the corona bond area, the steels are bonded but not melted during welding. More cross-sections are presented in Publication II.

In dissimilar metal spot-welded joints, the fatigue cracks initiated at the tip of the corona bond of both non-stainless steel and stainless steel. After initiation, the crack propagation occurred through the thickness of the sheets in the heat-affected zone.

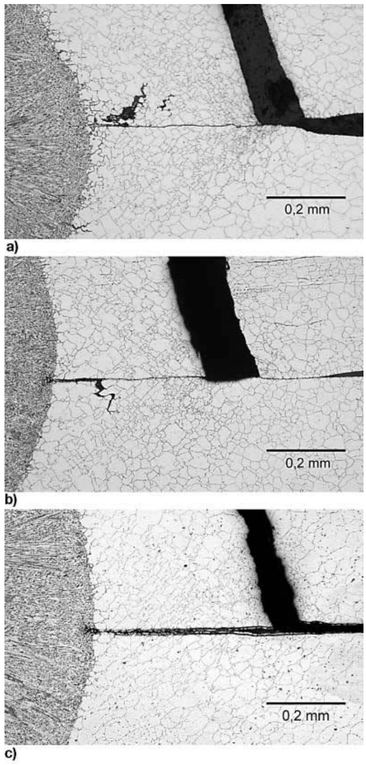

Figure 12. Cross-sections of the a) air-fatigue and b) corrosion-fatigue cracks of spot-welded specimens and c) corrosion fatigue of weld-bonded specimen of EN 1.4301 2H steel. [Publ. III]

At the heat-affected zone of the weld nugget of weld-bonded samples, the adhesive layer vaporizes and is damaged due to the high temperature. In Fig. 13, it can be seen that the adhesive layer is burnt circumferentially around the weld nugget. The width of the damaged zone is around 1 mm.

The typical failure mode of the adhesive layer of a corrosion-fatigue tested weld-bonded specimen is presented in Fig. 14a and 14b. The failure mode is an adhesive failure, i.e. the failure occurs at the adhesive/metal interface. Some corrosion products formed in the crevice can be seen in Fig. 14b. From the figures can be seen that the typical failure mode of the adhesive layer of a weld-bonded air-fatigue tested specimen was mainly cohesive, i.e. the adhesive broke. Those results are presented in Publ. III.

The difference in the failure mode of the weld-bonded joints did not affect the fatigue crack initiation of the stainless steel spot weld. The crack always initiated at the outer edge of the corona bond area.

Figure 13. The blue adhesive layer near the weld nugget is damaged during spot welding. [Publ. III]

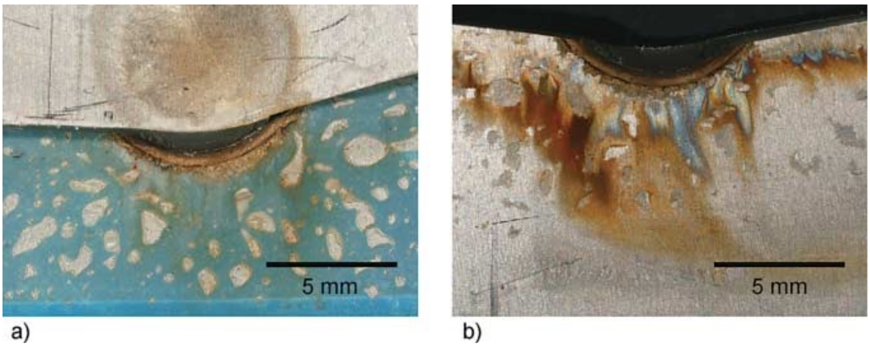

Figure 14. The failure of the adhesive layer of a corrosion-fatigue tested, weld-bonded specimen (EN 1.4301 2B). The specimen halves in a) and b) are opposite sides. The blue adhesive area at a) is on the non-loaded side of the specimen and b) is presenting the loaded side of the specimen. [Publ. III]

3.2 Chromium-depleted layer

The results of the surface analysis and electrochemical measurements of the heat-tinted oxides are presented in Publication I.

In Fig. 15 the depth profile of chromium at the yellow heat-tinted area on an induction-heated sample of steel EN 1.4301 2B (1.0 mm) was measured by GD-OES. The chromium content is increased near the surface on the base material, but is decreased in the yellow heat-tinted oxide. It indicates that there is a chromium-depleted layer under the yellow oxide film. The minimum chromium content in the depletion layer is about 13 %.

