

# **STRUCTURAL APPLICATIONS OF FERRITIC STAINLESS STEELS (SAFSS)**

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## Summary

The present report deals with the test results obtained from the welded connections of 11–20 % Cr ferritic stainless steels. Three common welding methods were used: metal active gas welding, tungsten inert gas and manual metal arc welding. The welding methods spread the heat inputs between the materials and, therefore, some influence of the heat inputs could be determined. In addition, thermal simulation tests were included to clarify the effects of different heat inputs.

In total of 19 materials were received from three manufacturers. Thicknesses varied 1–6 mm, four of those were in hot rolled and 15 in cold rolled condition. Five different filler metals were used, two of those were austenitic and three ferritic. Transversal tension tests were done for the base metals and welds at room temperature. Impact toughness tests were carried out within a temperature bandwidth from -40 to +20 °C for the base metals, high-temperature heat-affected zones (HTHAZs) and weld metals. Microstructures were studied in the weld regions as well as in the heat-affected zones (HAZs) by using straightforward optical microscopy and SEM. The focus was on grain structures, i.e. grain sizes and the extent of different phase structures, i.e. ferrite/martensite ratio, and the width of the heat-affected zone. Hardness tests accompanied the metallographic observations. A few selected corrosion tests were prepared for the welds to study their susceptibility for intergranular corrosion. Postweld heat treatments (PWHTs) were also prepared to study their influence to mechanical and corrosion properties of the welds.

Stabilised grades did not contain any martensite in the HAZ, unstabilised 1.4003 is essentially lath martensitic in as-welded state, and the traditional 1.4016 had 10 to 25 % martensite in the HTHAZ. Hardness profiles for the unstabilised grades indicate that the width of the HAZ varied 4–6 mm. It also became evident that the thicknesses from 4 mm and above experienced somewhat a 3-dimensional cooling, which narrowed the width of the HTHAZ significantly.

According to the results, the ultimate tensile strength (UTS) of autogenous welds rarely matched that of the base metals. Grades 1.4003, 1.4509 and 1.4621 were seen the most suitable for autogenous welding because those weldments ruptured from the base metal. Austenitic filler metals are preferred over ferritic ones, as the welds fabricated with these ductile filler metals have excellent toughness and preferred fracture behaviour. The ferritic 430LNb filler metal resulted in wretched toughness in welds due to coarse columnar grain structure.

The major limiting factor in using ferritic grades for structural components is the lack of toughness. Impact toughness tests for the HTHAZs and weld metals clarified this assumption. However, if the sheet thickness is limited to 3 mm, all stabilised grades behaved in ductile manner in Charpy tests at room temperature when reasonable heat inputs were used. Only the grade 1.4003 can be considered to be used in thicker sections.

Sensitisation was only found in unstabilised welds. All selected stabilised materials passed the Strauss tests for intergranular corrosion. Grade 1.4003 sensitised when a multipass X-type joint configuration was used. Grade 1.4016 suffered from intergranular corrosion even when the lowest heat inputs were used. However, a PWHT at 750 °C for 2 hours restored the corrosion resistance of the 1.4016 welds.

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## 1 Introduction

Nickel-free ferritic stainless steels are gaining increasing attention from customers and steel manufacturers. Stable price is one of the most important reasons for choosing a ferritic grade. However, ferritic stainless steels can be used for many applications that austenitics cannot. Magnetism, low thermal expansion, high thermal conductivity, and the immunity for chloride-induced stress-corrosion cracking (SCC) are some of the other features of ferritic stainless steel grades.

Ferritics are already used for many types of applications, including household wares, sinks, water boilers and exhaust parts. However, the structural use of these materials is uncommon. Only the grade 1.4003 or its siblings have been used for structural purposes e.g. in bridges, carriages, railway wagons and masts. This limited use is explained by several factors. First of all, the traditional and still very common ferritic grade 1.4016 (Type 430) is considered not to be suitable for welding because of many embrittlement phenomena. The modern stabilised ferritic grades have improved corrosion resistance in as-welded condition, but the toughness is considered to be inadequate for structural use.

Many of the assessments of ferritic grades are based on old assumptions. However, modern steelmaking techniques have increased the performance of old materials and, furthermore, lately introduced grades, e.g. 1.4509 (Type 441), lack of available data. Therefore, it is reasonable to study the present state of these materials, including their capability for structural purposes. Welding is an essential joining technique and it is utmost important method in structural fabrication. Therefore, the influence of welding to materials performance needs to be studied.

## 2 Objectives

The mechanical properties of welded ferritic stainless steels are very dependent on the alloy type i.e. the amount of alloying elements. In welding, the heat-affected zone (HAZ) experiences temperatures that are sufficient to cause significant microstructural changes. The formation of secondary phases may have a negative effect on the mechanical and corrosion properties of the weld region.

Ductile-to-brittle transition temperature (DBTT), which is characteristic of ferritic stainless steels, is affected by heat treatment such as welding. In order to understand deeper the effect of heat input on the mechanical properties of the welds, practical welding tests for different heat inputs will be carried out with conventional welding methods, including MAG, TIG and MMA. Gleeble thermal simulations will be used as a comparison for practical welding tests, and furthermore, for determining the influence of different heat inputs.

Tension tests and impact toughness tests at different temperatures will be carried out on welded samples. The microstructures of the welds and HAZs will be analysed. This will give information about the grain size, phase structure and width of the HAZ with different welding methods and heat inputs.

Corrosion resistance of the welded joints will be tested for intergranular corrosion by using a conventional Strauss test, and a modified version of this for low chromium 1.4003.

Design guidance will be prepared based on the results of these laboratory investigations. The guidance will also cover the performance of welded joints subject to fatigue, based on a review of previous test programmes.

### 3 Experimental work

#### 3.1 Test materials

In total of 19 materials from three manufacturers were studied. Four materials were in hot rolled condition (1D), and 15 in cold rolled condition (2B, 2R or 2E). The materials and their analysed chemical compositions are given in Table 1.

**Table 1. List of the test materials used in WP5 and some key alloying elements.**

Chemical compositions from analyses (wt%)														C+N		
THK	Grade	Mfr.	Cond.	C	Si	Mn	Cr	Ni	Mo	Ti	Nb	Cu	Al	N	ppm	KFF
1.0	1.4003	B	CR	0.012	0.26	1.43	11.3	0.4	0.0	0.00	0.00	0.1	0.00	0.010	200	7.7
2.0	1.4003	B	CR	0.015	0.26	1.45	11.4	0.4	0.0	0.00	0.01	0.1	0.00	0.013	300	7.4
4.0	1.4003	B	HR	0.009	0.28	1.41	11.3	0.4	0.0	0.00	0.01	0.1	0.00	0.014	250	7.6
6.0	1.4003	B	HR	0.010	0.27	1.45	11.1	0.4	0.0	0.00	0.00	0.2	0.00	0.009	200	7.5
1.0	1.4016	C	CR	0.039	0.37	0.39	16.2	0.2	0.0	0.01	0.01	0.1	0.00	0.029	700	14.3
2.0	1.4016	C	CR	0.023	0.36	0.46	16.3	0.2	0.0	0.01	0.01	0.1	0.01	0.028	500	14.8
2.0	1.4016	B	CR	0.046	0.30	0.48	16.1	0.2	0.2	0.00	0.02	0.1	0.00	0.027	750	14.1
3.0	1.4016	C	HR	0.064	0.27	0.32	16.1	0.1	0.0	0.01	0.01	0.1	0.01	0.025	900	13.2
1.0	1.4509	C	CR	0.016	0.48	0.33	17.7	0.3	0.0	0.17	0.48	0.1	0.09	0.016	300	19.1
1.0	1.4509	B	CR	0.014	0.52	0.45	17.9	0.2	0.0	0.11	0.41	0.1	0.01	0.016	300	19.2
2.0	1.4509	C	CR	0.017	0.55	0.45	17.8	0.2	0.0	0.14	0.49	0.0	0.05	0.018	350	19.3
2.0	1.4509	B	CR	0.020	0.55	0.48	17.9	0.3	0.0	0.12	0.40	0.1	0.01	0.030	500	18.4
3.0	1.4509	A	CR	0.017	0.53	0.34	17.5	0.1	0.0	0.14	0.43	0.1	0.01	0.014	300	19.5
3.5	1.4509	C	HR	0.018	0.36	0.26	17.6	0.2	0.0	0.16	0.47	0.1	0.07	0.019	350	18.4
4.0	1.4509	B	CR	0.027	0.51	0.44	18.3	0.2	0.0	0.12	0.42	0.2	0.01	0.017	450	18.9
1.0	1.4521	B	CR	0.011	0.37	0.52	18.0	0.2	2.1	0.15	0.33	0.1	0.01	0.012	250	26.9
2.0	1.4521	C	CR	0.011	0.48	0.44	17.7	0.3	2.0	0.17	0.43	0.1	0.00	0.016	250	26.6
2.0	1.4521	B	CR	0.015	0.52	0.49	18.0	0.1	2.0	0.13	0.40	0.2	0.01	0.019	350	27.3
1.5	1.4621	A	CR	0.014	0.21	0.23	20.6	0.2	0.0	0.01	0.45	0.4	0.00	0.014	300	19.7

THK = thickness, Mfr. = manufacturer, Cond. = condition, CR = cold rolled, HR = hot rolled,  
KFF = ferrite factor = Cr + 6Si + 8Ti + 4Mo + 2Al + 4Nb – 40(C+N) – 2Mn – 4Ni [1]

#### 3.2 Experimental work

Welding tests were carried out at the Outokumpu Stainless Oy Tornio Research Centre, as well as tension, hardness and corrosion tests and the metallographic examinations. Impact toughness tests were done at the Kemi-Tornio University of Applied Sciences, and Gleeble® thermal simulations were done at the University of Oulu.

- Pulsed gas metal arc-welding (GMAW, MIG/MAG) was carried out for 1.5 to 3.5 mm test materials by using two austenitic filler metals (308LSi, 316LSi) and three ferritic filler metals (409LNb, 430LNb, 430Ti). The used shielding gas was 98%Ar + 2%O<sub>2</sub>, root gas being pure argon.

- Pulsed gas tungsten arc-welding (GTAW, TIG) was carried out for 1.0 to 2.0 mm materials. These welds were fabricated autogenously, i.e. without filler metal. Pure argon gases were used for shielding.
- Shielded metal arc-welding i.e. stick welding (SMAW, MMA) was carried out primarily for 3.0 to 6.0 mm materials. Basic austenitic electrodes were used (E308L-15).

The chemical compositions of the filler metals are given in Table 2. All welds were prepared parallel to the rolling direction of the plates. Welding machine calculated the arc energy, which then was manually converted into approximated heat input by using commonly used factors for thermal efficiency: MAG and MMA = 0.8, TIG = 0.6. A scope of the resulting welding parameters is given in Table 3.

**Table 2. Chemical compositions of the filler metals.**

Chemical compositions of the filler metals (wt%)											C+N	
Method	Filler	C	Si	Mn	Cr	Ni	Mo	Ti	Nb	Cu	N	ppm
MAG	308LSi	0.02	0.87	1.9	20.5	10.9	0.07	n/a	n/a	0.03	n/a	n/a
MMA	308L-15 (2.5)	0.04	0.30	1.8	19.6	9.5	0.09	n/a	n/a	0.09	n/a	n/a
MMA	308L-15 (3.2)	0.04	0.28	1.6	19.7	9.6	0.09	n/a	n/a	0.06	n/a	n/a
MAG	316LSi	0.01	0.88	1.9	18.1	11.8	2.5	n/a	n/a	0.10	0.05	600
MAG	409Nb	0.03	0.65	0.72	11.7	0.3	0.02	n/a	0.37	0.05	0.007	350
MAG	430LNb	0.012	0.39	0.48	18.33	0.14	0.01	n/a	0.41	0.02	0.0154	250
MAG	430Ti	0.081	0.8	0.52	17.4	0.28	0.16	0.469	n/a	0.1	0.0236	1050

**Table 3. A scope of the welding parameters.**

THK	Method	Current [A]	Voltage [V]	Travel speed [mm/min]	Heat input [kJ/mm]
1.0–2.0	TIG	46–94	8–10	106–455	0.05–0.25
1.5–3.5	MAG	105–189	20–26	480–1040	0.14–0.41
3.0–6.0	MMA	44–80	20–22	n/a	0.22–1.51
2.0	Gleeb HTHAZ simulations			0.10–0.40	

TIG: shielding: Ar, 7 l/min; backing: Ar, 10 l/min; gas cup Ø 11.2 mm; 120° tip angle

MAG: shielding: Ar + 2% O<sub>2</sub>, 14 l/min; backing: Ar, 18 l/min

Gleeb HTHAZ simulations: Rykalin 2D heat flow; peak temperature 1350 °C

Tested samples (hardness, tension and impact toughness tests) were transverse to welding direction. After welding, some of the samples were postweld heat treated (PWHT) in a laboratory furnace to study its effect on mechanical and corrosion properties. Optical microscopy and SEM was used to study the grain structures of the welded joints. Numerous hardness tests by using Leco M-400-H1, including profiles, were made alongside the metallographic observations. Tension tests for welded joints were performed at room temperature in accordance with EN 10002-1. The weld reinforcement and root were removed prior testing to maintain a constant thickness ratio along the gauge length.

Impact toughness tests were conducted in four different temperatures, -40 °C, -20 °C, 0 °C and +20 °C. Test locations were the unaffected base metal, high-temperature heat-affected zone (HTHAZ) and centre of the weld metal. As the material thickness is light, the impact toughness test samples are sub-sized. Certain precautions are mandatory when extrapolating these results to represent the actual standardised test samples. This is especially the case with 2.0 mm and lighter materials, which are below the minimum required thickness (2.5 mm) for ISO 148-1:2009. Thermal simulations were conducted to

compare the actual heat inputs resulted from welding to simulated HAZ structures. Furthermore, the thermal simulations were included to clarify the effect of extensive heat input to mechanical properties, i.e. potential loss of impact toughness. Rykalin 2D heat flow model was used in thermal simulations with a peak temperature of 1350 °C for 0.1 s.

Intergranular corrosion in welds was examined with the traditional Strauss test, in according to the standard EN ISO 3651-2. A modified version from this was required for low chromium grade 1.4003 welds [2].

### 3.3 Test matrix

The test matrix for the WP5 materials is presented in Table 4. The material selections for tests were made based on the Task 5.1 literature survey.

**Table 4. The test matrix for the WP5 materials.**

Test matrix for the materials									
THK	Grade	Mfr.	Cond.	Met	Gle	Har	Ten	Imp	Cor
1.0	1.4003	B	CR	x			x		
2.0	1.4003	B	CR	x		x	x	x	
4.0	1.4003	B	HR	x		x	x	x	
6.0	1.4003	B	HR	x		x	x	x	x
1.0	1.4016	C	CR	x			x		x
2.0	1.4016	C	CR	x	x	x	x	x	x
2.0	1.4016	B	CR	x	x	x	x	x	x
3.0	1.4016	C	HR	x		x	x	x	
1.0	1.4509	C	CR	x			x		
1.0	1.4509	B	CR	x			x		
2.0	1.4509	C	CR	x	x	x	x	x	x
2.0	1.4509	B	CR	x	x	x	x	x	x
3.0	1.4509	A	CR	x		x	x	x	
3.5	1.4509	C	HR	x		x	x	x	
4.0	1.4509	B	CR	x			x	x	
1.0	1.4521	B	CR	x			x		
2.0	1.4521	C	CR	x		x	x	x	
2.0	1.4521	B	CR	x	x	x	x	x	x
1.5	1.4621	A	CR	x		x	x	x	

Met = metallography

Gle = Gleebel tests

Har = hardness tests

Ten = tension tests

Imp = impact toughness tests

Cor = corrosion tests

## 4 Results and observations

This section deals with the metallographic observations, and results obtained from mechanical and corrosion tests. Only the essential information is given. All relevant supplements are included as appendices.

### 4.1 Metallographic and hardness examinations

The metallographic observations focuses on the heat-affected zone microstructures, autogenous ferritic welds as well as welds fabricated with ferritic filler metals. High-temperature heat affected zone is usually considered to be the most detrimental region for ferritic stainless steels because of the excessive grain coarsening. Therefore, the main focus is on this region.

Every steel grade is examined for both HAZ and weld metal characteristics. Hardness profiles are included to study the width of the HAZ and to emphasise the differences of the welded joints.

#### 4.1.1 Grade 1.4003

The grade 1.4003 did only contain materials from Producer B, therefore, limited information will be acquired and no comparisons for other manufacturers could be made. Material thicknesses varied from 1 to 6 mm in both cold and hot rolled conditions.

##### HAZ characteristics

This grade exhibits typically a low carbon lath martensitic structure in the heat-affected zone. However, the standard 1.4003 grade can display different types of HAZ microstructures where ferrite-martensite ratio varies considerably. Due to this discrepancy, properties of the welds may differ between manufacturers.

Fig 1 gives an outline of the various zones in the HAZ of grade 1.4003. HTHAZ region is identified easily, as the martensite lath size is larger than in the low temperature region. Fig 2 represents the HTHAZ structure with various heat inputs. Lath martensitic structure stays similar in each, although the width of the region varies.

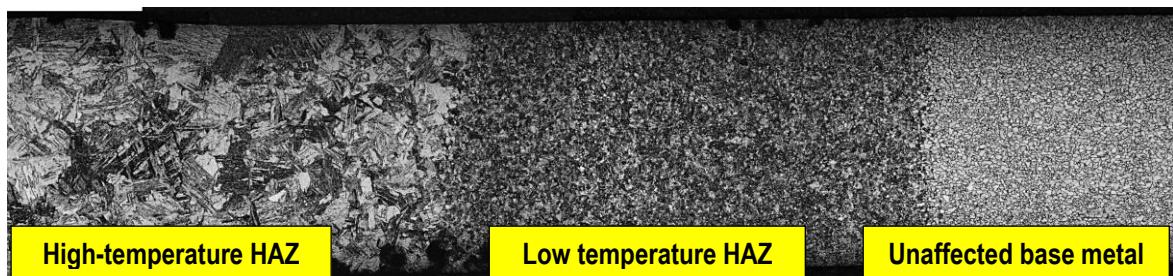
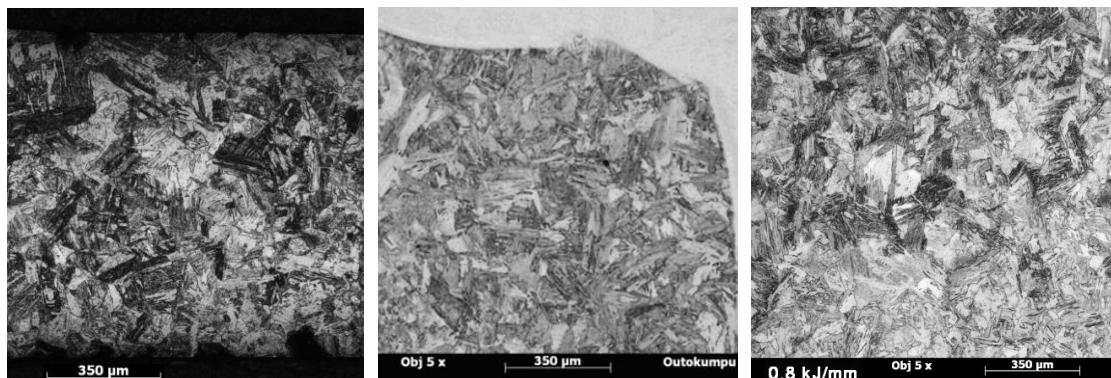


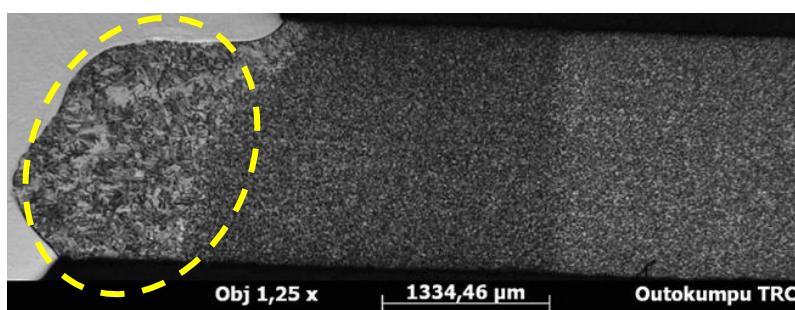
Fig 1. Heat-affected zone regions of 1.4003, 1 mm sheet thickness, heat input 0.06 kJ/mm, autogenous TIG.



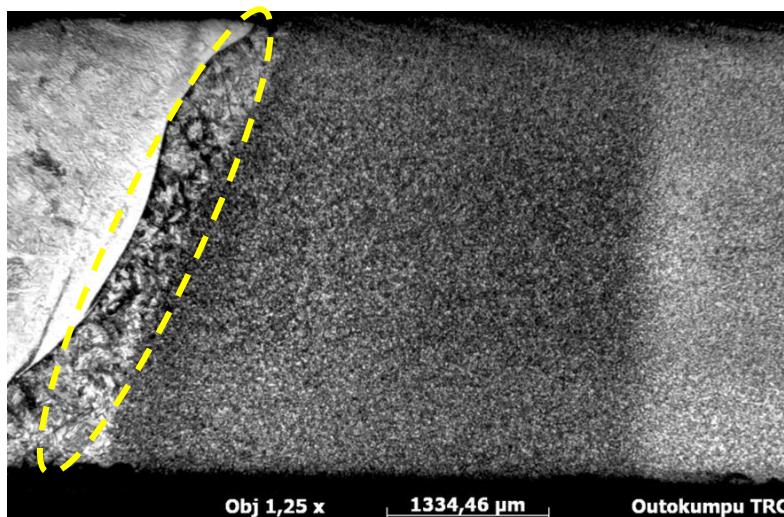
**Fig 2.** A closer look at the HTHAZ of 1.4003. Low heat input 0.06 kJ/mm (left), intermediate heat input 0.25 kJ/mm (middle), high heat input 0.80 kJ/mm (right).

The width of HTHAZ region varies considerably depending on material thickness. Although the heat input increases with the material thickness to achieve adequate penetration, the width of the HTHAZ actually narrows down, as seen in Figs 3 and 4, and from measurements in Table 5. This phenomenon occurs likely because of the change in the cooling dimension. 1 to 2 mm materials cooled in 2-dimension manner, while the 4 and 6 mm materials cooled more in 3-dimensional manner, i.e. including the thickness dimension. The width of the HTHAZ in 2 mm sample (Fig 3) is almost twice to that of the 4 mm sample (Fig 4).

Due to this discrepancy, the forthcoming Charpy-V notched impact toughness tests will characterise the HTHAZ toughness for lighter materials, and general HAZ toughness for thicker materials.



**Fig 3.** HAZ microstructure, 2 mm thickness, heat input 0.22 kJ/mm.

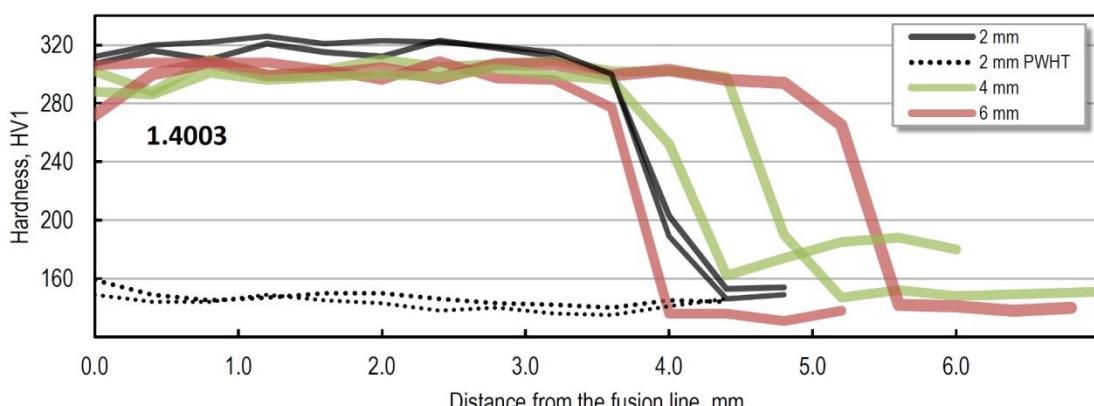


**Fig 4.** HAZ microstructure, 4 mm thickness, heat input 0.60 kJ/mm.

**Table 5. Widths of the weld regions for grade 1.4003 (optical microscopy).**

Material	Heat input [kJ/mm]	HTHAZ [mm]	WM [mm]	Total width of the joint [mm]
Producer B TIG 1 mm	0.06	1.0 to 1.4	1.6 to 1.8	7.6
Producer B MAG 2 mm	0.22	1.0 to 1.9	2.1 to 2.9	10.3 to 11.4
Producer B MAG 2 mm	0.24	1.1 to 1.5	3.3	11.0
Producer B MAG 2 mm	0.26	1.2 to 1.4	2.4 to 2.9	10.9
Producer B MMA 4 mm	0.61	0.5 to 1.2	n/a	n/a
Producer B MMA 6 mm	0.60 + 0.80	0.4 to 1.1	n/a	n/a

A representative hardness profiles for the HAZs are presented in Fig 5. The width of the HAZ for studied materials varied 4 to 6 mm. Hardness profiles specify the martensitic region in these welds accurately. Lath martensitic heat-affected zone is evidently harder than the parent base metal. The differences between the widths of the 2 and 6 mm welds are slight, quite likely because of the change in the cooling dimension, as discussed.

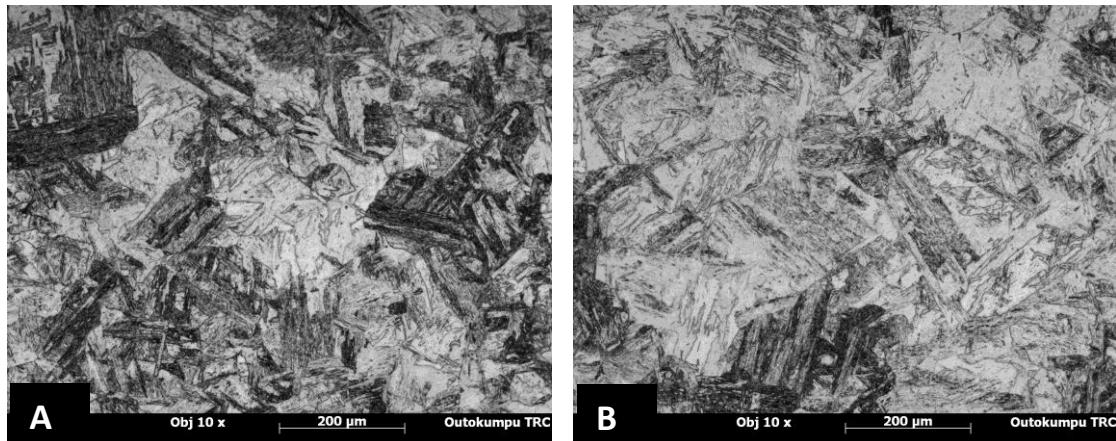


**Fig 5. Representative hardness profiles of the grade 1.4003 HAZs.**

Hardness peaks at about 300 to 320 HV in the HAZ. Larger laths near the fusion line may have a slightly lower hardness but this region is very narrow for thicker materials, so generally the hardness is constant throughout the HAZ. Postweld heat treatment at 750 °C for 1 hour sufficiently drops the hardness for 2 mm material due to martensite tempering (2 mm PWHT).

## Characteristics of the welds

Autogenous welds for this grade resemble that of the HTHAZ structure, i.e. the weld metal is entirely lath martensitic and only the lath size has increased from that of the HTHAZ. A comparison of these very similar structures is presented in Fig 6.

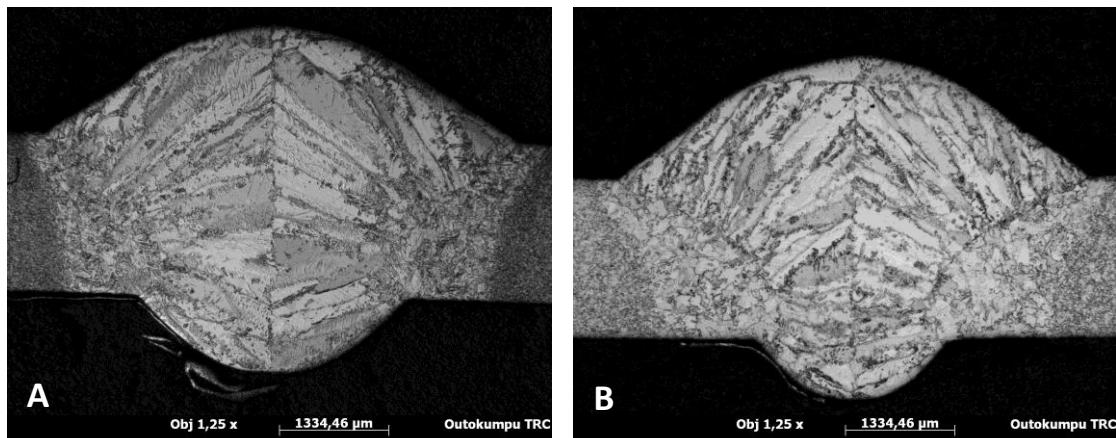


**Fig 6. HTHAZ (A) and WM (B) comparison of autogenous TIG. Low heat input, 0.06 kJ/mm. Very similar structures, only the lath size has increased in the weld metal.**

The higher peak temperature of the weld metal could initiate some amount of retained delta-ferrite, as the time above  $A_5$  temperature is the longest. However, with optical microscopy, no delta-ferrite was observed. Hardness measurements could be an alternative method to locate the softer delta-ferrite regions, but it is likely that the larger lath size of the martensite will also lower the hardness in the welds.

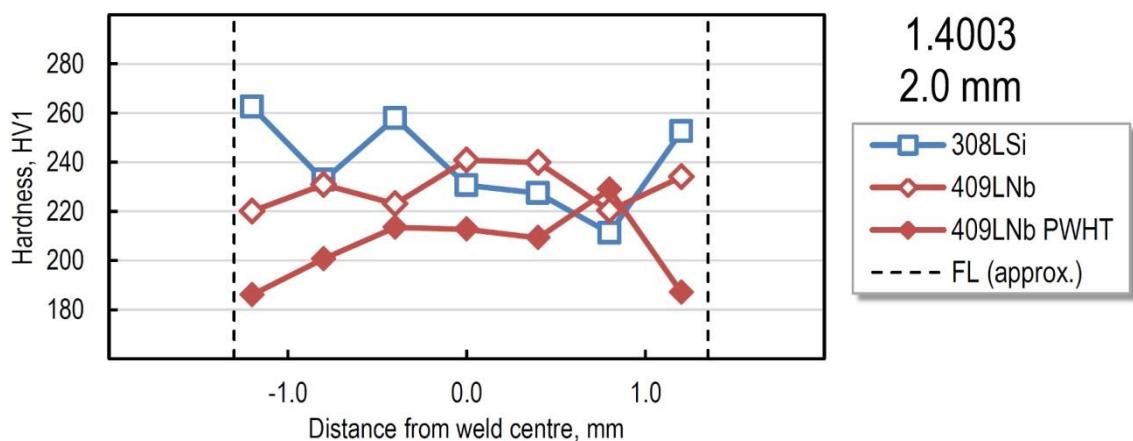
MAG weldings were made with two types of filler metal: austenitic 308LSi and ferritic 409LNb. The usage of stabilised ferritic filler metal 409LNb is questionable, as the niobium stabilisation will partially prevent the transformation to martensite by forming niobium-based precipitates. Because of this, the weld metal consists of a mixture of ferrite, intra- and intergranular martensite, and niobium-based precipitates, as shown in Fig 7A. A noticeable feature in the ferritic weld is the coarse columnar grain structure, which impinges at the weld centre. This epitaxial growth morphology is a common feature in many alloys, including ferritic grades.

To study the effect of a postweld heat treatment for ferritic weld metal, a tempering at 750 °C for 1 hour was used to transform the mixture of ferrite-martensite to alpha-ferrite and carbides. A postweld heat-treated weld metal microstructure is presented in Fig 7B. Overall, the weld metal has become cleaner, and the sharp martensite laths have transformed into carbide-lines.



**Fig 7. MAG weld metals of grade 1.4003. Ferritic 409LNb filler metal, heat input 0.24...0.26 kJ/mm. As-welded (A) and postweld heat treated (B).**

Hardness profiles for the MAG weld metals are presented in Fig 8. The large variation in the weld metal hardness is due to the presence of intra- and intergranular martensite. Tempering decreases the hardness by 20 HV, but still the hard carbides and Nb-precipitates exist.



**Fig 8. Hardness profiles of the grade 1.4003 MAG weld metals.**

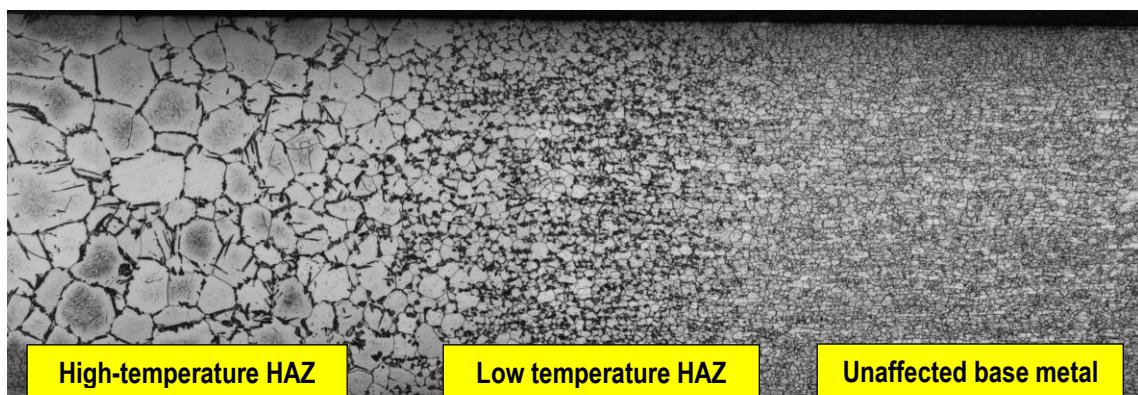
A more feasible alternatives for 409LNb filler metal are the martensitic 410L or 410NiMo filler metals. However, these could require preheating and/or postweld heat treatment, whether a stress-relief treatment at 500 to 600 °C or tempering at 700 to 800 °C. Because of this, the austenitic filler metals are usually preferred, like the studied 308LSi. When using an austenitic filler metal, the weld metal typically consists of a mixture of austenite, martensite and ferrite (A+M+F). However, this was not studied here in detail.

#### 4.1.2 Grade 1.4016

Four materials from two sources were tested, the thicknesses ranging from 1 to 3 mm. Three of the materials were in cold rolled condition and the 3.0 mm material was in hot rolled condition. There was a noteworthy difference between the chemical compositions of the materials, i.e. the cold rolled materials by Producer C had somewhat low carbon contents.

#### HAZ characteristics

This grade is essentially semi-martensitic in the HAZ, i.e. somewhat high carbon grain boundary martensite is observed alongside the ferritic matrix. Typical HAZ microstructure is presented in Fig 9 for 1 mm material. This type of microstructure is highly unwanted as the hard and brittle martensite surrounds the adjacent soft ferrite grains. Major losses in ductility and toughness are expected. The absence of stabilising elements exposes this grade also to intergranular corrosion and to high-temperature embrittlement (HTE). The overall decrease in corrosion resistance is expected due to the presence of martensite, which typically has about 2 % lower chromium content. Due to these problems, this grade is not recommended to be used in as-welded condition as it requires a postweld heat treatment to restore some of its properties.



**Fig 9. Heat-affected zone regions for grade 1.4016, sheet thickness 1.0 mm, heat input 0.06 kJ/mm, autogenous TIG.**

HAZ subzones are somewhat similar to that of the grade 1.4003, but the highest martensite content is usually around 30 %. The highest amount of martensite is observed at the low temperature HAZ (LTHAZ) because this region spends the most time at the dual-phase region. Near the fusion line, less martensite is observed due to the higher peak temperature and fewer time spent in the dual-phase region. Table 6 represents some of these measurements.

**Table 6. Martensite contents in 1.4016 welds, according to image analysis.**

Material	Heat input [kJ/mm]	LTHAZ [%]	HTHAZ [%]	WM [%]
Producer C TIG 1 mm	0.06	26 to 35	11 to 16	10 to 12
Producer C Gleeble 2 mm	0.10	n/a	11 to 14	n/a
Producer C MAG 2 mm	0.20	24 to 28	10 to 12	n/a
Producer C TIG 2 mm	0.23	27 to 35	10 to 12	7 to 9
Producer C Gleeble 2 mm	0.23	n/a	12 to 13	n/a
Producer C Gleeble 2 mm	0.40	n/a	14 to 16	n/a
Producer B Gleeble 2 mm	0.10	n/a	16 to 18	n/a
Producer B TIG 2 mm	0.22	30 to 34	16	14 to 16
Producer B Gleeble 2 mm	0.23	n/a	21 to 22	n/a
Producer B MAG 2 mm	0.25	31 to 35	17 to 25	n/a
Producer B Gleeble 2 mm	0.40	n/a	21 to 24	n/a
Producer C MAG 3 mm	0.32	n/a	26 to 28	n/a
Producer C MMA 3 mm	0.34	33 to 34	20 to 22	n/a

The measured martensite contents varied from 10 to 25 % in the HTHAZ, and 26 to 35 % in the LTHAZ. The Producer C 1 and 2 mm materials had higher ferrite factors, e.g. lower carbon contents than the Producer B material. Therefore, this has resulted in lower martensite contents in the HAZ subzones.

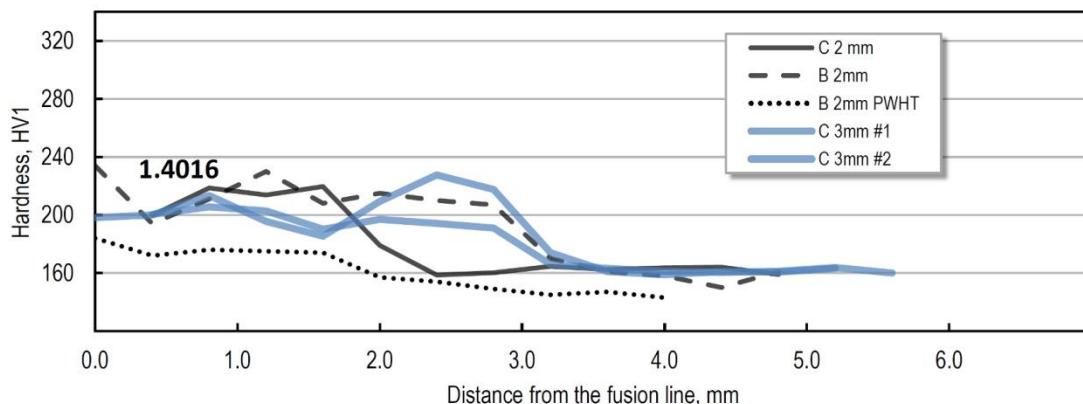
Alongside grain boundary martensite, dense chromium-based precipitates are observed both intra- and intergranular. Martensite has gathered most of the carbon available near the grain boundaries but still the chromium carbide precipitation is inevitable due to high carbon content for a ferritic grade and the rapid diffusion rates associated with the BCC crystal structure. Due to the rapid formation of chromium-based precipitates, corrosion problems are likely to occur, i.e. sensitisation and high-temperature embrittlement.

The change in cooling dimension, observed in 1.4003 weldments, affects slightly to the widths of the weld regions for 3 mm material in Table 7.

**Table 7. Widths of the weld regions for grade 1.4016.**

Material	Heat input [kJ/mm]	HTHAZ [mm]	WM [mm]	Total width of the joint [mm]
Producer C TIG 1 mm	0.06	1.0 to 1.2	1.5 to 1.7	5.7 to 5.9
Producer C MAG 2 mm	0.20	1.6 to 1.9	1.8 to 2.0	7.5 to 7.7
Producer C TIG 2 mm	0.23	1.7 to 2.0	2.6 to 2.8	8.5 to 9.1
Producer B TIG 2 mm	0.22	1.5 to 1.7	2.6 to 2.8	7.8 to 8.1
Producer B MAG 2 mm	0.25	0.9 to 2.4	2.4 to 3.7	8.3 to 10.5
Producer C MAG 3 mm	0.32	1.2 to 1.7	1.7 to 1.8	7.4 to 8.0
Producer C MMA 3 mm	0.34	0.4 to 1.5	n/a	n/a

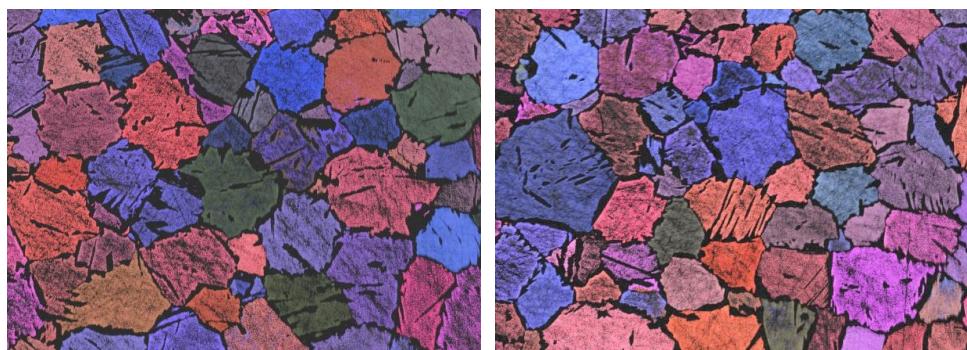
A moderate increase in hardness is observed in Fig 10 due to the presence of grain boundary martensite. The mean hardness profile is not steady as some of the measurements are from the soft delta-ferrite grains and some are from the hard grain boundary martensite. Width of the HAZ is slightly smaller (~1 mm) than the case with 1.4003, likely due to the higher  $A_1$  temperature, which has prevented the austenite transformation further away from the fusion line.