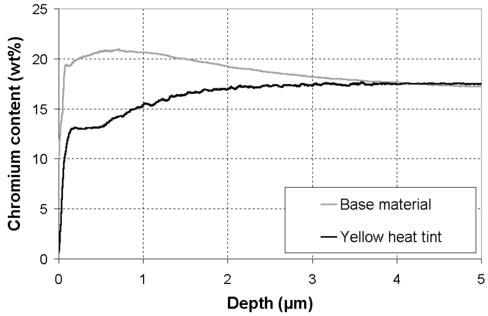

Figure 15. The chromium content of the base material and the yellow heat-tinted oxide film of an induction-heated sample of EN 1.4301 2B steel measured by GD-OES. [Publ. I]

3.3 Residual stresses

In the boiling magnesium chloride test, the spot welds (5√t) of EN 1.4301 2B and EN 1.4301 2H steels were cracked circumferentially around the weld and radially from the weld nugget, as can be seen in Fig. 16a and 16b. Fig. 16c shows a detail of cracks which initiate at several sites from the surface. In Fig. 17, the fracture surface from the crevice side is presented. It can be seen in Fig. 17b that stress-corrosion cracking is intergranular. The cracks have initiated from several sites of the outer surface.

The residual stresses were measured on a spot-welded sample of EN 1.4301 2B steel. The diameter of the X-ray beam was 1 mm. The results are presented in Fig. 18. Outside the spot-weld nugget area, the radial tensile stress is on the level of the yield strength of the steel, and the tangential stress is compressive. No effect of the rolling direction could be found. In the induction-heated sample, tensile stresses were present in the whole heat-tinted area. The stresses are higher in the samples which were heated to higher temperatures. The measured and modelled stresses of a spot-welded sample of EN 1.4310 2B steel are shown in Fig. 19. The measured and calculated stresses are in good accordance.

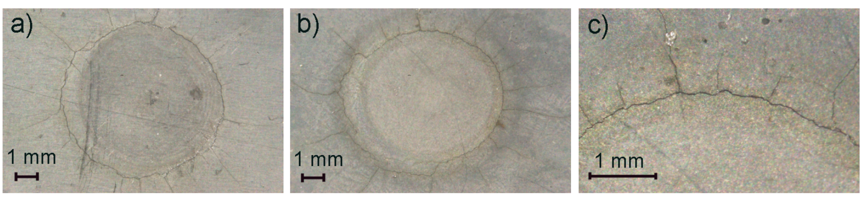

Figure 16. Stress corrosion cracking of the spot-welded a) EN 1.4301 2B steel, b) and c) EN 1.4301 2H steel in boiling (156 °C) magnesium chloride solution after 19 h. The rolling direction is horizontal in the image. [Publ. I]

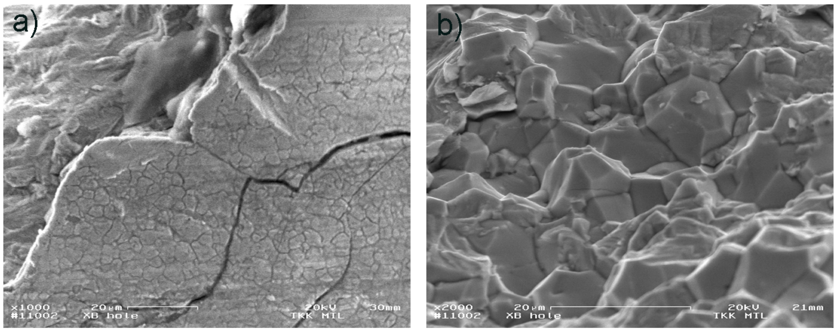

Figure 17. SE images of a) the fracture surface from the crevice side and b) intergranular fracture surface of a spot weld of EN 1.4301 2B steel cracked by stress corrosion. [Publ. I]

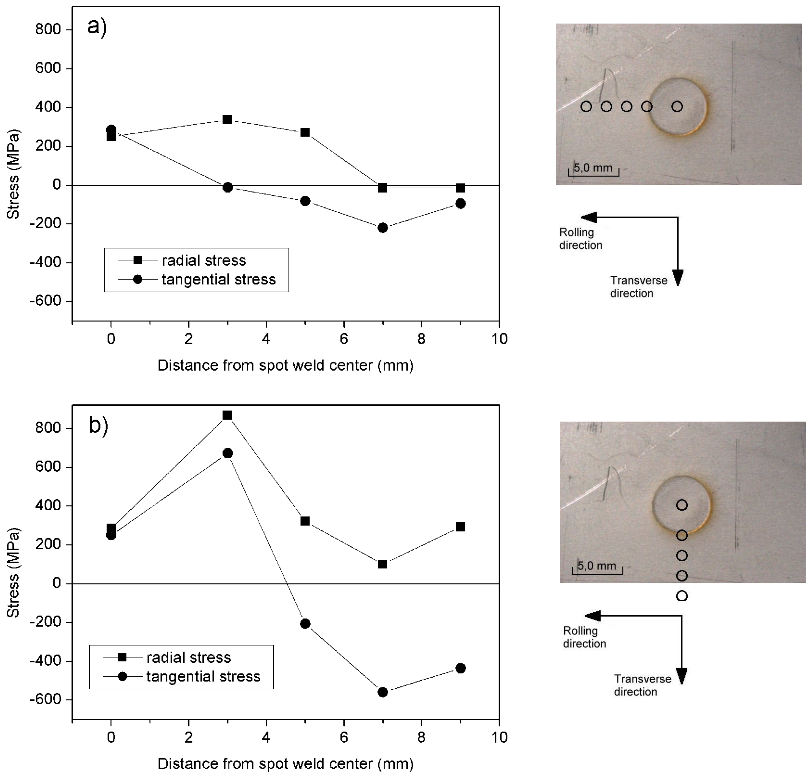

Figure 18. The residual stresses measured a) in the rolling direction and b) in transverse to the rolling direction on a spot weld of EN 1.4301 2B steel. The diameter of the X-ray beam was 1 mm. [Publ. I]

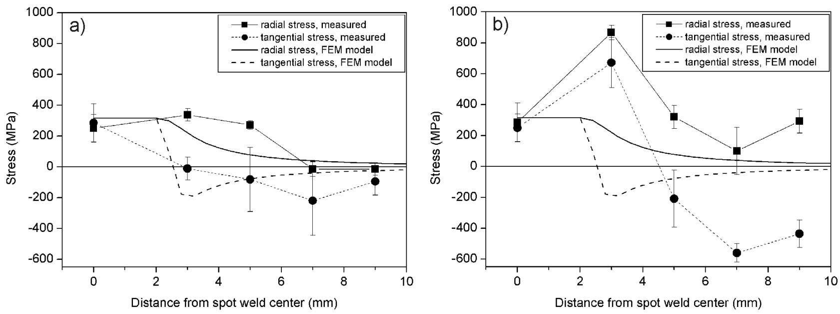

Figure 19. The modelled and measured residual stresses over a spot weld (5√t) of EN 1.4301 2B steel a) in the rolling direction and b) in transverse to the rolling direction. [Publ. I]

3.4 Crevice corrosion of spot welds

In immersion tests, only a few corrosion pits were found on the heat-tinted area of the spot-weld surface, but the corrosion products coming out of the crevice indicated crevice corrosion. After cutting out the spot welds, the samples were opened and studied by optical stereomicroscope and SEM. Crevice corrosion was found at the heat-tinted area around the spot weld as can be seen in Fig. 20. The diffusion-bonded area close to the nugget was not corroded. Outside the diffusion-bonded area, intergranular corrosion has also taken place. Detailed SEM images of the corroded area are presented in Fig. 21. The weld nugget is in the upper left corner. The area close to the nugget in Fig. 21a is the diffusion-bonded area that has not corroded. Outside the diffusion-bonded area, intergranular corrosion has also taken place (Fig. 21b). The light area in Fig. 21a has corroded remarkably as can be seen in Fig. 21c. In Fig. 21d an image of the un-attacked surface is presented. The fatigue crack initiation sites did not coincide with the areas where crevice corrosion was found.

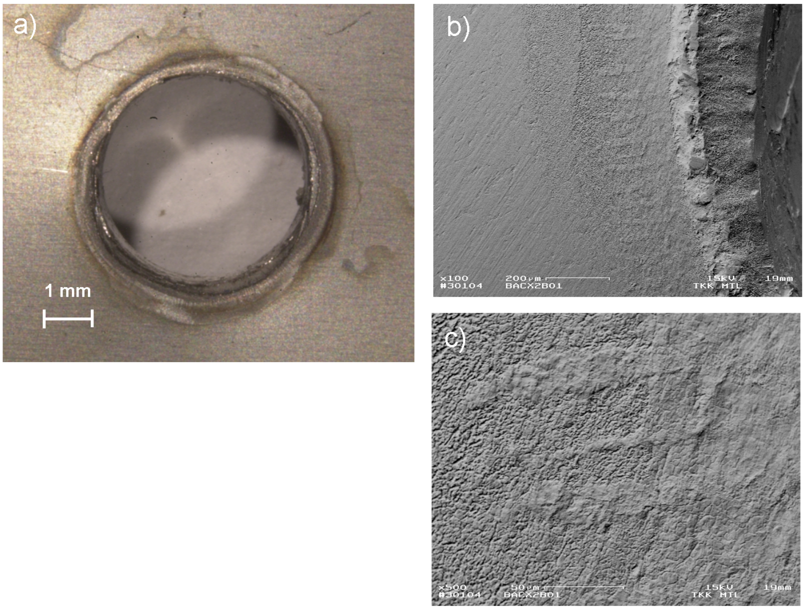

Figure 20. a) Crevice corrosion around a spot weld of EN 1.4301 2B steel after immersion in 3.5 % NaCl solution for 88 days, b) and c) BSE SEM images of the corroded area. The weld nugget has been drilled away. [Publ. I]