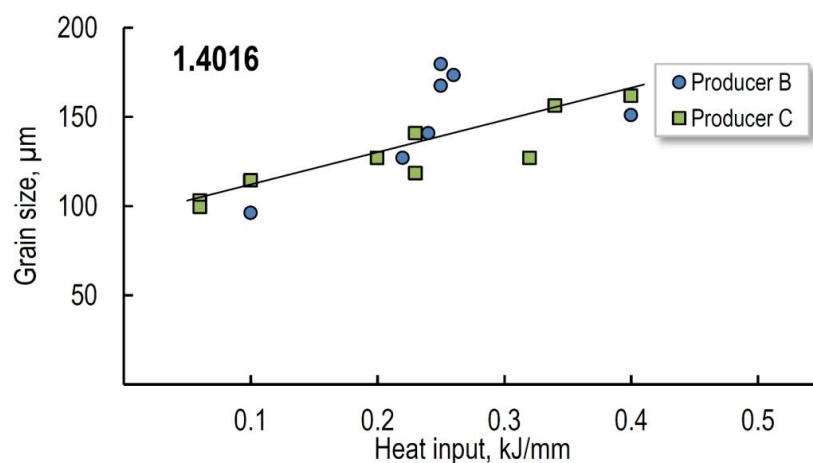
**Fig 10. Representative hardness profiles of the grade 1.4016 HAZs.**

Grain size analyses were made to clarify the effect of different heat inputs to grain sizes in the HTHAZ. The average increase in grain size is plotted in Fig 12. Most of the practical welds resulted in heat inputs from 0.20 to 0.26 kJ/mm, therefore, a few Gleeble simulations were made for lower heat inputs (0.10 kJ/mm) and higher heat inputs (0.40 kJ/mm). Based on these results, the grain growth in the HTHAZ has been rapid even with the lowest heat inputs.

A few SEM-EBSD analyses were also made to estimate if the grain boundary martensite hinders the actual grain size, Fig 11. As a conclusion, there could be some underestimation for grain size, but the amount is likely small.



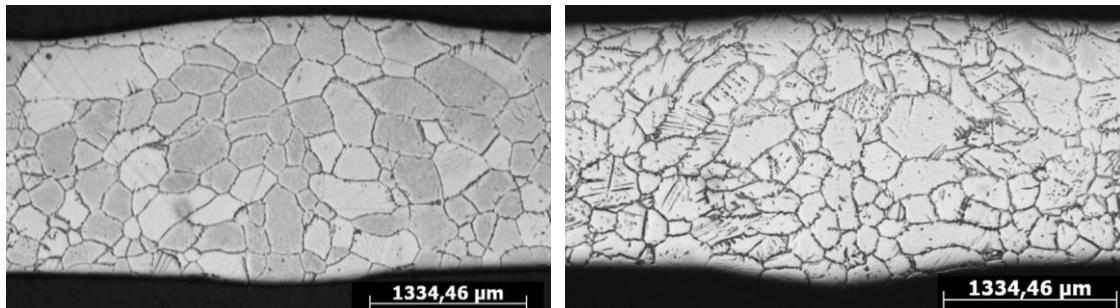
**Fig 11. SEM-EBSD analysis of grade 1.4016 HAZ grain size.**



**Fig 12. Ferrite grain size in the HTHAZ of 1.4016.**

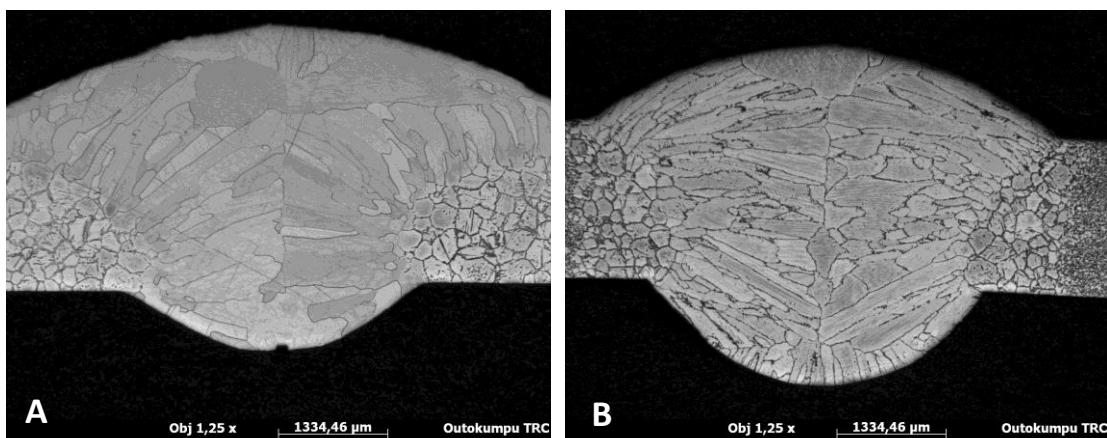
## Characteristics of the welds

The autogenous weld metal of grade 1.4016 resembles that of the HTHAZ. A semi-martensitic weld metal is obtained, as presented in Fig 13. Martensite content is lower in Producer C material due to lower carbon content.



**Fig 13.** Autogenous TIG weld metal of Producer C (left) and Producer B (right) grade 1.4016. 2.0 mm thickness, heat input 0.22...0.23 kJ/mm. Martensite along grain boundaries 7 to 9 % in Producer C, and 14 to 16 % in Producer B.

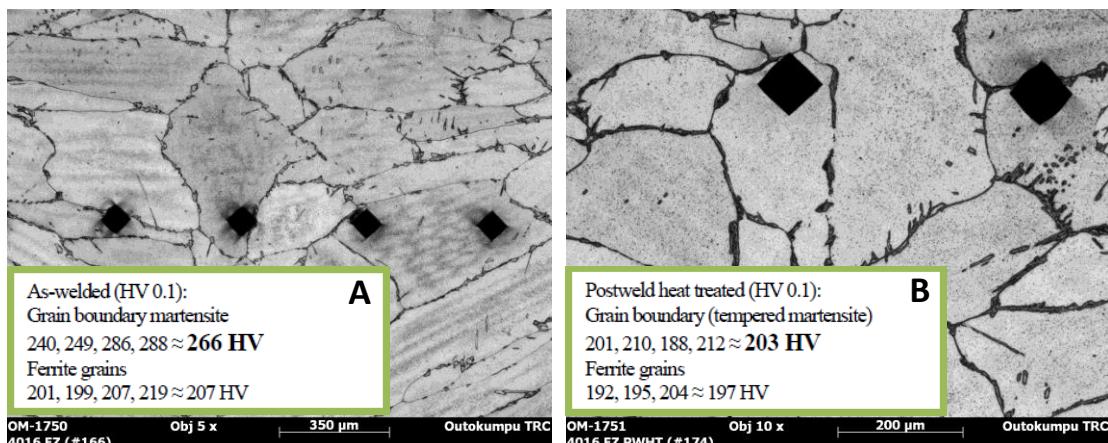
MAG weldments were done with three filler metals: austenitic 308LSi and ferritics 430LNb and 430Ti. Weld metal microstructures of ferritic filler metals are presented in Fig 14, notice the distinct coarse columnar grain structure in both welds.



**Fig 14.** Weld metals of grade 1.4016 weldments with ferritic filler metals. MAG welding, 430LNb (A) and 430Ti (B). Heat input 0.25...0.26 kJ/mm.

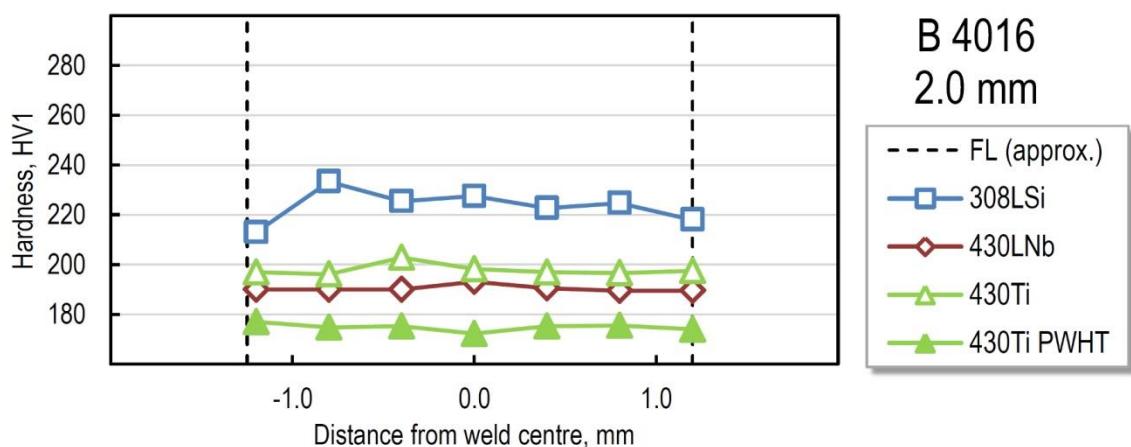
Grain boundary martensite is observed in the 430Ti weld metal because of the moderately high carbon content of the filler metal accompanied with the high carbon content of the base metal itself. Furthermore, the columnar-to-equiaxed transition has not occurred, preferably due to lower amount of titanium overall, which has not provided nucleation sites for grain refinement. Interestingly though, the niobium stabilising content in 430LNb filler metal seems to be sufficient to prevent the harmful grain boundary martensite.

Because of the grain boundary martensite, some of the 430Ti weldments were also postweld heat treated at 750 °C for 2 hours. Microstructures before and after are presented in Fig 15, along with some microhardness measurements. Even though the structures look very similar to each other, martensite has lost its sharpness and the grain boundaries have become darker during the PWHT. Hardness measurements clearly indicate a drop in hardness at the grain boundaries due to the effective tempering.



**Fig 15.** As-welded microstructure of grade 1.4016 430Ti weldment (A). Similar tempered structure (B). Notice the major drop in hardness at grain boundaries.

The hardness variations in the MAG weld metals of grade 1.4016 are presented in Fig 16. Ferritic filler metals have lower hardness than that of 308LSi welds. The PWHT sufficiently tempers the martensite in 430Ti welds and it results in lower overall hardness in the weld region.



**Fig 16.** Hardness profiles in the grade 1.4016 MAG weld metals. 2.0 mm thickness. Producer B material.

#### 4.1.3 Grade 1.4509

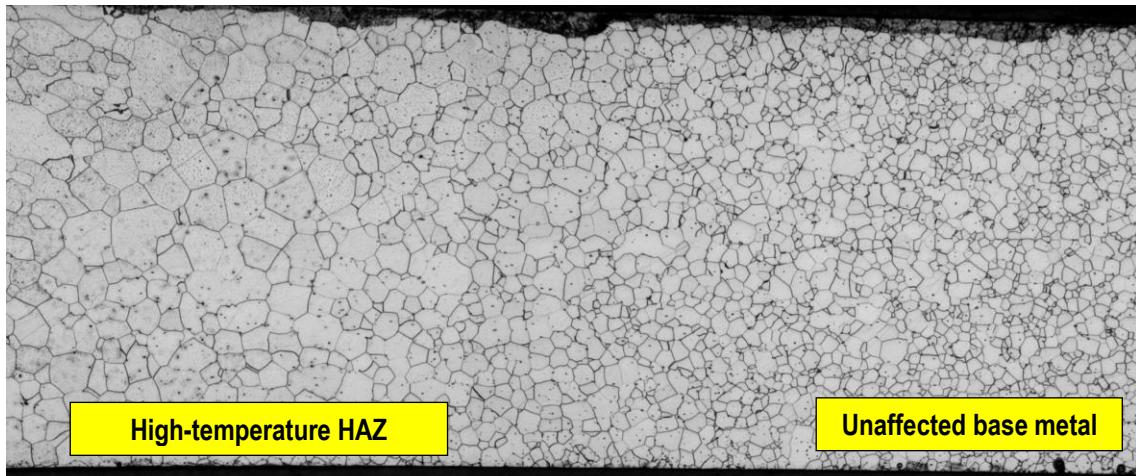
Seven 1.4509 materials from all three manufacturers were studied. Two materials were hot rolled, others being in cold rolled condition.

##### HAZ characteristics

This grade is fully ferritic, i.e. no brittle martensite is formed in the HAZ or in the weld metal. The absence of phase transformations somewhat increases the risk for grain coarsening. However, the precipitates of stabilising elements have a tendency for pinning the grain boundaries, similar to that of austenite in unstabilised grades.

A typical outline of the HAZ for 1.4509 is presented in Fig 17. Larger cuboidal precipitates are titanium nitrides and smaller precipitates are niobium carbides. Both intra- and intergranular precipitates exist, although higher heat inputs have a tendency for coarsening these precipitates. The Nb and Ti precipitates have beneficial effects by preventing

chromium carbide precipitation, i.e. sensitisation, and restricting the HTHAZ grain coarsening. However, excess amounts of stabilising elements could lead to a harmful coarsening of precipitates, leading to inferior properties.



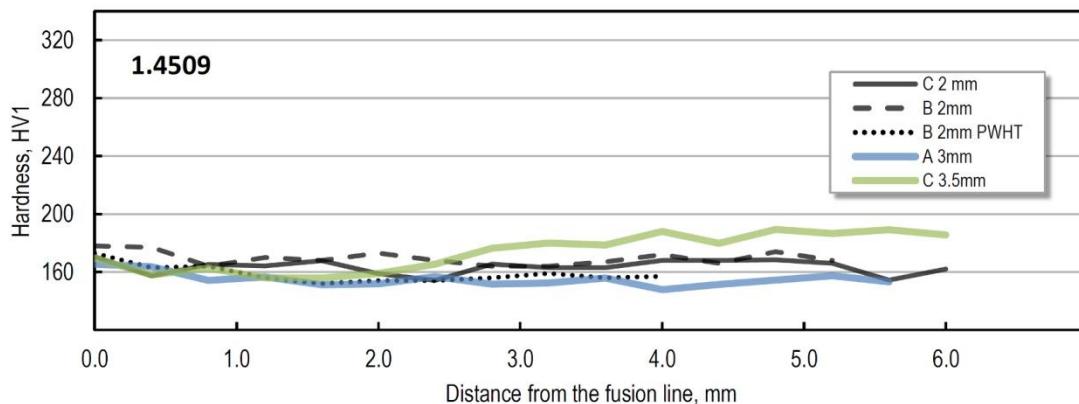
**Fig 17. Typical grain coarsening in the HTHAZ for grade 1.4509, 1.0 mm thickness, heat input 0.06 kJ/mm, autogenous TIG.**

Only two regions are visible: HTHAZ and the unaffected base metal. This is because only the grain size has increased when moving towards the fusion line, and no secondary phases like martensite exists. This grain growth region is considered to be the HTHAZ. The absence of phase transformation makes it difficult and rather unnecessary to approximate the total width of the HAZ. Overall, the width of the HTHAZ region remains quite constant at 1 to 2 mm for the studied materials.

**Table 8. Widths of the weld regions for grade 1.4509.**

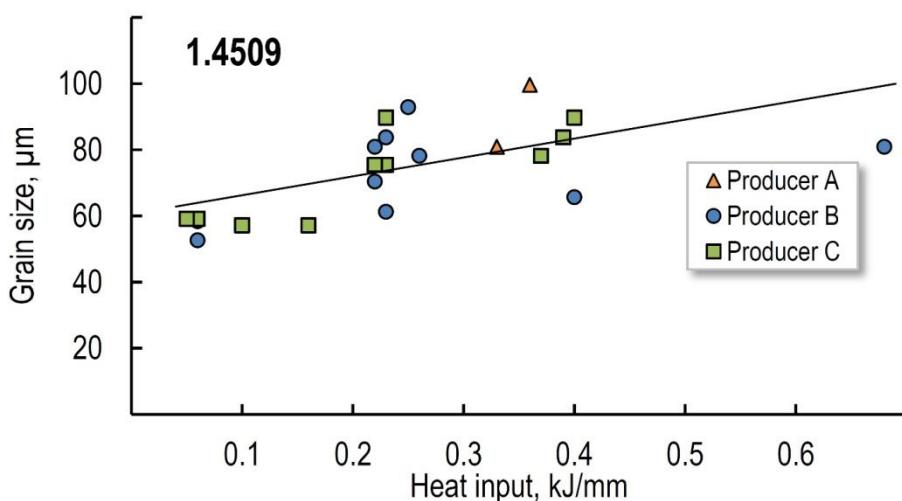
Material	Heat input [kJ/mm]	HTHAZ [mm]	WM [mm]	Total width of the joint (approx.) [mm]
Producer C TIG 1 mm	0.06	0.8 to 0.9	1.9 to 2	4.9 to 5.5
Producer B TIG 1 mm	0.06	0.8 to 1.0	2.1 to 2.4	5.3 to 5.7
Producer C MAG 2 mm	0.16	1.2 to 2.0	1.4	5.2
Producer C MMA 2 mm	0.22	1.4 to 1.8	n/a	n/a
Producer C TIG 2 mm	0.23	2.1 to 2.2	3.4	8.7 to 9.2
Producer B TIG 2 mm	0.23	1.7 to 2.1	3.1 to 3.5	7.8 to 8.0
Producer B MAG 2 mm	0.23	1.2 to 2.1	1.5 to 3.4	6.8 to 8.2
Producer B MMA 2 mm	0.26	1.5 to 1.9	n/a	n/a
Producer A MAG 3 mm	0.33	1.4 to 1.7	1.9	6.6 to 7.0
Producer A MMA 3 mm	0.36	1.0 to 2.2	n/a	n/a
Producer C MAG 3.5 mm	0.37	1.9 to 2.7	1.8 to 2.1	8.9 to 9.5
Producer C MMA 3.5 mm	0.39	1.8 to 2.6	n/a	n/a
Producer B MMA 4 mm	0.68	1.4 to 2.4	n/a	n/a

This grade has roughly unchanged hardness throughout the heat-affected zone as shown in Fig 18. Minor softening has occurred for the hot rolled Producer C 3.5 mm material.



**Fig 18. Representative hardness profiles of the grade 1.4509 HAZs.**

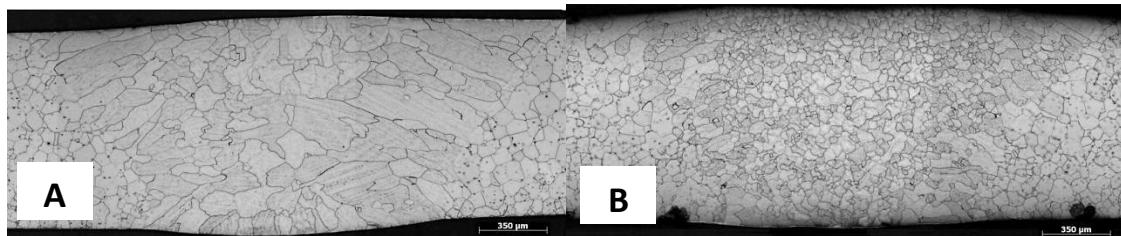
Grain size analyses were made to clarify the effects of different heat inputs to the grain sizes in the HTHAZ region. The increase in grain size is plotted in Fig 19. A detailed data for the grain size measurements is included to appendices. It can be seen that the grain growth in the HTHAZ region is much more restricted in 1.4509 than in 1.4016 due to pinning capability of the stabilising precipitates.



**Fig 19. Grain size in the HTHAZ of 1.4509.**

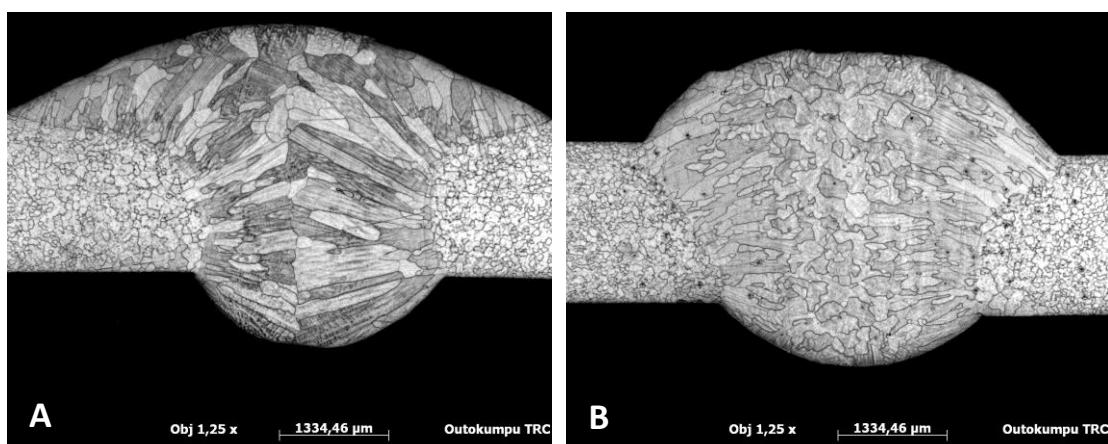
### Characteristics of the welds

The amount of equiaxed grains in the weld metal depends on the chemical composition of the materials and the welding specifications, e.g. method, speed, pulse parameters, etc. Two examples for 1 mm autogenous TIG weld metals are presented in Fig 20. Grain size and morphology diverges between these two. Producer C material has solidified columnar-like and the equiaxed region vaguely exists at the weld centreline. Grain size in the weld metal is much larger than in the Producer B grade. The equiaxed grain content in the Producer B's 1 mm 1.4509 material is superb to that of Producer C.



**Fig 20. Autogenous TIG weld metals of 1.4509, Producer C (a) and Producer B (b). Material thickness 1.0 mm, heat input 0.06 kJ/mm, welding speed 455 mm/min.**

MAG weld metals with different filler meals were also studied. Producer B 2.0 mm materials were welded with previously discussed 430LNb and 430Ti ferritic filler metals. The microstructures of these are presented in Fig 21.