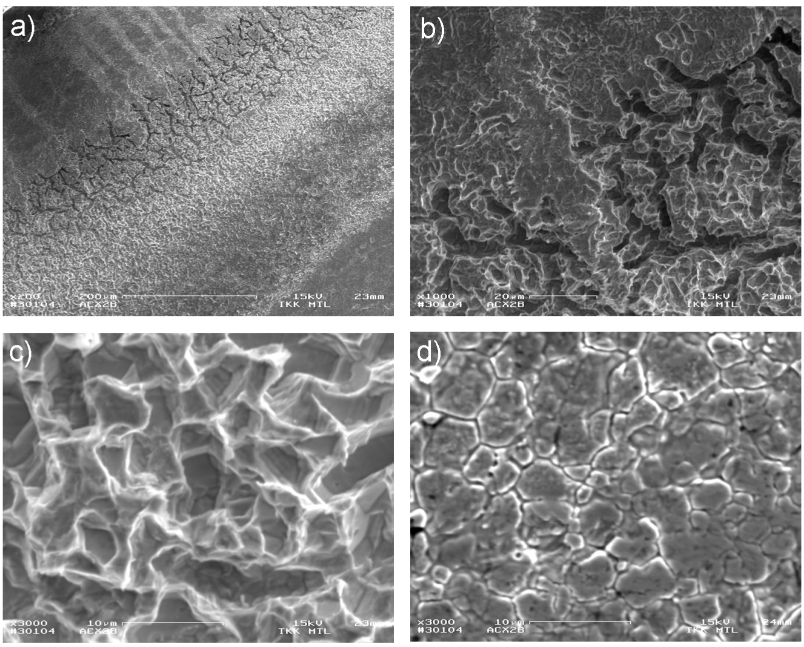

Figure 21. SE images on crevice corrosion attack around the spot weld of EN 1.4301 2B steel immersed in 3.5 % NaCl solution for 88 days at room temperature. a) General view of the corroded area around the weld nugget, b) intergranular corrosion outside the diffusion-bonded area, c) actively corroded metal surface (the light area in the image a), and d) the uncorroded surface about 3 mm from the weld nugget inside the crevice. [Publ. I]

4 Discussion

Fatigue resistance of spot-welded and weld-bonded specimens was studied in the air and an aqueous corrosive environment containing 3.5 % sodium chloride. For both joints, the corrosive environment reduced the fatigue strength of the spot-welded austenitic stainless steels significantly compared to the ambient air conditions. The phenomenon has been reported for spot-welded stainless steel in earlier studies [3, 4], but no data on corrosion fatigue properties of weld-bonded joints of stainless steel has been published.

In this study, the steels were used both as annealed and as cold-worked conditions. The EN 1.4318 steel was also studied in high-strength condition. In fatigue tests, both in ambient air at 20 °C and in the 3.5 % NaCl solution at 50 °C, the fatigue resistance of spot-welded specimens of annealed 2B and 2F grade steels were higher than those of the spot-welded specimens of cold-rolled 2H grade steels, even though the cold-worked steels have higher strength in static loading.

In the air, similar findings have been made by Söderlund [12], who studied fatigue behaviour of annealed and cold-stretched spot-welded specimens of AISI 304 (similar to EN 1.4301) steel. He found that the annealed specimens had slightly better fatigue resistance than the cold-stretched specimens of the same steel in the same testing conditions. He attributed the lower fatigue resistance to the sheet thickness reduction due to cold stretching. However, the phenomenon might also be attributed to the lower fracture toughness of the cold-stretched material due to spot welding.

The lower corrosion resistance of EN 1.4318 steel compared to EN 1.4301 steel seems to result in a more significant reduction of the fatigue strength of EN 1.4318 steel in the corrosive environment. However, in the earlier study, better corrosion resistance of the base material did not significantly affect the corrosion-fatigue strength of the spot-welded stainless steels even with a different microstructure [4].