**Fig 21. MAG weld metals of grade 1.4509 with different ferritic filler metals. Nb-stabilised 430LNb (a) and Ti-stabilised 430Ti (b).**

Like previously with 1.4003 and 1.4016, the grain structure in the weld metal is columnar-like, when using Nb-stabilised filler metals like 409LNb or 430LNb. Harmful impingement of columnar grains can cause hot cracking, as the impurities could segregate to the weld centreline. Large and aligned columnar grains can also decrease the toughness by allowing effortless crack propagation through the grain boundaries.

Titanium stabilised 430Ti has much more equiaxed grain content, as the titanium-rich particles have been acted as nucleation sites for new grains. These nucleation particles are obstacles for planar/columnar solidifying fronts and lead to change in grain morphology.

Figures 22, 23, 24 and 25 represent the hardness profiles obtained from various thicknesses of the grade 1.4509 weld metals.

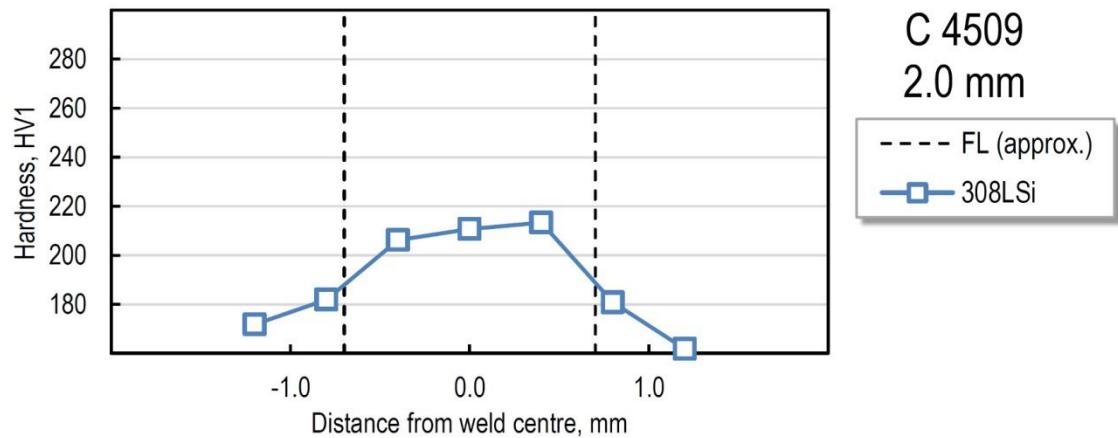


Fig 22. Hardness profile for the Producer C MAG weld metal, 2.0 mm thickness.

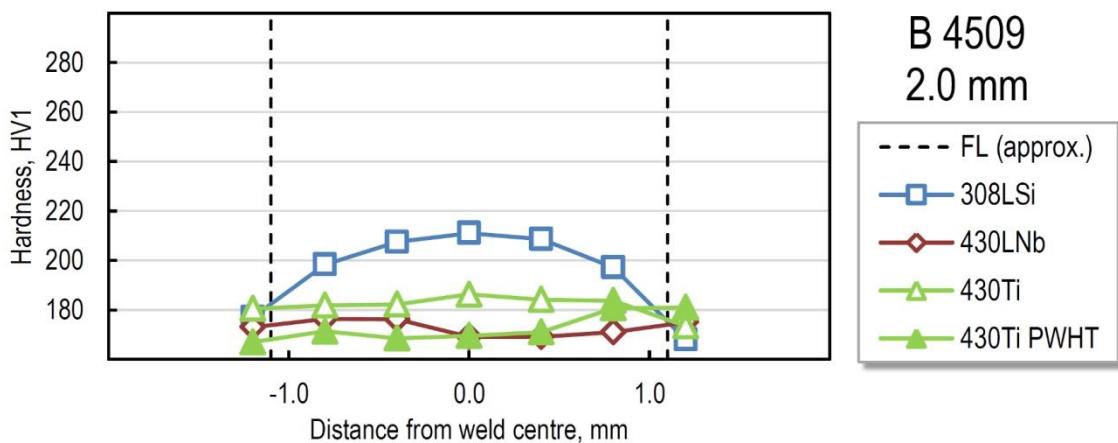


Fig 23. Hardness profiles for the Producer B MAG weld metals, 2.0 mm thickness.

Austenitic weld metal peaks at about 215 HV. Ferritic filler metals have about 20 HV lower hardness, and very similar to that of the HAZ. In this case, the PWHT does not decrease the hardness of the 430Ti weld metal significantly due to the absence of martensite. Slight decrease might be in connection with stress relief and/or coarsening of the precipitates during the heat treatment.

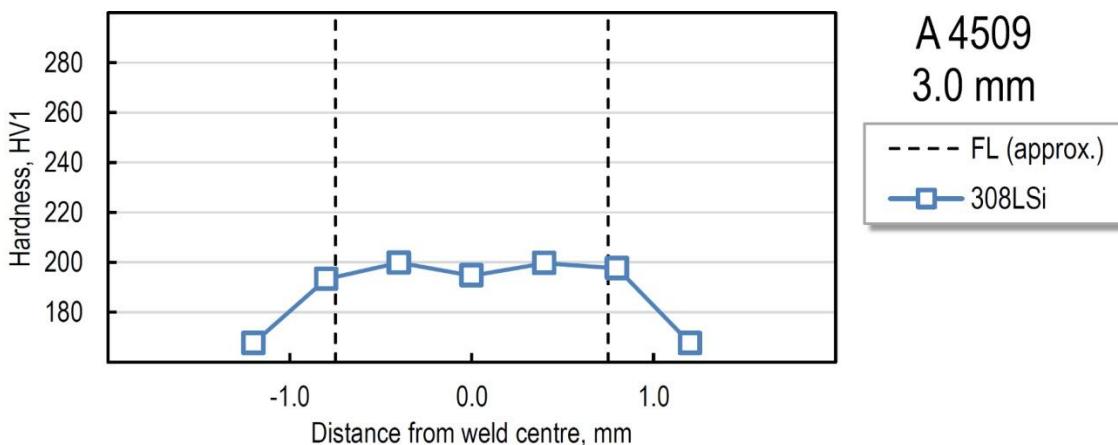
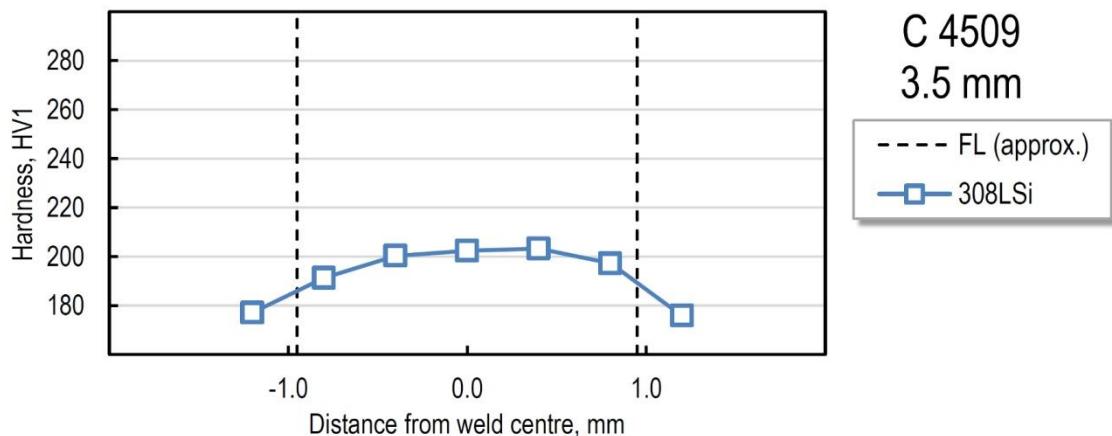


Fig 24. Hardness profile for the Producer A MAG weld metal, 3.0 mm thickness.



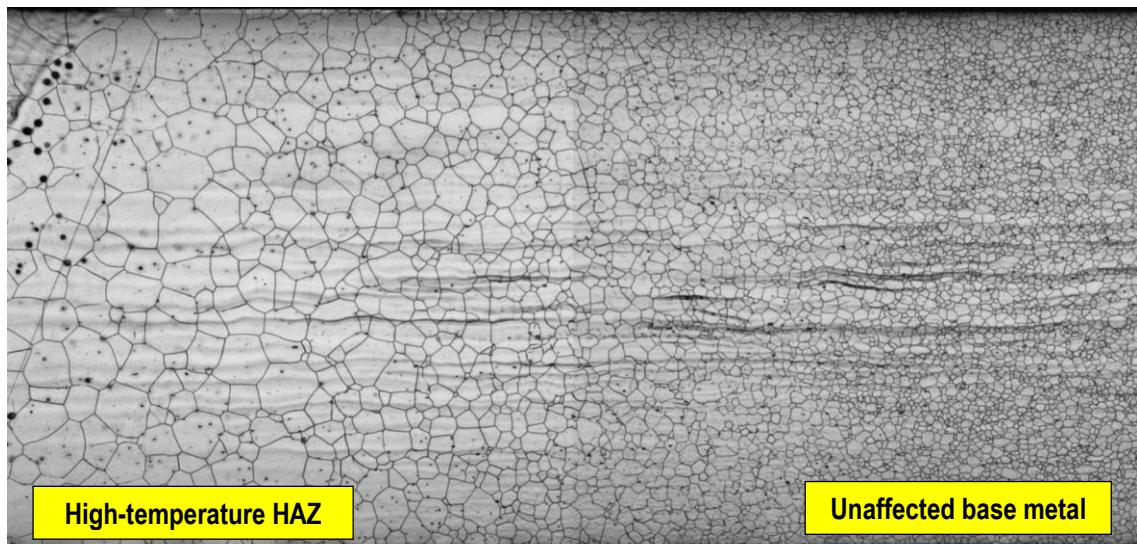
**Fig 25. Hardness profile for the Producer C MAG weld metal, 3.5 mm thickness.**

The 3.0 mm and 3.5 mm materials share similar behaviour to each other, i.e. hardness of the welds fabricated with austenitic filler metal peaks roughly at 200 HV.

#### 4.1.4 Grade 1.4521

##### HAZ characteristics

Three cold rolled materials were studied from Producers B and C, thicknesses varied from 1 to 2 mm. This grade is similar to that of 1.4509 but has a 2 % addition of molybdenum, which enhances especially the pitting corrosion resistance. Typical microstructure in the HAZ is shown at Fig 26.



**Fig 26. Typical grain coarsening in the HAZ for grade 1.4521, 1.0 mm thickness, heat input 0.06 kJ/mm, autogenous TIG.**

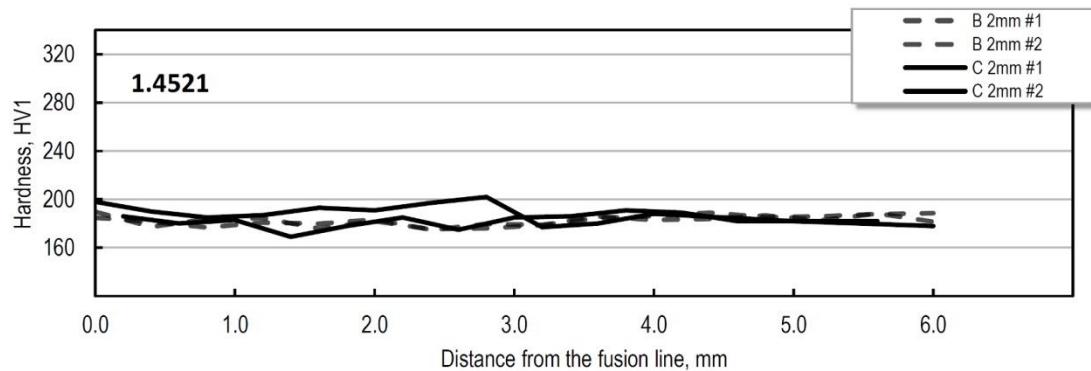
The microstructure in the HAZ is identical to that of the grade 1.4509. However, molybdenum content is known to increase the risk for sigma- and Laves-phase embrittlement. These embrittlement phenomena are usually avoidable during welding of sheet materials, but could come to attention when welding thicker sections, i.e. when the cooling rate is slow. Furthermore, crudely chosen service temperatures are the most likely sources for these phenomena to occur, rather than welding.

Width of the weld regions were measured like previously and summarised in Table 9.

**Table 9. Widths of the weld regions for grade 1.4521.**

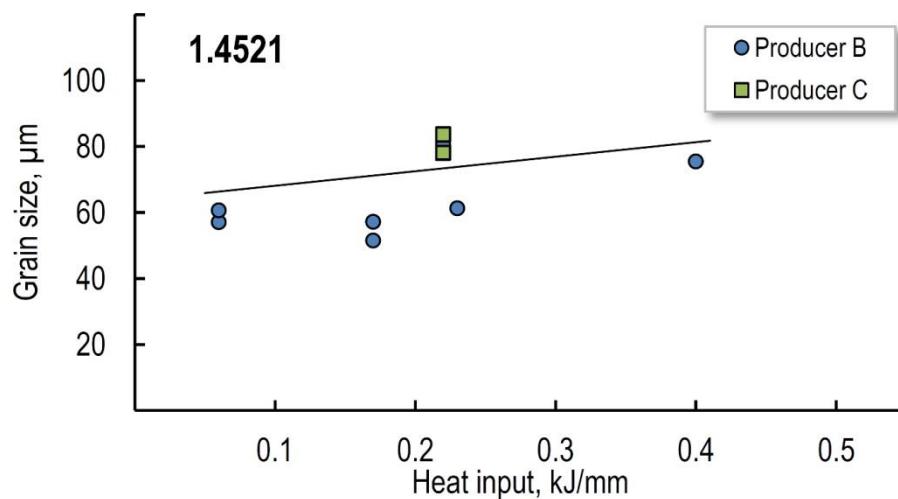
Material	Heat input [kJ/mm]	HTHAZ [mm]	WM [mm]	Total width of the joint (approx.) [mm]
Producer B TIG 1 mm	0.06	0.9 to 1.2	2.4 to 2.7	5.7 to 6.3
Producer C MAG 2 mm	0.22	1.6 to 2.5	2.0	6.0 to 6.6
Producer C TIG 2 mm	0.22	1.2 to 2.0	3.8	7.2
Producer B MAG 2 mm	0.17	1.2 to 1.5	1.2 to 1.8	5.2 to 5.8
Producer B TIG 2 mm	0.22	1.6 to 1.8	3.7 to 4.0	7.8 to 8.0

Hardness profile in Fig 27 is similar to that of grade 1.4509, i.e. the hardness remains steady because no martensite is present. However, the overall hardness is slightly higher than in the 1.4509 due to solid solution strengthening effect of molybdenum.



**Fig 27. Representative hardness profiles of the grade 1.4521 HAZs**

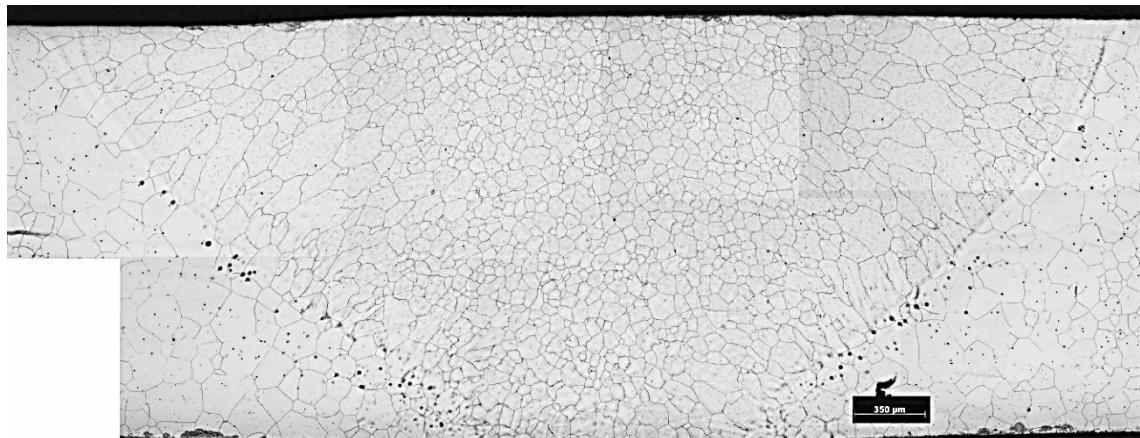
Grain growth evaluation was done for the 1.4521 like with previous grades. Grain growth in the HTHAZ region is limited, much like in 1.4509, because of the pinning effect of Nb and Ti precipitates. However, the limited amount of materials and thicknesses reduces the accuracy.



**Fig 28. Grain size in the HTHAZ of 1.4521.**

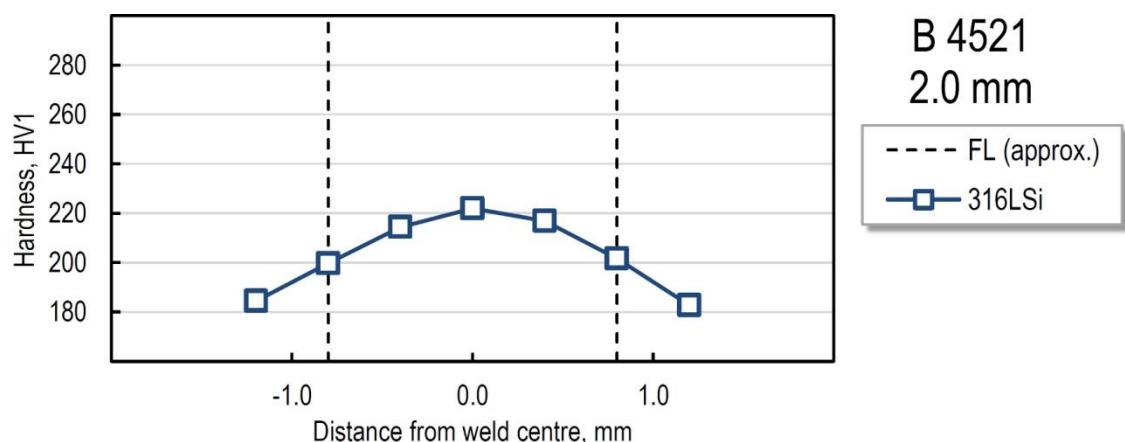
### Characteristics of the welds

Weld metals within this grade are similar to those of grade 1.4509. The molybdenum content does not alter the microstructure in the HAZ nor in the weld metal. Fig 29 represents an example of the autogenous TIG weld metal for Producer C 2.0 mm material. The observed equiaxed grain content is high in this weld metal, certainly improving the forthcoming toughness properties.



**Fig 29. Autogenous TIG weld metal of Producer C grade 1.4521. 2.0 mm thickness, heat input 0.22 kJ/mm.**

Hardness profile for the weld fabricated with the molybdenum alloyed austenitic 316LSi filler metal is presented in Fig 30. Hardness is similar to ones presented previously for 1.4509 welds due to very similar compositions.



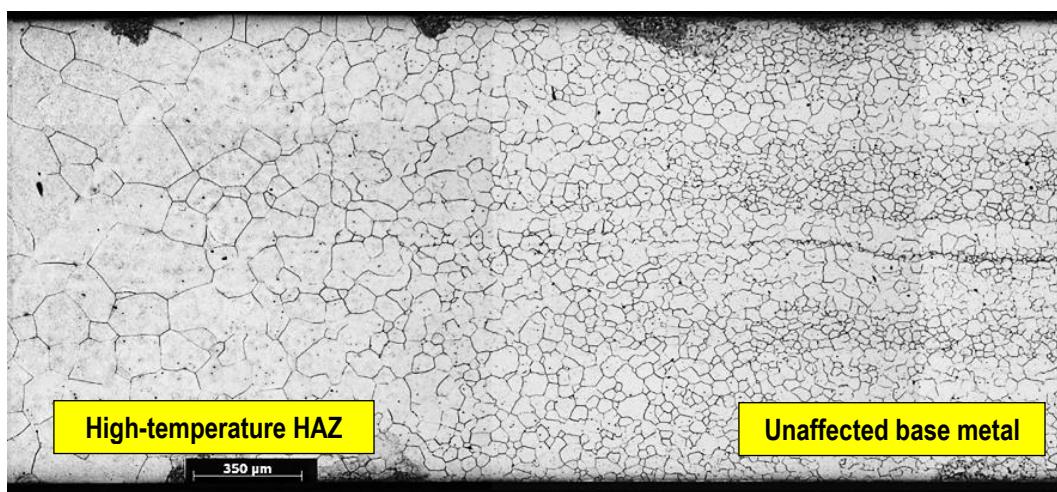
**Fig 30. Hardness profile of the Producer B MAG 316LSi weld metal, 2.0 mm thickness.**

#### 4.1.5 Grade 1.4621

##### HAZ characteristics

Only one 1.5 mm material was studied, and it was manufactured by Producer A. This lately standardised ferritic stainless steel grade has gained increasing attention due its capability for replacing common austenitic grades without the use of added molybdenum, when compared to that of 1.4521.

The HAZ microstructure for 1.4621 is presented in Fig 31. Again, there is not much difference to previously discussed stabilised grades 1.4509 or 1.4521. However, being only Nb stabilised, the material does not contain renowned cubic TiN precipitates.

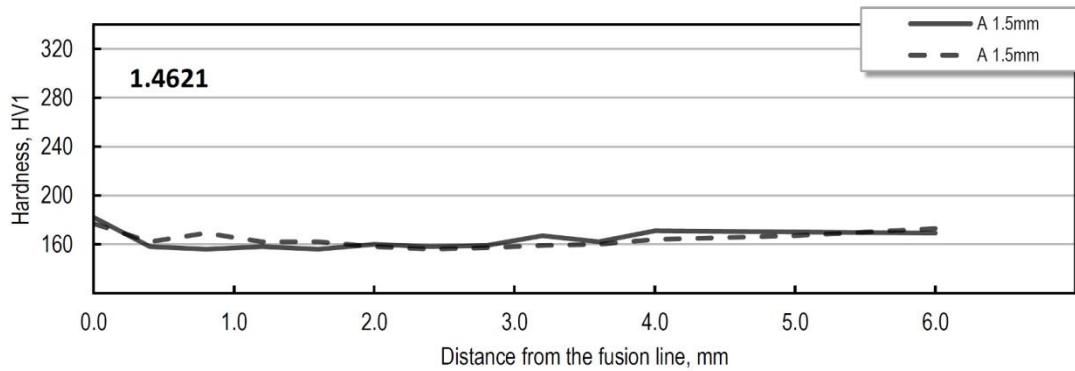


**Fig 31. Heat-affected zone microstructure for grade 1.4621, 1.5 mm thickness, heat input 0.16 kJ/mm, autogenous TIG.**

HTHAZ width is similar to that of other stabilised grades, presented in Table 10. The absence of molybdenum decreases the hardness from that of 1.4521. Still, the hardness is unchanged (Fig 32) and resembles that of the 1.4509.

**Table 10. Widths of the weld regions for grade 1.4621.**

Material	Heat input [kJ/mm]	HTHAZ [mm]	WM [mm]	Total width approx. [mm]
Producer A MAG 1.5 mm	0.15	0.7 to 1.4	n/a	n/a
Producer A TIG 1.5 mm	0.16	1.0 to 1.3	3.0	6.0 to 6.2



**Fig 32. Hardness profiles of the grade 1.4621 HAZs.**

Because only one material was used for this grade, the grain size analyses are limited, presented in Table 11. The increase is slightly higher than comparable welds in 1.4509 and 1.4521 but further conclusions cannot be made.

**Table 11. Grain size analyses for 1.4621 welds.**

Material	Heat input [kJ/mm]	Base metal [µm]	HTHAZ [µm]
Producer A MAG 1.5 mm	0.15	27	90
Producer A TIG 1.5 mm	0.16	27	96

### Characteristics of the welds

The absence of titanium increases substantially the grain size in the weld metal, because the Nb-based precipitates are not as effective nucleation sites for new grains. The columnar grain structure is partially avoided, because of the somewhat slow welding speed. Slower welding speeds also prevent the impingement of columnar grains.



**Fig 33. Autogenous TIG weld metal of grade 1.4621, 1.5 mm thickness, heat input 0.16 kJ/mm, welding speed 106 mm/min. Large-grained weld metal.**

## 4.2 Tension tests

Due to the heterogeneous nature of the transverse tension weld test, the ultimate tensile strength (UTS) and the location of the fracture is evaluated. Minimum UTS is reported to emphasise the scatter obtained during the tests. In addition, when the fracture is located at the base metal, it merely indicates that the weld metal has a higher strength than the parallel base metal. Because of this, any comparisons for different weld metals is prohibited.

### 4.2.1 Test results

Tension test results for grade 1.4003 are presented in Table 12.

**Table 12. Tension test results (TD) for the base metals and weldments for grade 1.4003.**  
**Results are averages of multiple samples. Red indicates significantly lower UTS than that of the base metal (< -5 MPa), yellow slightly lower UTS (> -5 MPa) and green above or similar the UTS of the base metal.**

Grade	Mfr.	Thickness (mm)	Method	Filler	UTS (N/mm <sup>2</sup> )	UTS min (N/mm <sup>2</sup> )	Location of fracture
1.4003	B	1.0	-	-	478	477	-
			TIG	autog.	477	476	BM
	B	2.0	-	-	496	495	-
			MAG	308LSi	504	491	BM
			MAG	409LNb	524	501	BM
			MAG	409LNb	496	476	BM and HAZ
				PWHT			
	B	4.0	-	-	577	567	-
			MMA	308L	524	509	BM
	B	6.0	-	-	483	482	-
			MMA	308L	488	484	BM

Based on these results, the strengths of the as-welded joints usually matched that of the parallel base metals. Only the notable high-strength 4.0 mm material resulted in lack of UTS in welds. Furthermore, the fracture occurs consistently from the base metal, which is preferred.

Tempering (PWHT) decreases the UTS and the fracture occurs either from the base metal or from the HAZ.

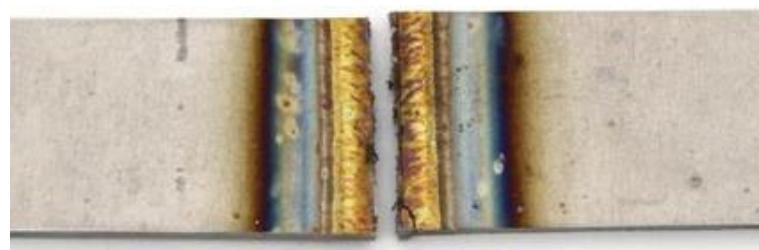
Mean tension test results for grade 1.4016 are presented in Table 13.

**Table 13. Tension test results (TD) for base metals and weldments of grade 1.4016.**

Grade	Mfr.	Thickness (mm)	Method	Filler	UTS (N/mm <sup>2</sup> )	UTS min (N/mm <sup>2</sup> )	Location of fracture
1.4016	C	1.0	-	-	519	516	-
C	-	2.0	TIG	autog.	502	501	BM
			TIG	autog.	496	496	-
			MAG	308LSi	461	445	WM
B	-	2.0	-	-	501	498	BM
			TIG	autog.	488	488	-
			MAG	308LSi	480	462	BM and WM
			MAG	430LNb	515	508	BM
			MAG	430Ti	503	499	BM
			MAG	430Ti	507	500	BM
C	-	3.0	-	-	495	490	BM
			MAG	308LSi	524	523	-
			MMA	308L	546	540	BM
					510	502	BM

It is evident that the autogenous TIG weldments do not match the base metal strength as the materials by both manufacturers lack of UTS. In addition, the MMA welds for 3.0 mm material resulted in lack of UTS. On the other hand, all MAG weldments have at least similar strength to that of the base metal.

TIG weldments showed an increasing tendency for an unwanted weld metal fracture, Fig 34. MAG and MMA weldments fractured consistently from the base metal.



**Fig 34. A brittle weld metal fracture in autogenous TIG weld of 1.4016.**

Mean tension test results for grade 1.4509 are presented in Table 14.

**Table 14. Tension test results (TD) for base metals and weldments of grade 1.4509.**

Grade	Mfr.	Thickness (mm)	Method	Filler	UTS (N/mm <sup>2</sup> )	UTS min (N/mm <sup>2</sup> )	Location of fracture
1.4509	C	1.0	-	-	<b>479</b>	<b>478</b>	-
			TIG	autog.	478	477	BM
	B	1.0	-	-	<b>482</b>	<b>479</b>	-
			TIG	autog.	484	482	BM
	C	2.0	-	-	<b>489</b>	<b>489</b>	-
			TIG	autog.	482	481	BM
			MAG	308LSi	505	502	BM
	B	2.0	-	-	<b>497</b>	<b>496</b>	-
			TIG	autog.	482	480	BM
			MAG	308LSi	503	495	BM
			MAG	430LNb	486	477	FL
			MAG	430Ti	509	500	FL
			MAG	430Ti	509	494	WM
				PWHT			
	A	3.0	-	-	<b>461</b>	<b>460</b>	-
			MAG	308LSi	484	474	BM
			MMA	308L	470	465	BM
	C	3.5	-	-	<b>579</b>	<b>578</b>	-
			MAG	308LSi	557	549	HAZ
			MMA	308L	533	523	HAZ
	B	4.0	-	-	<b>494</b>	<b>493</b>	
			MMA	308L	500	497	BM

The 1.0 mm materials have roughly the same strengths than that of the base metals, but the 2.0 mm TIG welds lack of UTS. Titanium stabilised ferritic welds (430Ti) matched the base metal strength but the niobium-stabilised welds metal (430LNb) results in lack of UTS. Austenitic MAG welds match the 2.0 mm base metals strength but the 3.5 mm welds lack of UTS. MMA welds surpassed the base metal UTS in Producer A 3.0 and Producer B 4.0 mm materials. It should be emphasised that the UTS in 3.5 mm Producer C base metal surpassed all the other materials.

In austenitic welds, the fracture occurs frequently from the base metal, except for that of Producer C 3.5 mm material. Although lacking UTS, the autogenous TIG welds fractured from the parallel base metal (Fig 35), which is preferred. Ferritic MAG welds suffered from fractures from the fusion line or weld metal.



**Fig 35. A ductile base metal fracture in autogenous TIG weldment of 1.4509.**

Mean tension tests for grade 1.4521 are presented in Table 15.

**Table 15. Tension test results (TD) for base metals and weldments of grade 1.4521.**

Grade	Mfr.	Thickness (mm)	Method	Filler	UTS (N/mm <sup>2</sup> )	UTS min (N/mm <sup>2</sup> )	Location of fracture
1.4521	B	1.0	-	-	<b>585</b>	<b>583</b>	-
			TIG	autog.	564	554	WM
	C	2.0	-	-	<b>550</b>	<b>548</b>	-
	TIG		autog.	534	530	WM	
	MAG		316LSi	569	564	BM	
	B	2.0	-	-	<b>576</b>	<b>574</b>	-
	TIG		autog.	554	542	WM	
	MAG		316LSi	576	570	BM	

Curiously, the autogenous TIG welds showed a notable decrease in the UTS. MAG welds fabricated with austenitic filler metals matched the base metal strengths. The TIG welds fractured frequently through the weld region, and MAG welds from the base metal.

Therefore, there is a clear difference between the TIG weldments of 1.4509 and 1.4521. The autogenous welds of 1.4521 have inferior features in both the UTS and fracture behaviour.

Mean tension tests for grade 1.4621 are presented in Table 16.

**Table 16. Tension test results (TD) for base metals and weldments of grade 1.4621.**

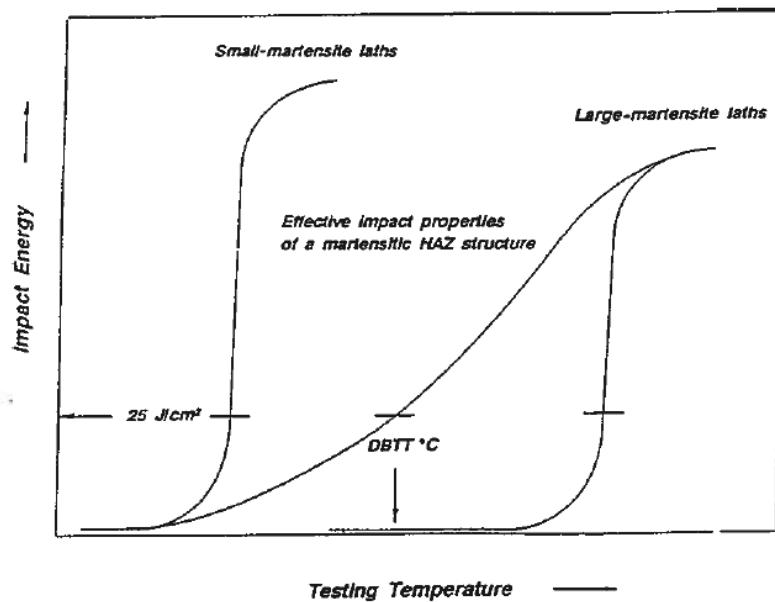
Grade	Mfr.	Thickness (mm)	Method	Filler	UTS (N/mm <sup>2</sup> )	UTS min (N/mm <sup>2</sup> )	Location of fracture
1.4621	A	1.5	-	-	<b>479</b>	<b>478</b>	-
			TIG	autog.	479	476	BM
			MAG	316LSi	496	482	BM

TIG and MAG welds for 1.4621 matched or surpassed the base metal strength and the fracture occurred preferably from the base metal.

### 4.3 Impact toughness tests

In total of 1580 impact toughness tests were made for the base metals, HTHAZs and weld metals of 2 to 6 mm materials. A few Gleeble simulated samples are included for grades 1.4016, 1.4509 and 1.4521.

The previously observed change in the cooling dimension influences essentially to the HTHAZ impact toughness tests for grade 1.4003. The forthcoming test results for notched 4 to 6 mm samples are *in fact* a combination of high and low temperature HAZs, while the test results for the 2 mm samples represent most accurately the HTHAZ region. Larger laths have somewhat inferior mechanical properties, as it increases the ductile-to-brittle transition temperature, like presented in Fig 36 by Zaayman [3].



**Fig 36. Influence of martensite lath size to the DBTT. [3]**

#### 4.3.1 Grade 1.4003

Impact toughness test results for studied 1.4003 materials are presented in Figs 37–39.

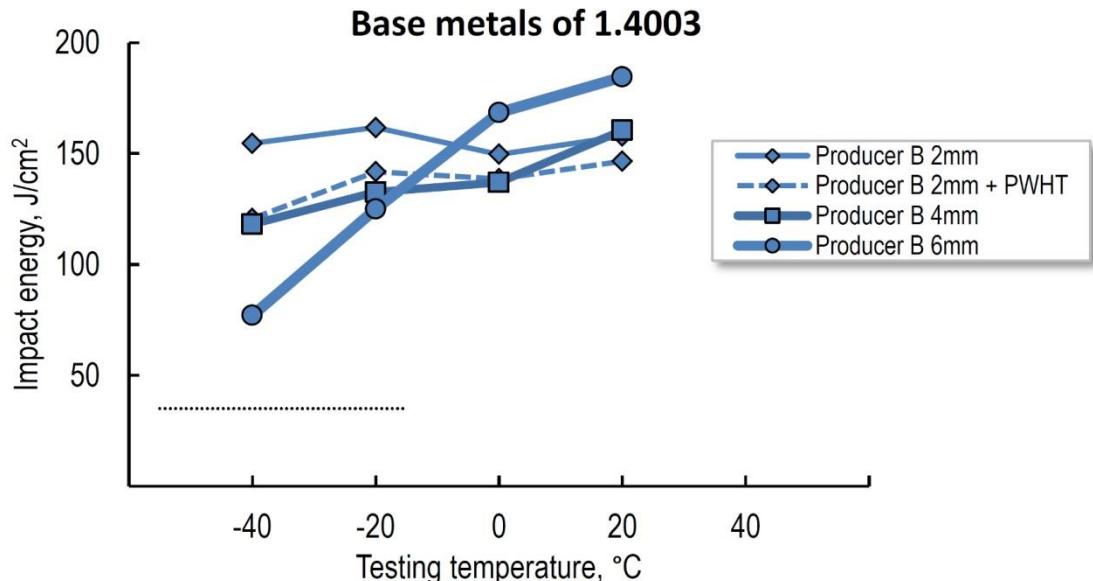


Fig 37. Base metal impact toughness for grade 1.4003.

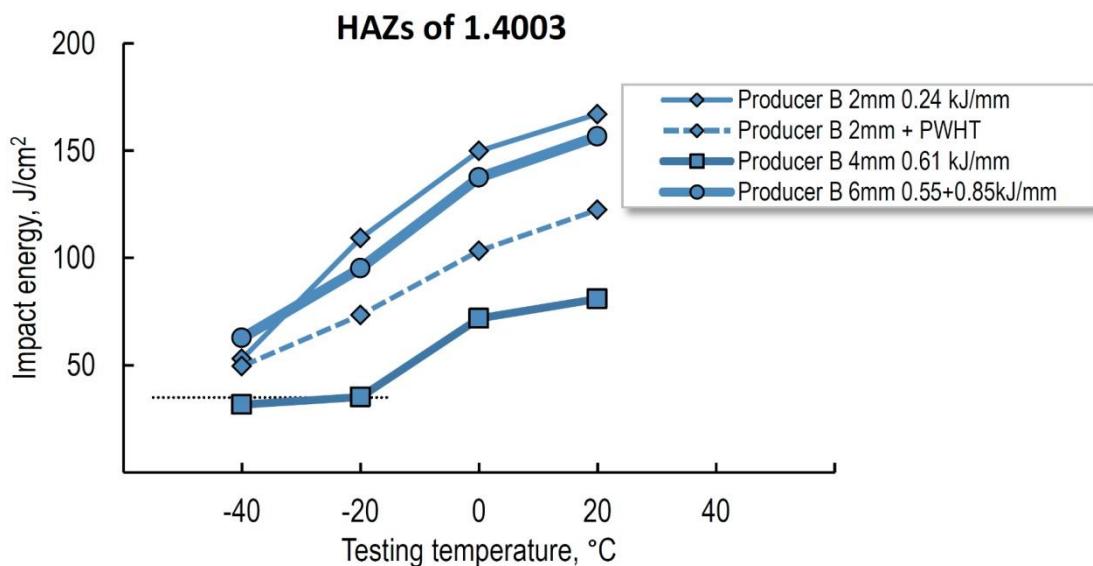
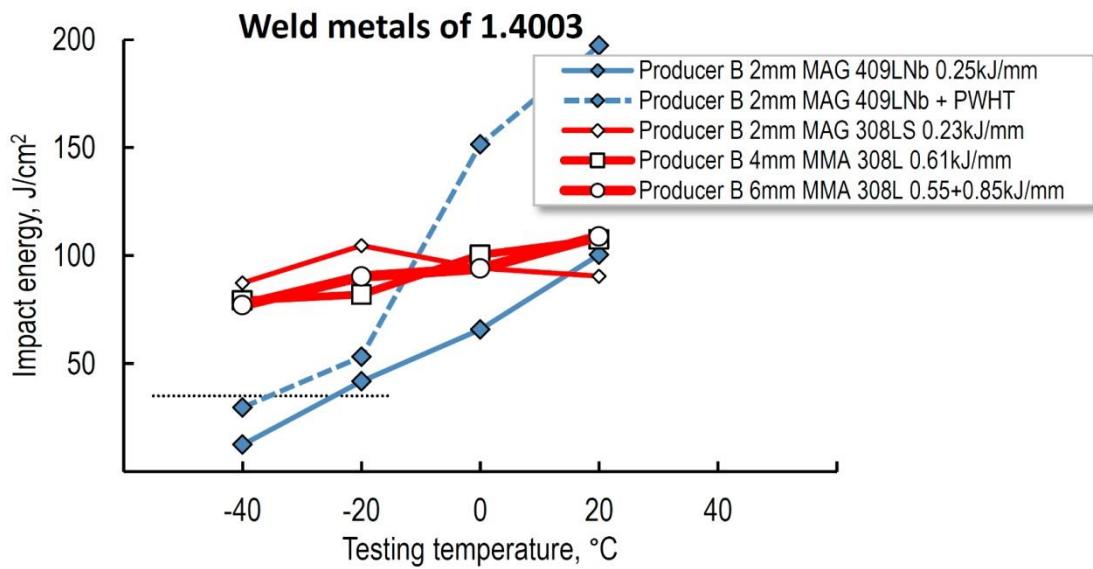


Fig 38. HAZ impact toughness for grade 1.4003. Only the 2 mm thickness can be considered to represent the HTHAZ. Others are a mixture of LTHAZ and HTHAZ.



**Fig 39. Weld metal impact toughness for grade 1.4003.**

All studied base materials have excellent toughness down to -40 °C, and none of the materials exhibits the DBTT. The PWHT applied for some of the 2.0 mm welds did not affect drastically to the base material toughness.

The HAZ results are divided into three groups. The 2.0 mm materials HTHAZ toughness loses its upper shelf energy, but still behaves in ductile manner down to -40 °C. The 4.0 mm material behaves more in brittle manner, partially because of the thickness-effect, reaching to DBTT at -20 °C. The 6.0 mm material does not represent the HTHAZ toughness, as the curve is practically similar to that of 2.0 mm. This curve represents the combined toughness of the HTHAZ and LTHAZ regions.

Weld metal results indicate that the semi-martensitic weld of 409LNb has the lowest toughness, reaching the DBTT at -20 °C. The PWHT improves mainly the upper shelf energy. Welds fabricated with the austenitic filler metals 308L and 308LSi are the most ductile.

#### 4.3.2 Grade 1.4016

Impact toughness test results for studied 1.4016 materials are presented in Figs 40–42.

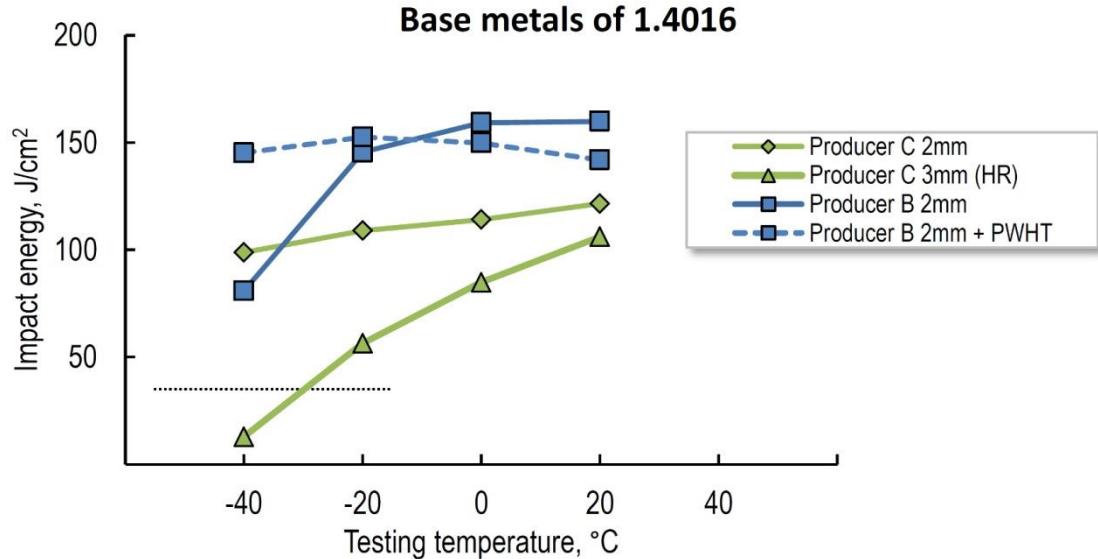


Fig 40. Base metal impact toughness for grade 1.4016.