According to this study, the explanation for the observed inferior fatigue strength behaviour of the spot-welded 2H grade steels may be that the heating during spot welding locally softens the HAZ of the 2H steels and the good mechanical properties of the steel obtained by cold working are locally lost. The spot welds of EN 1.4318 2H steel yield locally during the loading, and the high residual stresses of the 2H grade steels at the spot-weld area influence the process. Because the residual stresses around the spot weld can be at the level of the yield strength of the steel, in 2H grade steels, the residual stresses can become much higher than those in 2B grade steel. The difference of the yield strengths between 2B/2F and 2H grade steels is exceptionally high in EN 1.4318 steel, where also a more significant drop in fatigue strength was observed. This explanation is supported by an investigation where the spot-welded specimens consisted of two sheets of different thickness. In fatigue testing in air, the fatigue crack propagation took place in the thicker sheet at long lives, but in both sheets at short lives [2]. Since the thicker sheet is stiffer than the thinner, the phenomenon was probably related to the stress concentration at the notch. When the applied maximum load is low and the fatigue life is long, the residual stresses have a significant influence on the total stress level at the notch, whereas at short lives, the external load is so high that the impact of the residual stresses on the total stress level is negligible.

This study assumed that the heat-tinted oxides in the crevice around the spot weld affect the fatigue crack initiation in the corrosive environment. However, the pre-exposure of the spot welds to the corrosive environment did not reduce the fatigue strength of the spot-welded specimen. During the pre-exposure, crevice corrosion is taking place on the heat-tinted areas located outside the diffusion-bonded zone. These areas are at some distance away from the notch where the cracks initiated, and hence the crevice corrosion cannot initiate the corrosion-fatigue cracks.

A chromium-depleted layer was detected under the yellow heat-tinted oxide by GD-OES measurements. It is presumably the reason for the reduced corrosion resistance of spot-welded stainless steel. The excellent corrosion resistance of the stainless steel can be restored by removing the heat-tinted oxides, but the heat-tinted oxides in the crevice between the steel sheets cannot be removed.

In the spot welds, two different microstructural zones are present. In the nugget, which has melted during welding, the microstructure consists of austenite and delta ferrite. At the heat-affected zone (HAZ), the two sheets have joined together by diffusion bonding, and the microstructure is locally finer than that of the base material at the tip of the notch, where also a hardness peak is present. Both in air and the corrosive environment, the fatigue cracks initiate outside the edge of the diffusion-bonded zone of the spot weld from the notch.

In the case of spot-welded carbon steels, the highest stress concentration has also been located earlier at this notch [10].

Another finding of this study was that the better corrosion-fatigue resistance of the base material did not affect significantly the corrosion-fatigue strength of the spot-welded stainless steels when the sheet thickness is equal. In addition, the corrosion-fatigue resistance of spot-welded high-strength stainless steel can be lower than that of the standard strength steel.

Using the line-load range analysis where the load is divided by the length of the joint, the fatigue strength of the spot-welded 2H steels of different thicknesses are all at the same level. Also, for the dissimilar metal joints, the sheet thickness was the main factor affecting the fatigue strength in a wet, corrosive environment. For dissimilar steel joints, the fatigue strength in the corrosive environment increased with the increasing sheet thickness, but the strength levels of the base material had only a minor role. The fatigue strength of the dissimilar metal joints was between the fatigue strength of the non-stainless steel and stainless steel. In the dissimilar metal joints, the fatigue cracks initiated at the tip of the corona bond of both non-stainless and stainless steel.

The presence of the adhesive layer in the weld-bonded specimen improves the fatigue strength both in the air and in the corrosive environment. The difference between the fatigue data of the weld-bonded and the spot-welded specimens was more significant in the air than in the corrosive environment. The failure mode of the weld-bonded specimen was different in the corrosive environment than in the air. The failure mode in the corrosive environment was an adhesive failure that indicates that the corrosive environment affects rather the adherence of the adhesive than the other properties of the adhesive layer.

Because in the standard boiling magnesium chloride test the environment is very severe, the test is not representative for practical applications. The results indicate, however, that the residual stresses in spot welds of both grade 2B and grade 2H steels are high enough to cause stress-corrosion cracking without external load. The possibility of stress-corrosion cracking of spot-welded structure in hot chloride containing environments has to be taken into account even though the spot welds were not loaded.

There are high residual tensile stresses in the radial direction around the spot welds. External tensile stress has been reported to lower the pitting corrosion potential of the stainless steel containing manganese sulphide (MnS) inclusions [49]. The residual stresses around the spot weld may have the same effect. The measured residual stresses and the stresses modelled by FEA in this study are in good accordance with each other, and they explain the circumferential stress-corrosion cracking of the spot weld. The radial cracks are formed after the nugget has cracked and the high radial tensile stress is released. The radial cracks are caused by more minor tangential tensile stresses caused by the yielding of the base material during spot welding.

The corrosion-fatigue test results obtained by the Taguchi Method® indicate that an increase of the load, a rise of temperature and lowering the frequency reduce the corrosion-fatigue life of the spot-welded specimens of austenitic stainless steel significantly. The type of chloride had only a minor effect on the fatigue life in a wet, corrosive environment. The results confirm the expectations that since the corrosion reactions are usually accelerated at higher temperatures and lower loading frequency when the corrosion reactions have more time to occur. The results only gave the relative importance of the factors because no duplicate measurements were performed.

5 Conclusions

The corrosive environment 3.5 % NaCl solution at 50 °C reduces significantly the fatigue strength of both spot-welded and weld-bonded test specimens of austenitic stainless steels EN 1.4301 and EN 1.4318. The weld-bonded specimens perform significantly better than the spot-welded specimens, so corrosion fatigue resistance of spot-welded austenitic stainless steel structures can be improved by adding an adhesive layer.

The spot-welded specimens of the 2B grade steels exhibit better fatigue resistance than the cold-worked 2H grades of the same steels. The benefits obtained by using high-strength steels seem to be lost when using spot-welded joints. The thicker EN 1.4318 2H steel exhibit better corrosion-fatigue endurance than the thinner ones. However, there is no significant difference in the corrosion-fatigue resistance between them when the sheet thickness is eliminated by line-load range analysis. That indicates that in spot-welded structures, the fatigue resistance of the steel is strongly dependent on the thickness of the sheet. The fatigue strength of the dissimilar metal joints was between the fatigue strength of the non-stainless steel and stainless steel.

The fatigue endurance of the weld-bonded specimens is higher than that of the spot-welded specimens. The difference is larger in air than in the corrosive environment, where the fatigue strength is reduced for both joints. The failure mode of the weld-bonded specimens is adhesive in the corrosive environment and cohesive in air. The difference in the failure mode of adhesive layer does not affect the fatigue crack initiation in the spot weld of the stainless steel.

The results of surface analysis show that there is a chromium-depleted layer under the coloured oxide film. That chromium-depleted layer is the reason to the reduced corrosion resistance at the heat-tinted areas.

The local corrosion in the crevice was assumed to influence the fatigue crack initiation. However, pre-exposure of the samples to the corrosive environment does not affect the fatigue strength of stainless steels. The fatigue cracks do not initiate at the area where the heat-tinted oxides can be found and the crevice corrosion occurred during immersion test, but at the outer edge of the corona bond area of the spot weld.

Spot welding causes residual stresses about the level of the yield strength of the steel and they may reduce the fatigue strength of the joint. The stresses are high enough to cause SCC in an aggressive environment. They may also affect the pitting susceptibility of the spot welds.

The relative importance of different factors on fatigue strength in corrosive environment obtained by Taguchi Method® indicates that an increase of the load, rise of temperature and lowering the frequency reduce the fatigue endurance of the spot-welded stainless steels. The type of chloride has only a minor effect.

Bibliography

[1] Anonymous, Weight reduction for safer, affordable passenger cars by using extra formable high strength austenitic steel, Final Technical Report GRD1-2000-25784 LIGHT&SAFE, European Community under the 'Competitive and Sustainable Growth' Programme 1998-2002, (2005).

[2] Linder, J., Melander, A., Larsson, M., Bergengren, Y., Fatigue design of spot-welded austenitic and duplex stainless sheet steels. Fatigue & Fracture of Engineering Materials & Structures, 21 (1998A), p. 673-686.

[3] Linder, J., Bergengren, Y., Thuvander, A., Melander, A., Gustavsson, A., Fatigue of spot welded stainless sheet steels. Proceedings of Fatigue '96: Sixth International Fatigue Congress, Berlin, Germany, May 6-10, 1996, Vol. II, p. 1111-1116.

[4] Linder, J., Melander, A., Fatigue strength of spot welded stainless sheet steels exposed to 3% NaCl. International Journal of Fatigue, 20 (1998B), p. 383-388.

[5] Vucko, F., LeBozec, D., Thierry, D., Weber, B., Dosdat, L., Luckeneder, G., Bschorr, T., Rother, K., Sciaboni, C., Sczepanski, J., Combined corrosion and fatigue performance of joined materials for automotive applications. Materials and Corrosion, 67 (2016), p. 1143-1151.

[6] Melander, A., Larsson, M., Stensiö, H., Gustavsson, A., Linder, J., Fatigue performance of weld-bonded high strength sheet steels tested in arctic, room temperature and tropical environments. International Journal of Adhesion & Adhesives, 20 (2000), p. 415-425.