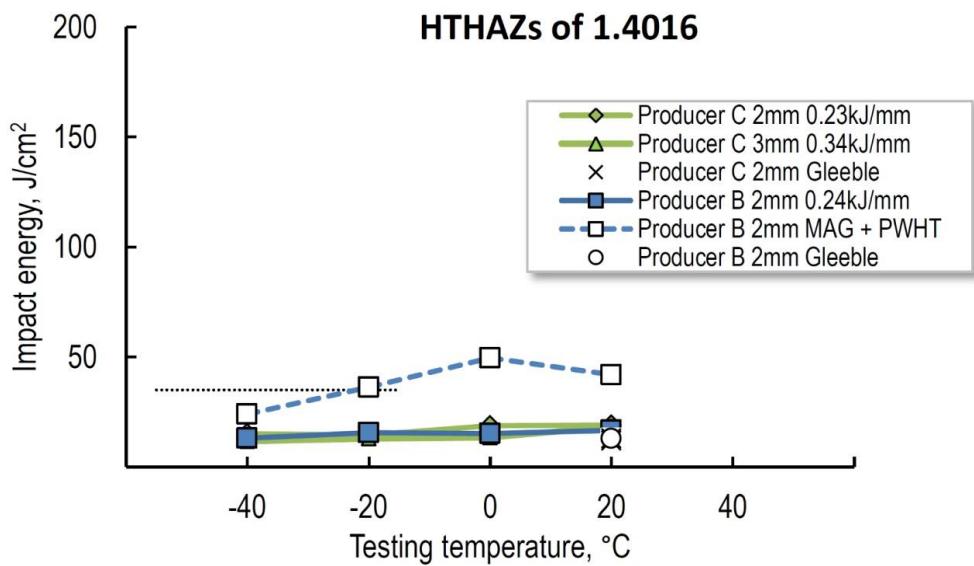
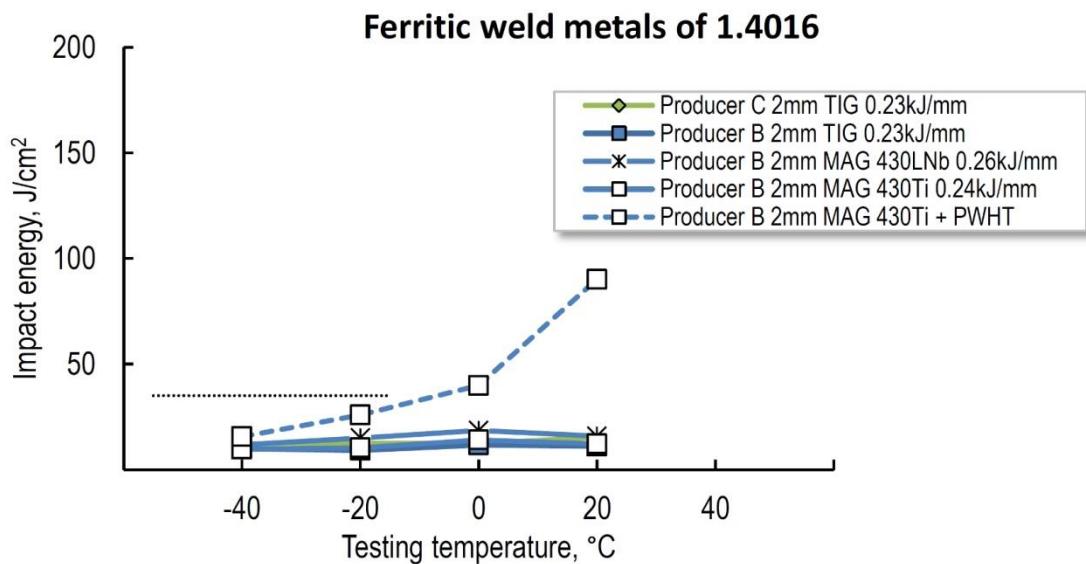


Fig 41. HTHAZ impact toughness for grade 1.4016.



**Fig 42. Weld metal impact toughness for grade 1.4016.**

The 2.0 mm cold rolled base metals behave in ductile manner down to -40 °C, and not reaching the DBTT. Hot rolled 3.0 mm Producer C material reaches the DBTT at roughly -30 °C. The PWHT applied has increased the toughness, likely because of carbide spheroidisation.

Nevertheless, all the as-welded HTHAZs behave in brittle manner, even at room temperature. Only the postweld heat treated HTHAZ can be considered as somewhat ductile down to -20 °C.

Ferritic welds have similar characteristics to that of HTHAZs. Only the PWHT welds behave in ductile manner down to 0 °C. Insufficient data exists for the welds fabricated with the austenitic filler metals due to the persistent crack propagation through the more brittle HTHAZ, as presented in Fig 43.



**Fig 43. Crack propagation in the weld metal impact toughness test. Welds fabricated with ferritic 430Nb (left) and austenitic 308LSi filler metals (right). The latter weld cracked through the HAZ, even though the notch is located at the centre of the weld.**

### 4.3.3 Grade 1.4509

Impact toughness test results for studied 1.4509 materials are presented in Figs 44–47.

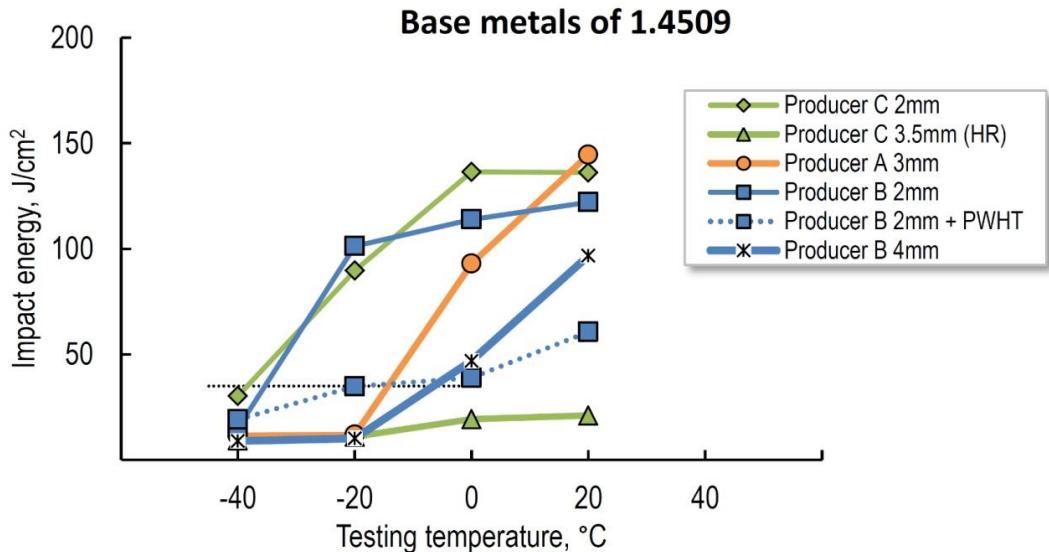


Fig 44. Base metal impact toughness for grade 1.4509.

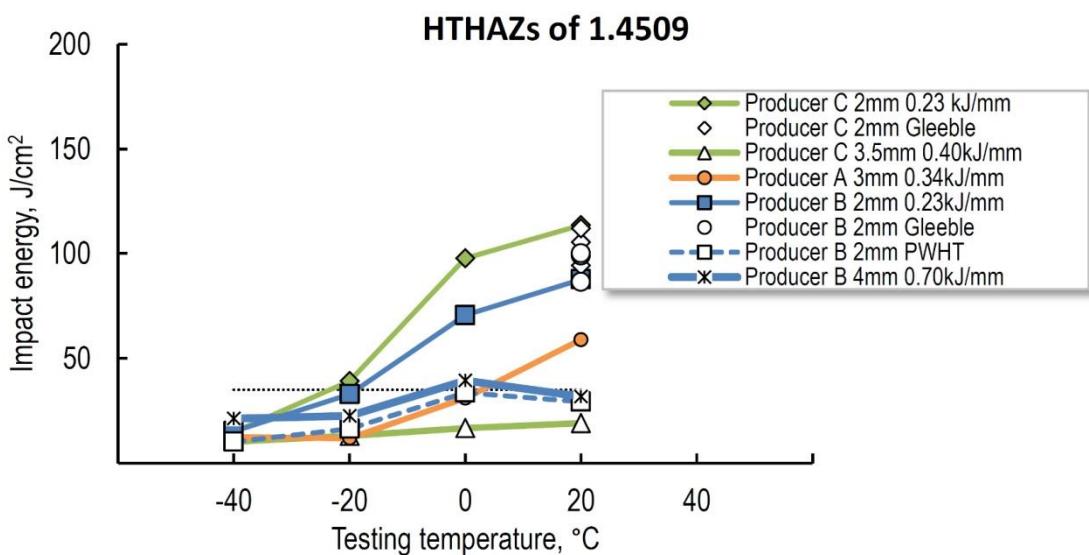
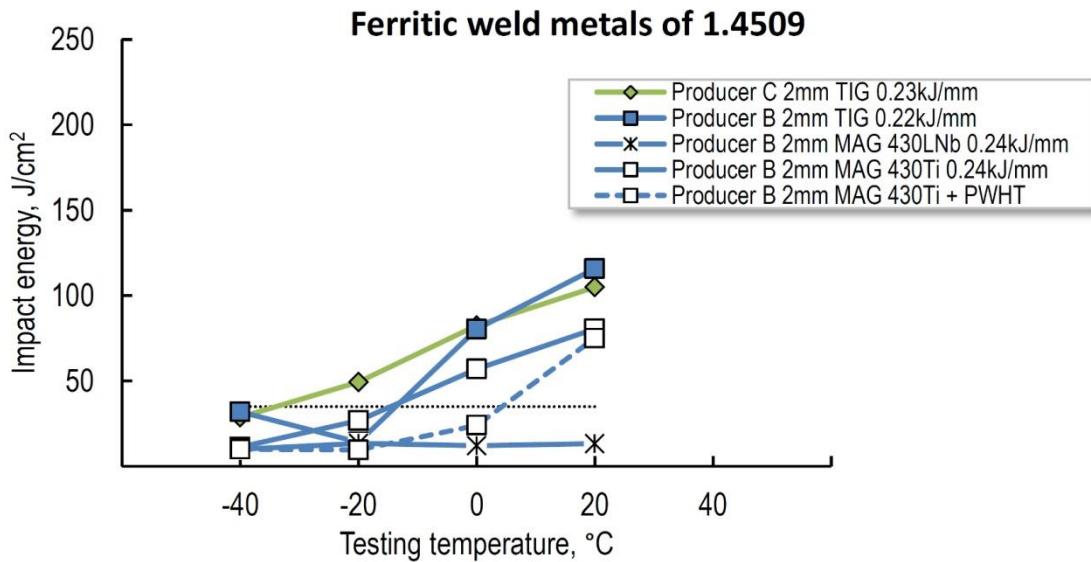
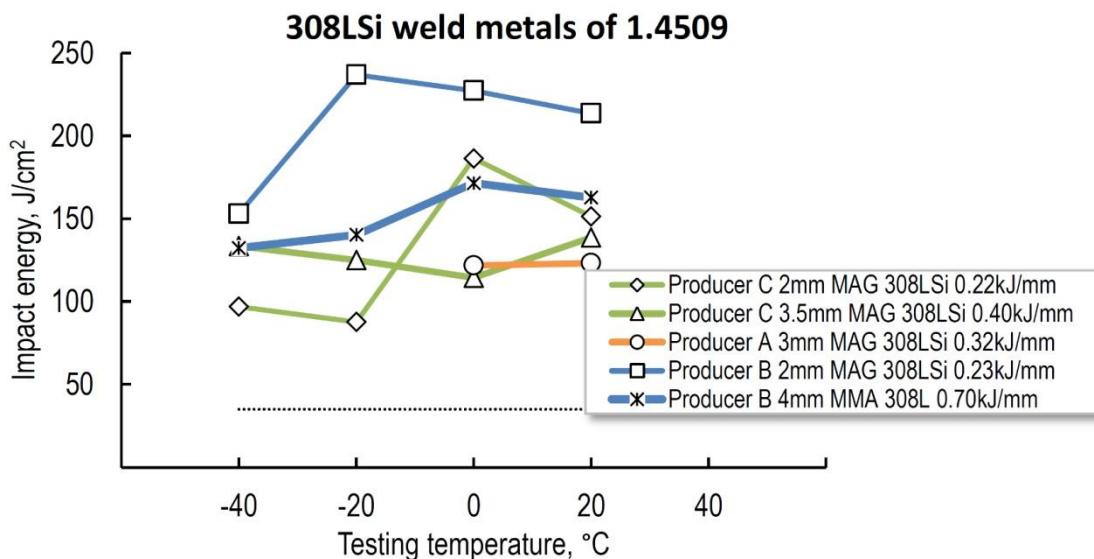


Fig 45. HTHAZ impact toughness for grade 1.4509.



**Fig 46. Ferritic weld metals impact toughness for grade 1.4509.**



**Fig 47. 308LSi weld metals impact toughness for grade 1.4509.**

The transition temperature occurs at -40 °C for the 2.0 mm materials. The PWHT applied to welded joints of 430Ti have dropped the base metal toughness, likely due to Laves phase embrittlement. The 3.0 mm Producer A material has slightly higher transition temperature, because of the larger grain size ( $53 > 35 \mu\text{m}$ ) and the thickness-effect. The hot rolled 3.5 mm Producer C material behaves in brittle manner even at the room temperature.

About 20 °C increase in transition temperature is observed for the HTHAZ samples. Unsurprisingly, the hot rolled 3.5 mm material has miserably toughness even at the room temperature. Similar to that of the base metal, the PWHT has decreased the HTHAZ toughness. Gleeble simulations for Producer B and C materials are consistent with the results obtained from the actual weldments, i.e. no significant drop in upper shelf energy is observed, even though heat inputs in Gleeble simulations varied from 0.10 to 0.40 kJ/mm.

Ferritic weld metals behave rather similarly to that of the HTHAZs. The 2 mm Producer C TIG weld behaves in more ductile than the Producer B one likely due to smaller grain size in the weld centre ( $55 < 73 \mu\text{m}$ ). The niobium stabilised filler metal 430LNb results in poor

toughness in 2 mm MAG welds. In addition, the PWHT decreases the weld metal toughness of 430Ti. Welds fabricated with austenitic filler metals are very ductile, and only a limited number of samples were valid due to persistent crack propagation through the more brittle HTHAZ.

#### 4.3.4 Grade 1.4521

Impact toughness test results for studied 1.4521 materials are presented in Figs 48–50.

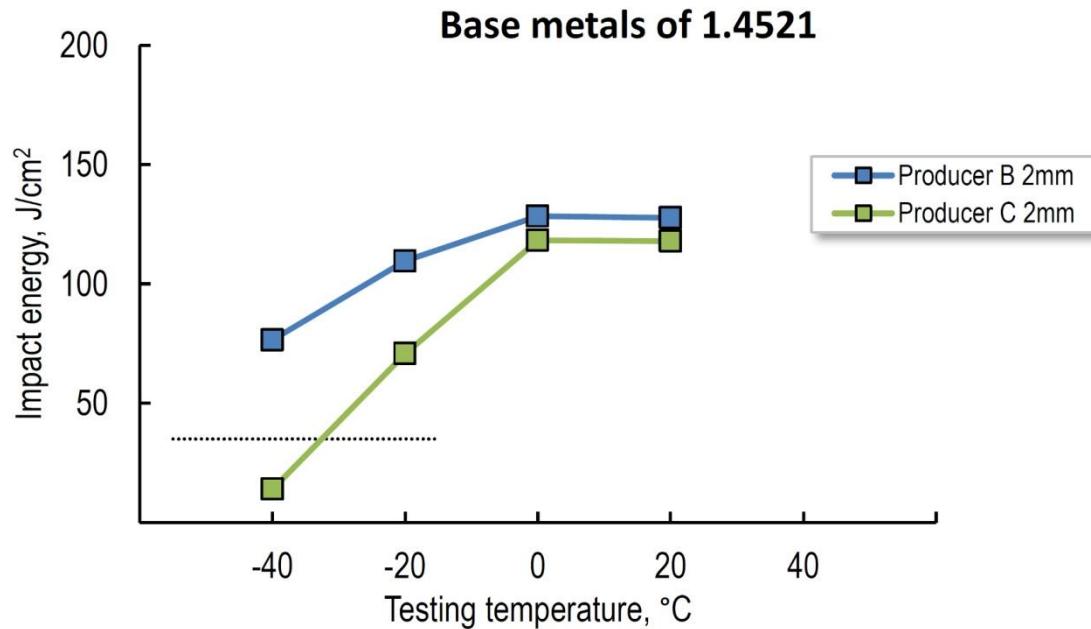


Fig 48. Base metal impact toughness for grade 1.4521.

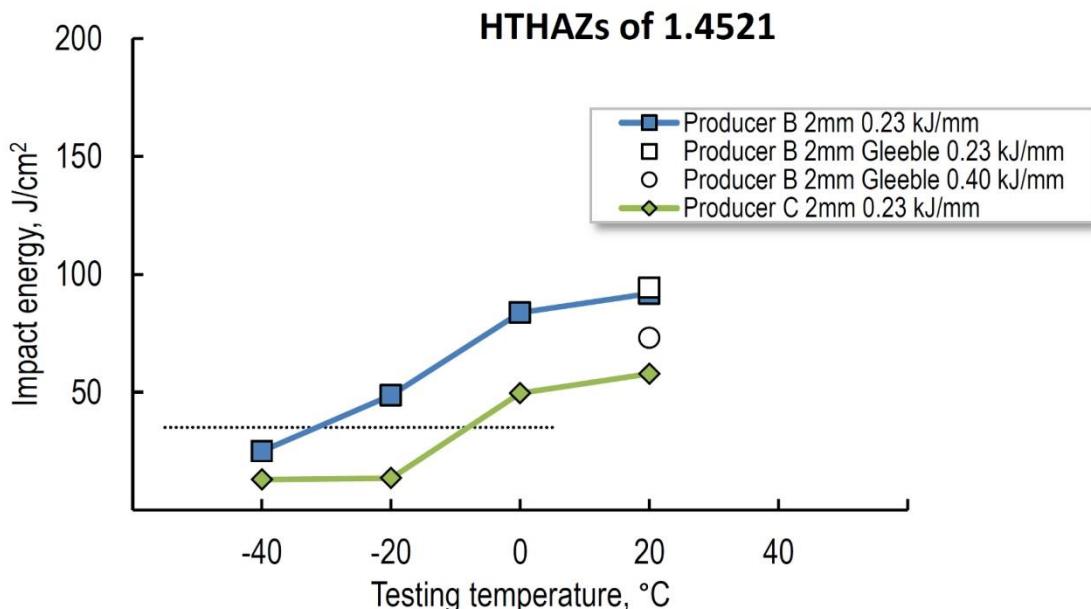
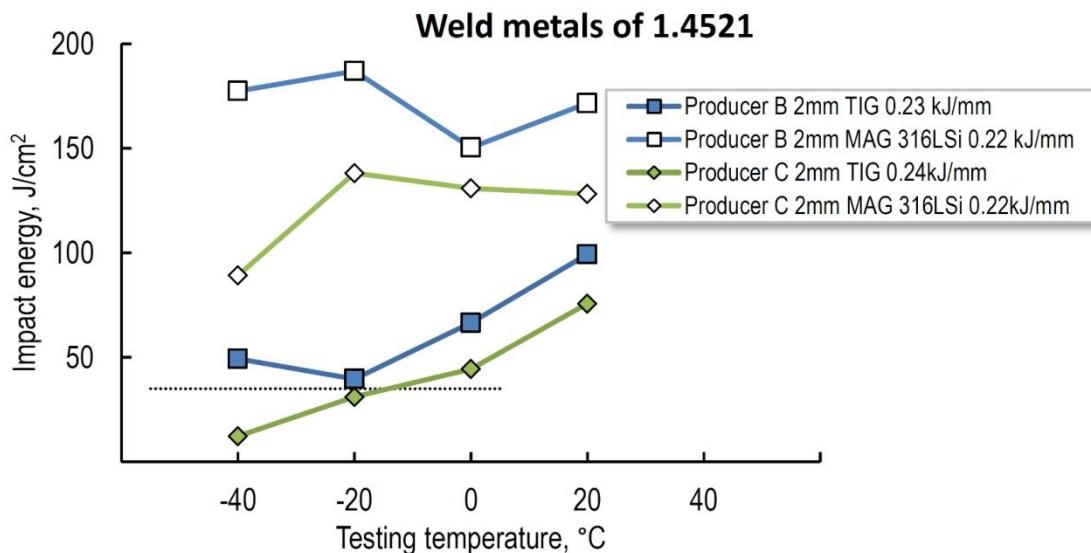


Fig 49. HTHAZ impact toughness for grade 1.4509.