[7] LeBozec, N., Thierry, D., Influence of test parameters in an automotive cyclic test on the corrosion and mechanical performance of joined materials. Materials and Corrosion, 66 (2015), p. 1051-1059.

[8] Jha, S. K., Noise inside and out. Automotive Design Engineers 11 (1972), No 11, p. 32-35.

[9] Hambling, S. J., Jones, T. B., Fourlaris, G., The influence of steel strength and loading mode on the fatigue properties of resistance spot-welded H-beam components. Engineering Integrity, 14 (2003), p. 14-18.

[10] Jones, T. B., Williams, N. T., The fatigue properties of spot welded, adhesive bonded and weld-bonded joints in high strength steels, *SAE Technical Paper 860583*, Society of Automotive Engineers, Warrendale, PA, 1986. 18 p.

[11] Triyono, Jamasri, Ilman, M. N., Soekrisno, R., Fatigue behavior of resistance spot-welded unequal sheet thickness austenitic stainless steel. Modern Applied Science, 6 (2012), No. 5, p. 34-42.

[12] Söderlund, P., Fatigue strength of spot welded joints in austenitic stainless steel. Svetsaren 47 (1993), No. 2, p. 30-33.

[13] Long, X., Khanna, S. K., Allard, L. F., Effect of fatigue loading and residual stress on microscopic deformation mechanism in a spot-welded joint. Materials Science and Engineering A, 454-455 (2007), p. 398-406.

[14] Budde, L. Hahn, O., Adhesive bonding in combination of spot welding or clinching. Welding in the World, 30 (1992), p. 26-32.

[15] Gosh, P. K., Vivek, Weldbonding of stainless steel. ISIJ International, 43 (2003), p. 85-94.

[16] Kela, J., The influence of surface finishing on the mechanical properties of weld-bonded, adhesive bonded and spot welded austenitic stainless steel joints. Master's Thesis, University of Oulu. 2000.

[17] Ring-Groth, M., Magnusson, C., Powell, J.; Fatigue properties of weld-bonded stainless steel joints, Journal of Advanced Materials, 32 (2000), p. 21-27.

[18] Campilho, R. D. S. G., Pinto, A. M. G., Banea, M. D., da Silva, L. F. M., Optimization study of hybrid spot-welded/bonded single-lap joints. International Journal of Adhesion and Adhesives, 37 (2012), p. 86-95.

[19] Fujii, T., Tohgo, K., Suzuki, Y., Yamamoto, T., Shimamura, Y., Ojima, Y., Fatigue properties of spot welded and spot weld-bonded joints of steel sheets. Procedia Engineering 10(2011), p. 1075-1080.

[20] Chang, B., Shi, Y., Dong, S., Comparative studies on stresses in weld-bonded, spot-welded and adhesive-bonded joints. Journal of Materials Processing Technology, 87 (1999A), p. 230-236.

[21] Chang, B., Shi, Y., Lu, L., Studies on the stress distribution and fatigue behavior of weld-bonded lap shear joints. Journal of Materials Processing Technology, 108 (2001), p. 306-313.

[22] Holubka, J. W., Chun, W., Krause, A. R., Shyu, J., Effect of corrosive environment on the locus and mechanism of failure of adhesives. Polymer Materials for Corrosion Control, Chicago, Illinois, USA, Sept. 8–13, 1985, p. 194-202.

[23] Kang, H. T., Li, Z., Khosrovaneh, A. K., Kang, B., Li, Z., Fatigue life predictions of adhesive joint of sheet steels. Procedia Engineering, 133 (2015), p. 518-527.

[24] Al-Bahkali, E. A., Es-Saheb, M. H., Herwan, J., Elastic plastic stress distributions in weld-bonded lap-joints under axial loading. Research Journal of Applied Sciences, Engineering and Technology, 23 (2014), p. 4931-4939.

[25] Al-Samhan, A., Darwish, S.M.H., Finite element modeling of weld-bonded joints. Journal of Materials Processing Technology, 142(2003, p. 587-598.

[26] Chang, B., Shi, Y., Dong, S., A study on the role of adhesives in weld-bonded joints. Welding Research Supplement, (1999B), p. 275-s -279-s.

[27] Khanna, S. K., He, C., Agrawal, H. N., Residual stress measurement in spot welds and the effect of fatigue loading on redistribution of stresses using high sensitivity Moiré interferometry. Transactions of ASME, 123 (2001), p. 132-138.

[28] Nachimani, C., Microstructural and fatigue properties of dissimilar spot welded joints of AISI 304 and AISI 1008. International Journal of Automotive and Mechanical Engineering (IJAME), 7 (2013), p. 882-899.

[29] Ishak, M., Shah, L. H., Aisha, I. S. R., Hafizi, W. Islam, M. R., Study of resistance spot welding between AISI 301 stainless steel and AISI 1020 carbon

steel dissimilar alloys. Journal of Mechanical Engineering and Sciences (JMES), 6 (2014), p.793-806.

[30] Vural, M., Akkus, A, Eryürek, B., Effect of welding nugget diameter on the fatigue strength of the resistance spot-welded joints of dissimilar steel sheets. Journal of Materials Processing Technology, 176 (2006), p. 127-132.

[31] Jamasri, Ilman, M. N., Soekrisno, R., Triyono, Corrosion fatigue behavior of resistance spot welded dissimilar metal welds between carbon steel and austenitic stainless steel with different thickness, Procedia Engineering, 10 (2011), p. 649-654.

[32] Triyono, Jamasri, Ilman, M. N., Soekrisno, R., Static and fatigue behavior of plug-welded dissimilar metal welds between carbon steel and austenitic stainless steel with different thicknesses. Journal of Mechanical and Materials Engineering, 9 (2014), No. 1, 6 p.

[33] Saggau, R., Pries, H., Finke, M., Schweissbedingte Anlauffarben und ihr Einfluss auf die Korrosion hochlegierter CrNi-Stähle. Zeitschrift fur Metallkunde, 92 (2001), p. 286-292.

[34] Hakkarainen, T., Carpén, L., Effects of heat tints on pitting susceptibility of stainless steel. Proceedings of 7th International Symposium on Electrochemical Methods in Corrosion Research (EMCR'2000) [CD-ROM], May 28 - June 1, 2000, Budapest, Hungary, Paper no. 061. 9 p.

[35] Tuthill, A. H., Avery, R. E., Heat tints on stainless steels can cause corrosion problems. Materials Performance, 38 (1999), p. 72-73.

[36] Finke, K. M., Einfluss thermisch erzeugter Deckschichten auf die Korrosionsbeständigkeit geschweisster CrNi-Stähle. Ph.D. Thesis, 1998, TU Braunschweig, Germany.

[37] Rastogi, P. K., Shah, B. K., Sinha, A. K., Kulkarni, P. G., Effect of oxide film on pitting susceptibility of 304 austenitic stainless steel. British Corrosion Journal, 29 (1994), p. 78-80.

[38] Pistorius, P. C., Moltke, T., Pitting corrosion of heat-tinted stainless steel. Proceedings of European Symposium on Modifications of Passive Films, Paris, France, February 15-17, 1993, pp. 316-321.

[39] Azuma, S., Miyuki, H., Murayama, J., Kudo, T., Effect of weld scale on corrosion resistance of stainless steels. Corrosion Engineering, 39 (1990), p. 667-676.

[40] Turner, S., Robinson, F. P. A., The effect of the surface oxides produced during welding on the corrosion resistance of stainless steels. Corrosion, 45 (1989), p. 710-716.

[41] Martín, Ó., De Tiedra, P., López, M., Artificial neural networks for pitting potential prediction of resistance spot welding joints of AISI 304 austenitic stainless steel. Corrosion Science 52 (2010), p. 2397-2402.

[42] De Tiedra, P., Martín, O., López, M, San-Juan, M., Use of EPR test to study the degree of sensitization in resistance spot welding joints of AISI 304 austenitic stainless steel. Corrosion Science 53 (2011), p. 1563-1570.

[43] Hafez, K. M., The effect of welding atmosphere on the pitting corrosion of AISI 304L resistance spot welds. The International Journal of Advanced Manufacturing Technology, 97 (2018), p. 243-251.

[44] [online], URL: http://www.matweb.com/search/datasheettext.aspx?matguid=2adc61011165404884e8b8411429f504

[45] ASTM Standard G 31 – 72 (Re-approved 1999), 1999.

[46] Nordberg, H., Fatigue properties of stainless steel lap joints. Spot-welded, adhesive bonded, weld bonded, laser welded and clinched joints of stainless steel sheets – A review of their fatigue properties. SAE Technical Paper 2005-01-1324, 2005.

[47] Roy, R. K., A primer on the Taguchi Method. Society of Manufacturing Engineers, 1990.

[48] ASTM Standard G 36 – 94, Standard Practice for Evaluating Stress-Corrosion-Cracking Resistance of Metals and Alloys in a Boiling Magnesium Chloride Solution, 1994. 7 p.

[49] Suter, T., Webb, E. G., Böhni, H., Alkire, R. C., Pit initiation on stainless steels in 1 M NaCl with and without mechanical stress, Journal of The Electrochemical Society 148(2001), No. 5, p. B174-B185.

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