**Fig 50. Weld metal impact toughness for grade 1.4521.**

Producer C base material exhibits the transition temperature at -30 °C while the Producer B material does not reach the DBTT within the studied temperature region. This might be because of the difference in grain size. Producer B 1.4521 has a grain size of 12 µm while the Producer C one has 24 µm. Similar trend is seen with the HTHAZ results; DBTT is increased for Producer C material by 20 °C and is now at -10 °C. Producer B material has somewhat improved toughness likely due to finer original grain size.

TIG welds are practically similar to that of the HTHAZ results. Both materials behave roughly in a similar manner down to -20 °C, although there is scattering at the lowest temperature regime. Austenitic filler metal results in ductile welds in both materials, even in the lowest temperature regime.

#### 4.3.5 Grade 1.4621

Impact toughness test results for studied 1.4621 materials are presented in Figs 51 - 53.

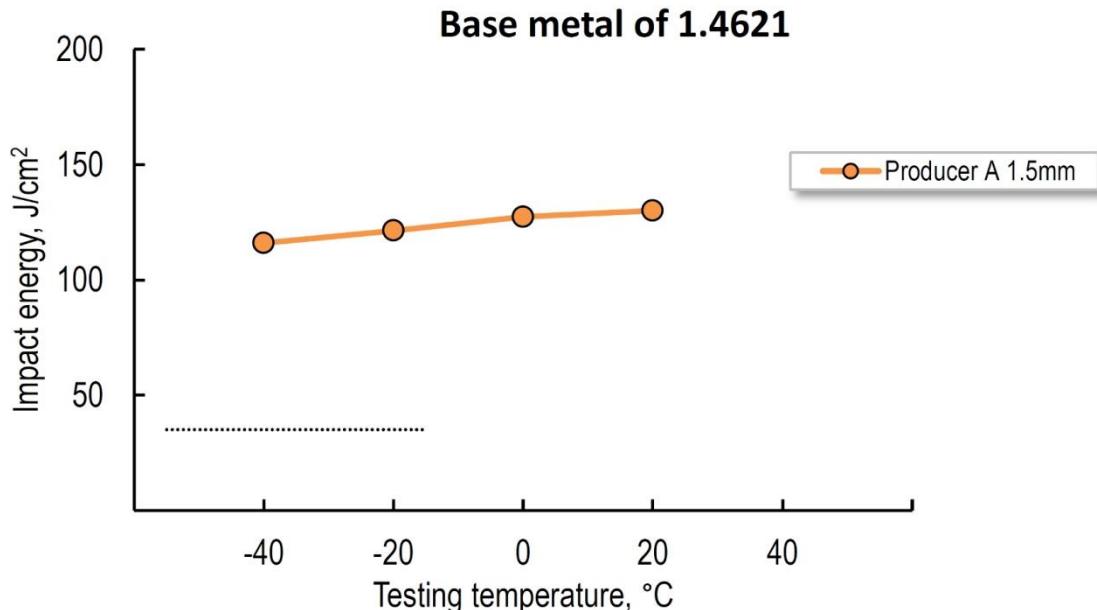


Fig 51. Base metal impact toughness for grade 1.4621.

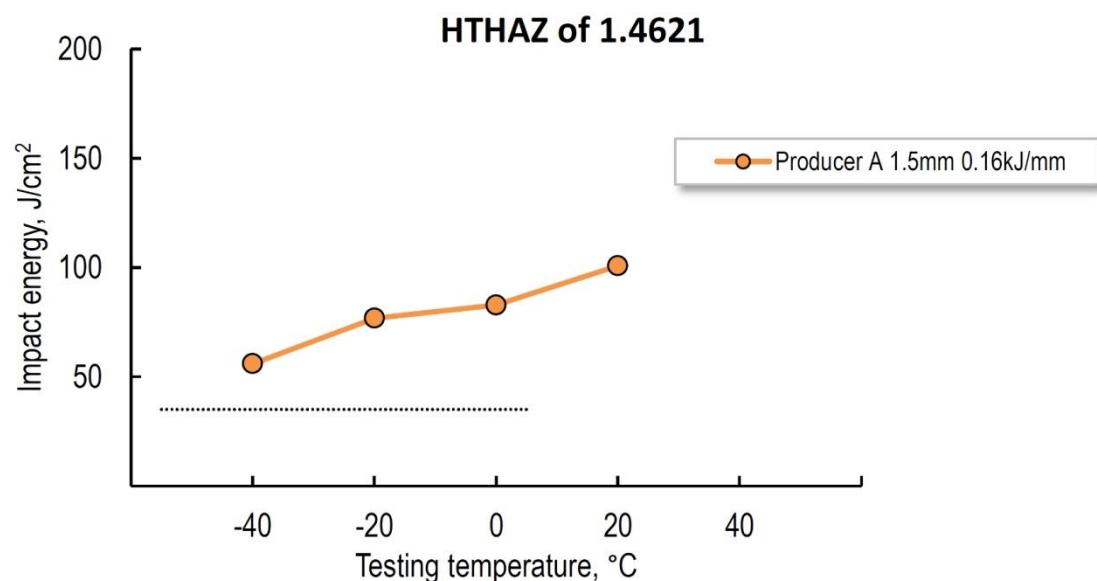
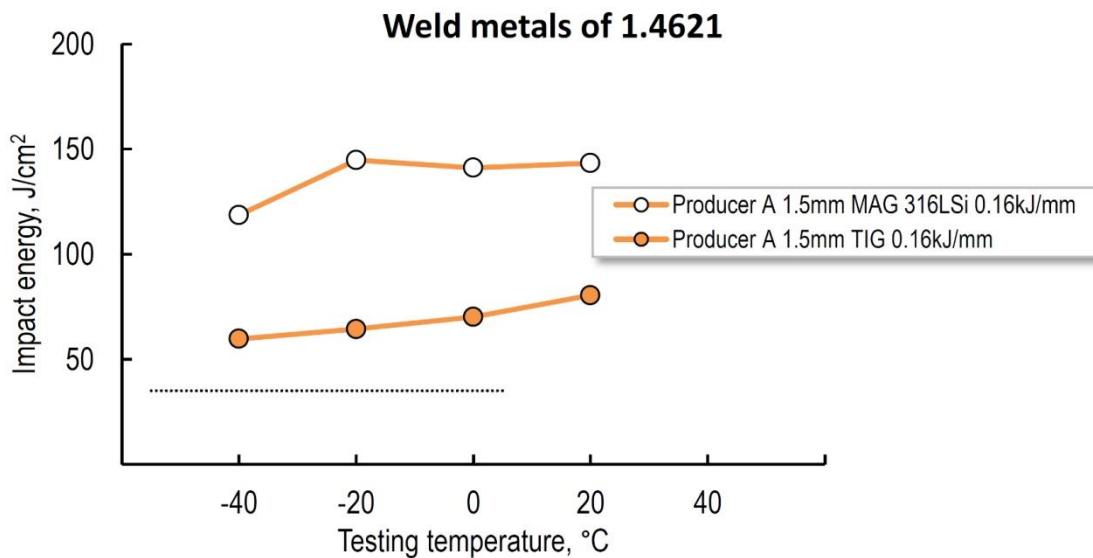


Fig 52. HTHAZ impact toughness for grade 1.4621.



**Fig 53. Weld metal impact toughness for grade 1.4621.**

Test results for Producer A 1.4621 1.5 mm material indicate, that within the studied temperature regime, the material behaves in ductile manner in the base metal, HTHAZ and in the weld metal. These results are understandable due to light sheet thickness, when compared to that of other materials studied.

#### 4.4 Corrosion tests for intergranular corrosion

Corrosion tests were included mainly because of the grade 1.4016, which is knowingly the most problematic for intergranular corrosion due to the high carbon content and the absence of stabilising elements. Chromium carbide precipitation is evident, although the heat input has a factor determining the extent of sensitisation. Sensitisation could hinder when lower heat inputs are used i.e. rapid cooling rate restricts the chromium carbide precipitation. This is supposedly not the case with ferritic stainless steel grades as the diffusion of carbon in ferrite matrix is so rapid.

Stabilised grades could become vulnerable to sensitisation when using lower heat inputs due to some dissolution of precipitates during welding. If the cooling rate is rapid, the recurrent formation of titanium- or niobium-based precipitates could hinder and chromium-based precipitates could form instead. Due to this dissolution, higher heat inputs could become more favoured as the time spent of high temperatures promotes the Ti and Nb precipitates.

#### 4.4.1 Strauss tests for 1.4016 welds

Three materials were studied from two manufacturers. Welds made for the 1 mm materials resulted in low heat inputs, approx. 0.07 kJ/mm, and those made with 2 mm materials exhibited heat inputs of 0.22 to 0.23 kJ/mm. Postweld heat treatments at 750 °C for 1 hour were also made. Samples are pickled after the test due to the oxidation, which would otherwise hinder the examination for the cracks.

Every as-welded test piece subjected to Strauss test failed the test, indicating that the resistance for intergranular corrosion is insufficient for grade 1.4016 even when using low heat inputs. However, the PWHT successfully restores the corrosion resistance as all the PWHT samples passed the test. Examples of the test samples are presented in Figs 54 and 55.

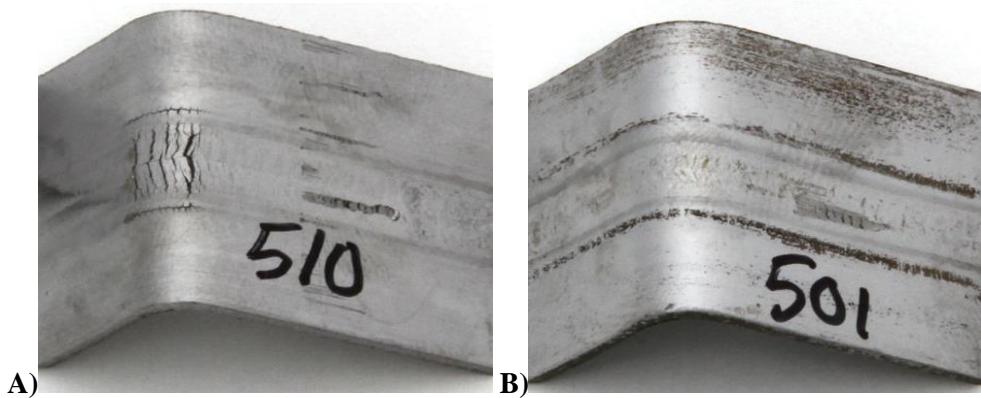


Fig 54. Strauss test samples: Failed as-welded sample (A) and passed PWHT sample (B). Material Producer C 1.4016, thickness 1.0 mm, heat input 0.07 kJ/mm.

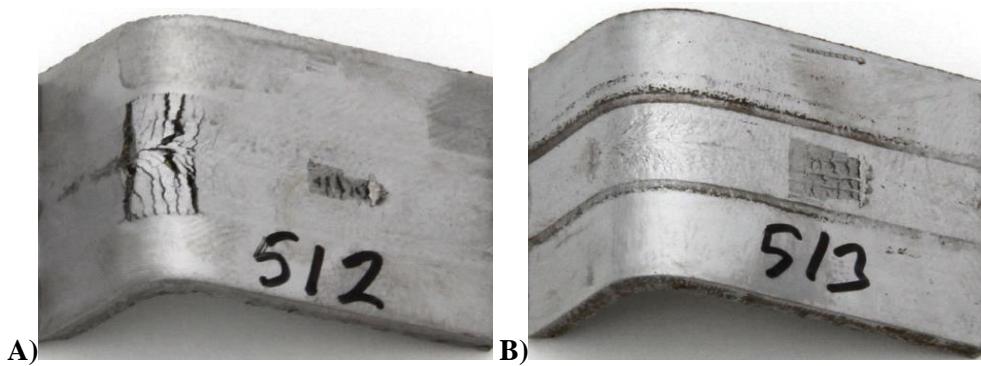
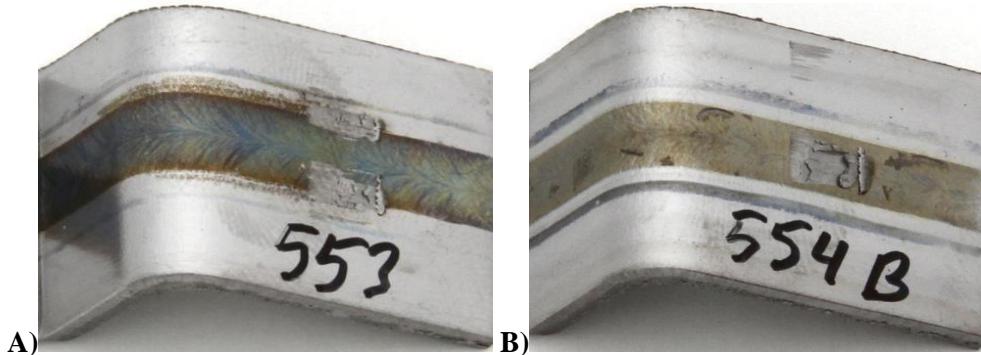


Fig 55. Strauss test samples: Failed as-welded sample (A) and passed PWHT sample (B). Material Producer C 1.4016, thickness 2.0 mm, heat inputs 0.21 and 0.22 kJ/mm.

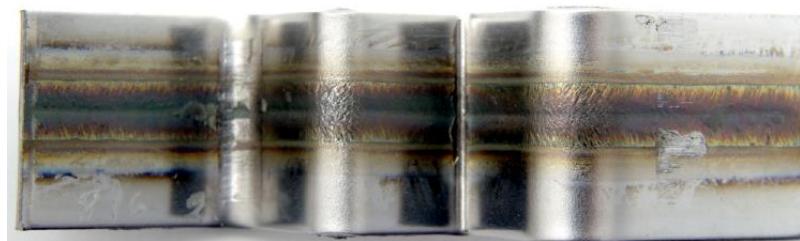
#### 4.4.2 Strauss tests for stabilised welds

Similar tests were made for selected stabilised grades, Producers B and C 2.0 mm 1.4509, and Producers B 2.0 mm 1.4521 materials were studied. Postweld heat treatments are considered not to be necessary, in fact, they might deteriorate these grades by Laves phase embrittlement. Because of this, a PWHT was employed for some of the 1.4509 welds.

All test pieces passed the Strauss test, including the PWHT ones. No cracking was observed, indicating a good resistance for intergranular corrosion, i.e. sensitisation has not occurred nor does the Laves phase embrittlement cause a failure in the Strauss test. Two examples from 1.4509 are presented in Fig 56, and one example from 1.4521 in Fig 57.



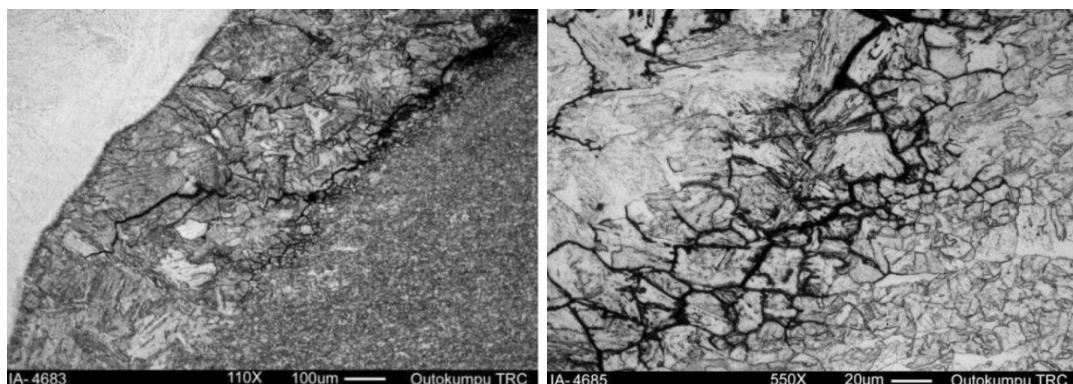
**Fig 56. Passed as-welded Strauss test samples: Producer C 1.4509 (A) and Producer B 1.4509 (B). Material thickness 2.0 mm, heat inputs 0.23 and 0.25 kJ/mm, respectively.**



**Fig 57. Autogenous TIG weld of Producer B 1.4521 after the Strauss test (passed). Heat input 0.19 kJ/mm.**

#### 4.4.4 Sensitisation of 1.4003

The sensitisation behaviour of Producer B 1.4003 was examined by using modified Strauss test [2]. Based on these results, the sensitisation does not occur in a single pass welding, if the austenite and subsequent martensite content is high, which is the case with Producer B 1.4003. However, the intergranular corrosion for this grade can occur when an X-joint type configuration is used in multipass welding. The HAZ of the second pass overlaps the HAZ of the first pass and by that way sensitises the martensite. V-type joint configuration did not lead to sensitisation in multipass welding.



**Fig 58. Intergranular corrosion at the first pass HAZ for grade 1.4003 by using X-type joint configuration. Material thickness is 6.0 mm. Heat input 0.42 + 0.42 kJ/mm.**

## 5 Discussion

### 5.1 Metallography of the weldments

Ferritic stainless steel weldments are notable different between each other. The unstabilised 1.4003 has a predominantly lath martensitic microstructure in the HAZ as well as in the autogenous weld metal. The extent of martensitic structure can vary depending on the chemical composition, heat input and subsequent cooling rate. Rapid cooling rates promote ferrite as the formation of austenite at high temperatures is restrained. Slower cooling rates allow more time for austenite nucleation and growth, and it results in higher martensite contents.

However, all the studied Producer B materials were entirely lath martensitic and delta-ferrite was not observed. While this is the most typical microstructure found in welds of this steel grade for major stainless steel manufacturers, the lack of other manufacturers materials in this study prevents a comprehensive analysis of the matter.

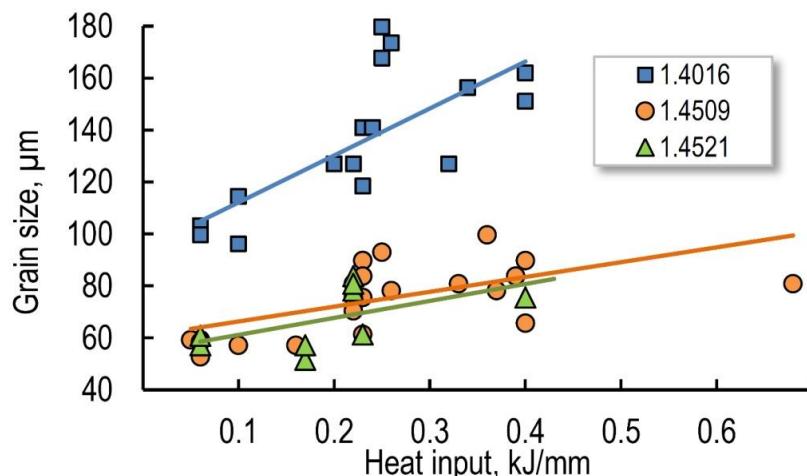
Grain coarsening is not considered to be a problem in welding of 1.4003, but the lath size affects to the toughness of the weldment regions. The lath size in the autogenous weld and in the HTHAZ region is the largest, resulting in a moderate decrease in toughness, as Zaayman [3] has pointed out in Fig 36. However, the change in the cooling dimension narrows the HTHAZ region significantly for thicker materials. In practical welding tests for 6 mm materials, the width of the HTHAZ region was approximately half that of the 2 mm materials.

Stabilised ferritic filler metal 409LNb results in semi-martensitic microstructure in the weld metal. The PWHT at 750 °C for 1 hour tempers the martensite in the weld metal as well as in the HAZ. According to the hardness profiles, the widths of the HAZs varied from 4 to 6 mm from the fusion line.

Unstabilised 1.4016 is semi-martensitic in the as-welded condition. Significant amount of martensite is formed in the HAZ, and in the autogenous welds, because the austenite formed at high temperatures has subsequently transformed into martensite. Highest austenite content was around 26 to 35 %, which results in corresponding martensite content in the LTHAZ. In the HTHAZ, the martensite content is lower because the temperature region has surpassed the austenite region and delta-ferrite is favoured. The observed grain boundary martensite in the HTHAZ is normally an outcome of the austenite formed during the cooling cycle. Observed martensite content in the HTHAZ region varied depending on thermal cycle and composition. Martensite in the Producer C 1 to 2 mm materials varied from 10 % to 16 %, while the Producer B materials had lower ferrite factors, resulting in higher martensite contents of 16 to 25 %. Hardness profiles indicate that the width of the martensitic region from the fusion line is about 3 mm for the studied materials.

The 430LNb ferritic filler metal efficiently suppresses the martensite formation in MAG welds. On the other hand, the titanium-rich filler metal 430Ti produces more equiaxed grains in the weld metal, but the number is limited.

Substantial grain coarsening occurs in the HTHAZ for grade 1.4016 even with lower heat inputs. The ferrite grain size has increased 7 to 14 times that of the unaffected base metal (12 µm), as presented in Fig 59.

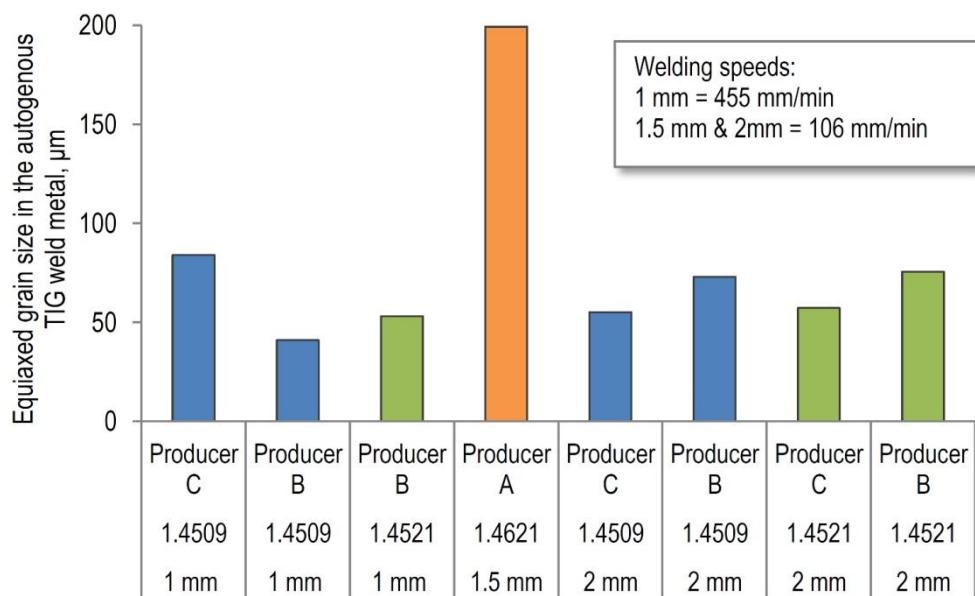


**Fig 59. Grain growth in the HTHAZ for selected materials with increasing heat input.**

All studied stabilised grades, 1.4509, 1.4521 and 1.4621 are fully ferritic grades, free carbon and nitrogen are entrapped by added titanium and/or niobium and the martensite formation is prohibited in every case. Therefore, the weldment microstructures are very similar to each other. Grain coarsening in the HAZ is the main embrittlement phenomenon, or at least the simplest one to observe. Because stabilised steel grades have fully ferritic microstructures, austenite is not restricting the ferrite grain growth. However, the beneficial pinning-effect of precipitates hinders the grain growth. It was observed that a limited grain coarsening occurs within the studied heat inputs, as is seen from Fig 59. The grain size in the HTHAZ region varied from 2 to 7 times that of the unaffected base metal with different heat inputs. If the stabilisation is only made with titanium, the grain coarsening could be more drastic, but this was not studied here.

The width of the coarse-grained HTHAZ region varied from 1 to 2 mm for the stabilised materials. The total width of the HAZ is difficult to measure accurately as the hardness and the microstructure of the joint remains practically unchanged in the remainder HAZ.

Ferritic weld metals may differ from each other notably. MAG welds revealed that the Nb-stabilised filler metals produced more columnar-like microstructure and Ti-stabilised filler metal produced more equiaxed grains. A similar phenomenon is seen with autogenous TIG welds in Fig 60. Producer C 1.0 mm 1.4509 weld metal has a coarser microstructure than the comparable Producer B one. The autogenous TIG weld metal of 1.4621 is coarser than any other studied stabilised material, likely because of the absence of Ti and/or Al in the weld metal. The typical coarse columnar grain structure is likely to occur with higher welding speeds.



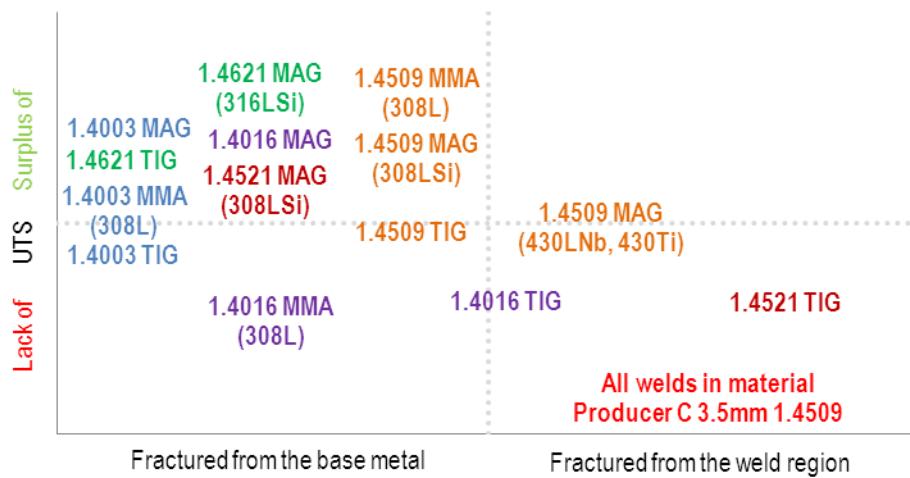
**Fig 60. Equiaxed grain sizes in the autogenous TIG weld metals of stabilised grades. Notice the much coarser grain size in the 1.4621 due to the absence of titanium.**

## 5.2 Feasibility of the welded joints

Whether welding autogenously or with filler metals, sufficient mechanical and corrosion properties are required. Welded joints have to match the properties of the base material as well as required. Strength, ductility and toughness are the key mechanical properties for structural purposes.

According to the tensile properties, autogenous TIG welds rarely matched the UTS of the base metals, as summarised in Fig 61. Grades 1.4003, 1.4509 and 1.4621 are most suitable for autogenous welding, even though the UTS may be lower than that of the base metal. Autogenous welds for 1.4016 and 1.4521 materials suffered from frequent weld metal fractures in tension tests, which is not preferred. In addition, the elongation in the latter was notably small, a fracture occurred occasionally with a non-existent elongation, Fig 62.

Studied austenitic filler metals are the most suitable for welding ferritic grades. Generally, the UTS is higher than the parallel base metal, and the fracture occurs frequently through the base metal. Hot rolled 3.5 mm Producer C 1.4509 suffered from poor results in tension tests despite the filler metal selection. According to the tension tests, the studied ferritic filler metals are suitable to be used with grades 1.4003 and 1.4016.

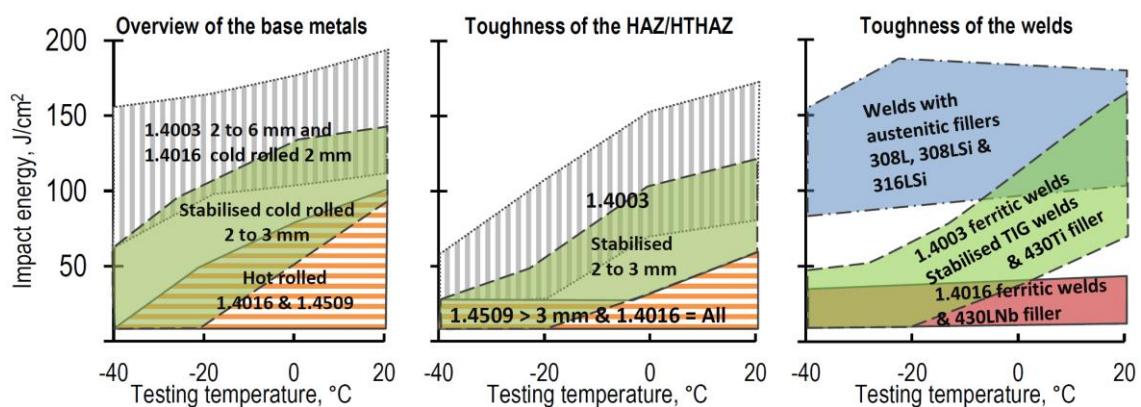


**Fig 61. Representative graph from the transverse weld tension tests.**



**Fig 62. Tension test samples, both originally 235 mm in length. Notice the brittle fracture in 1.4016 (top) without any elongation. A more ductile fracture has occurred with 1.4509 from the base metal (bottom).**

Toughness of ferritic stainless steels is a general concern. A summary from the impact toughness tests is presented in Fig 63.



**Fig 63. Representative graph from the impact toughness tests.**

According to the current study, the grade 1.4003, and other materials in cold rolled condition have adequate toughness down to 0 °C. Hot rolled materials had the lowest toughness, especially those of 1.4509. A more complete analysis about the base metal toughness is done in WP1 [4].

HTHAZ toughness remains reasonable for the 1.4003 materials and for 2 to 3 mm stabilised materials. The lath martensitic HAZ of 1.4003 is knowingly ductile and practically unaffected for different heat inputs. A PWHT is unnecessary and, in fact, it decreases the toughness slightly.

Although the current study for 4 to 6 mm materials was unable to determine the HTHAZ toughness, Lokka [5] has previously studied the HTHAZ of this grade extensively with Charpy-V and fracture toughness tests. Based on those studies, the Charpy-V toughness in HTHAZ region is adequate even with thicker materials (5 mm). In addition, the Charpy-V tests underestimate the fracture resistance of the HAZ.

Grade 1.4016 has poor toughness in the autogenous welds and in the HTHAZ despite the thickness or the ferrite grain size. The significantly reduced ductility is due to the presence of grain boundary martensite. The only effective way to improve the toughness of the joint is to carry out a PWHT. The martensite tempering at 750 °C for 2 hours proved to be at least somewhat beneficial to improve the toughness of otherwise brittle HTHAZ. During tempering, the harmful grain boundary martensite transforms into alpha-ferrite and carbides, which softens the heat-affected zone as a whole. The overall impact toughness remains modest because of the large ferrite grain size and the embrittling effect of carbides and nitrides at the grain boundaries and inside of the grains i.e. high-temperature embrittlement. However, the postweld heat treated HTHAZ is notable tougher than what was the case in as-welded condition.

The grain coarsening embrittlement is restricted for dual stabilised grades, as presented previously in Fig 59. This limited grain growth increases the DBTT of the studied grades only for about 20 °C. Thus, the HTHAZs of stabilised cold rolled materials (1.5 to 3 mm) behaved ductile in room temperature. Hot rolled materials, especially that of 1.4509 Producer C 3.5 mm suffered from poor toughness in both the base metal and the HTHAZ.

The autogenous TIG welds for stabilised grades have similar characteristics to that of HTHAZs. Transition temperature occurs about 20 °C higher than the base metals for 2.0 mm 1.4509 and 1.4521 materials. The autogenous welds for 1.5 mm 1.4621 do not reach DBTT, but the observed coarse weld metal grain size (Fig 60) could lead to a higher DBTT than the case with other stabilised grades.

The PWHT studies on stabilised grades indicate that the toughness of the joint could be deteriorated with improperly selected heat treatments. The 750 °C 2 hour “tempering” of the selected 1.4509 welds led to a Laves phase embrittlement, apparently Fe<sub>2</sub>Nb, which decreased notably the base metal and HTHAZ toughness. Sello et al. [6] have recently studied the effect of Laves phases in intermediate temperature annealing in comparable ferritic steel grade. The authors stated that even a short term 30 min annealing below 850 °C contributes to significant drop in room temperature impact toughness due to the Fe<sub>2</sub>Nb Laves phase embrittlement.

Welds fabricated with the austenitic filler metals resulted in superior impact toughness. In many cases, the crack propagation through the more brittle HTHAZ prevented the impact toughness measurements for these ductile welds. MAG welds with titanium stabilised 430Ti filler metal resulted in moderate toughness due to grain refinement. All ferritic welds for grade 1.4016 and welds made with 430LNb filler metal resulted in poor as welded toughness. Thus, the presence of grain boundary martensite and/or coarse columnar grain structure leads to a significant decrease in toughness.

Based on these findings, the studied austenitic filler metals produced most satisfying welds in terms of toughness and fracture behaviour. Austenitic filler metals are the most suitable consumables for structural purposes at ambient temperatures.

### 5.3 Corrosion behaviour

Several test combinations were made for the materials. The test results are consistent and reasonable, Table 17. Sensitisation is mainly the problem of a traditional unstabilised grade 1.4016. Even the low heat input welds suffered from intergranular corrosion and subsequent failure in Strauss test. A postweld heat treatment at 750 °C is sufficient to restore the corrosion resistance of the welded joint. All the studied stabilised grades passed the Strauss test, indicating a good resistance for intergranular corrosion i.e. the studied grades did not sensitise during the welding.

Multipass welding of the low chromium unstabilised 1.4003 can lead to sensitisation, if the joint configuration results in specific overlapping of the HAZs, which was clarified in X-type joint configuration.

**Table 17. Summary from the sensitization tests.**

THK	Grade	Mfr.	Method	Filler	Heat input [kJ/mm]	Condition	Test result
1.0 mm	1.4016	C	TIG	Autog.	0.06	As-welded	FAIL
	1.4016	C	TIG	Autog.	0.07	PWHT	PASS
2.0 mm	1.4016	C	TIG	Autog.	0.22	As-welded	FAIL
	1.4016	C	TIG	Autog.	0.23	PWHT	PASS
	1.4016	B	TIG	Autog.	0.23	As-welded	FAIL
	1.4016	B	TIG	Autog.	0.23	PWHT	PASS
	1.4509	C	TIG	Autog.	0.24	As-welded	PASS
	1.4509	B	TIG	Autog.	0.23	As-welded	PASS
	1.4521	B	TIG	Autog.	0.19	As-welded	PASS
6.0 mm	1.4003	B	MAG	308LSi	1.34	V-type, 2 passes	PASS
	1.4003	B	MAG	308LSi	0.82	X-type, 2 passes	FAIL

## 6 Conclusions

- The welded microstructures of common ferritic stainless steels deviate from each other notably. The existence of martensite is the most fundamental difference in the HAZ. It was observed that the low carbon lath martensitic HAZ structure of 1.4003 is beneficial in terms of tension and toughness properties, both of which are important factors for structural use.

The heat input analysis for this grade indicates that the microstructure in the HTHAZ region is similar despite the varying heat inputs. However, the width of the HTHAZ narrows down with thicker materials because of the change in the cooling dimension.

- The unstabilised 1.4016 has the most troublesome autogenous weld or HAZ features. The grain boundary martensite, measured to be 10 to 25 % in the HTHAZ depending on material, leads to a detrimental loss of ductility and toughness. Even though the tensile properties were moderate, there is a paramount lack of toughness in the HTHAZ. More so, the ferrite grain coarsening occurs rapidly, even with low heat inputs. The combination of brittle grain boundary martensite and large ferrite grain size results in poor weldability characteristics.

A postweld heat treatment can be employed for welds to improve their ductility, but this increase is modest. The most important feature of the PWHT is its capability to restore the corrosion resistance of the joint. Without the PWHT, the welded joints can suffer from intergranular corrosion, even when low heat inputs are used.

- All stabilised ferritic grades have very similar microstructural features. The dual stabilisation can suppress the grain coarsening efficiently. Only a moderate increase in ferrite grain size was observed in the HTHAZ, even when excessive heat inputs were used for the 2 mm materials in thermal simulations. The resulting impact toughness remains adequate, about 20 °C increase in DBTT was observed, despite the manufacturer.
- Austenitic filler metals are considered to be the most suitable consumables for use in ambient temperatures. This was clarified with tension and impact toughness tests. In tension tests, the ductile weld metal fabricated with an austenitic filler metal resulted in frequent base metal fracture, which indicates that these welds have adequate strength when compared to that of the studied base metals. Impact toughness tests clarify without a doubt that the welds produced with these filler metals have superior properties to that of the base metals, autogenous welds, or comparable ferritic filler metals.

Autogenous welding was seen appropriate for grades 1.4003 and 1.4509. The semi-martensitic weld metal of 1.4016 resulted in frequent fracture from the centre of the weld. This brittle and unexpected fracture occurred practically without any elongation. Similar unwanted behaviour was seen with the 1.4521 materials.

## References

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## Appendices

1. Welding parameters
2. Grain sizes, width of the regions, and martensite measurements
3. Hardness measurements
4. Tension tests at room temperature
5. Impact toughness tests at temperatures -40 ... +20 °C

## Appendix 1. Welding parameters

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### **Welding parameters**

<b>Weld # D-numbered</b>	<b>Mfr.</b>	<b>Base metal</b>	<b>THK [mm]</b>	<b>Filler wire</b>	<b>I [A]</b>	<b>U [V]</b>	<b>Air gap [mm]</b>	<b>Nozzle [mm]</b>	<b>Tilt [°]</b>	<b>Weld.speed [mm/min]</b>	<b>Wire feed [m/min]</b>	<b>Lenght [cm]</b>	<b>Energy* [kJ/mm]</b>	<b>Heat input [kJ/mm]</b>
30	B	4509	2	430Ti	128.8	25.5	0.6	13	0	710	7.1	38	0.32	0.26
31	B	4509	2	430Ti	141.4	21.9	0.6	13	0	710	7.1	38	0.30	0.24
32	B	4509	2	430Ti	136.5	22.0	0.6	13	0	710	7.1	37	0.30	0.24
33	B	4509	2	430Ti	128.1	22.0	0.6	13	0	710	7.1	36	0.28	0.22
34	B	4509	2	430Ti	139.1	22.1	0.6	13	0	710	7.1	38	0.29	0.23
37	B	4509	2	430Ti	128.8	22.0	0.6	13	0	710	7.1	37	0.29	0.23
38	B	4509	2	430Ti	131.3	22.0	0.6	13	0	710	7.1	38	0.29	0.23
40	B	4509	2	430Ti	144.8	21.8	0.6	13	0	710	7.1	39	0.31	0.25
41	B	4509	2	430LNb	133.1	22.2	0.5	13	0	710	7.1	40	0.28	0.22
42	B	4509	2	430LNb	141.6	22.3	0.5	13	0	710	7.1	40	0.29	0.23
43	B	4509	2	430LNb	133.1	22.3	0.5	13	0	710	7.1	38	0.29	0.23
44	B	4509	2	430LNb	142.8	22.4	0.5	13	0	710	7.1	38	0.30	0.24
45	B	4509	2	430LNb	139.3	22.3	0.5	13	0	710	7.1	38	0.30	0.24
46	B	4509	2	430LNb	142.6	22.2	0.5	13	0	710	7.1	37	0.30	0.24
47	B	4509	2	430LNb	135.1	22.2	0.5	13	0	710	7.1	39	0.28	0.22
48	B	4509	2	308LSi	138.2	22.4	0.5	13	0	710	7.1	38	0.29	0.23
49	B	4509	2	308LSi	135.5	22.4	0.5	13	0	710	7.1	37	0.29	0.23
50	B	4509	2	308LSi	138.9	22.3	0.5	13	0	710	7.1	38	0.30	0.24
51	B	4509	2	308LSi	144.6	22.2	0.5	13	0	710	7.1	39	0.30	0.24
52	B	4509	2	308LSi	134.4	22.3	0.5	13	0	710	7.1	39	0.29	0.23
53	B	4509	2	308LSi	128.1	22.3	0.5	13	0	710	7.1	39	0.27	0.22
54	B	4003	2	308LSi	134.0	22.3	0.5	13	0	710	7.1	38	0.29	0.23
55	B	4003	2	308LSi	136.2	22.2	0.5	13	0	710	7.1	39	0.29	0.23
60	B	4003	2	308LSi	139.9	21.8	0.5	13	0	710	7.1	38	0.28	0.22
61	B	4003	2	308LSi	143.8	21.5	0.5	11	0	710	7.1	39	0.28	0.22
62	B	4003	2	308LSi	138.2	21.8	0.5	11	0	710	7.1	40	0.27	0.22
63	B	4003	2	308LSi	150.5	21.6	0.5	11	0	710	7.1	40	0.29	0.23
64	B	4003	2	308LSi	153.9	21.3	0.5	11	0	710	7.1	40	0.29	0.23
65	B	4003	2	308LSi	140.0	21.6	0.5	11	0	710	7.1	39	0.28	0.22
75	B	4509	2	430Ti	133.7	21.3	0.5	11	0	710	7.1	39	0.27	0.22
76	B	4509	2	430Ti	149.1	21.1	0.5	11	0	710	7.1	39	0.29	0.23
77	B	4509	2	430Ti	133.9	21.3	0.5	11	0	710	7.1	38	0.28	0.22
78	B	4509	2	308LSi	145.6	21.6	0.5	11	0	710	7.1	39	0.29	0.23
79	B	4509	2	308LSi	140.2	21.7	0.5	11	0	710	7.1	36	0.28	0.22
81	B	4509	2	308LSi	144.8	21.6	0.5	10	0	710	7.1	38	0.29	0.23
82	B	4509	2	308LSi	153.8	21.5	0.5	10	0	710	7.1	37	0.31	0.25
83	B	4509	2	308LSi	140.1	21.7	0.5	10	0	710	7.1	38	0.29	0.23
84	B	4016	2	308LSi	142.1	21.5	0.5	10	0	710	7.1	38	0.29	0.23
85	B	4016	2	308LSi	142.7	21.4	0.5	10	0	710	7.1	38	0.29	0.23
86	B	4016	2	308LSi	144.9	21.4	0.5	10	0	710	7.1	38	0.30	0.24
87	B	4016	2	308LSi	151.5	21.2	0.5	10	0	710	7.1	38	0.31	0.25
88	B	4016	2	308LSi	155.0	21.2	0.5	10	0	710	7.1	37	0.31	0.25
89	B	4016	2	308LSi	154.2	21.1	0.5	10	0	710	7.1	38	0.30	0.24
90	B	4016	2	308LSi	155.3	21.0	0.5	10	0	710	7.1	38	0.31	0.25
93	B	4509	2	430LNb	148.9	21.9	0.6	10	0	710	7.1	38	0.30	0.24
94	B	4016	2	430LNb	136.4	21.6	0.6	10	0	710	7.1	38	0.27	0.22
115	B	4003	2	308LSi	157.4	21.8	0.6	10	0	710	7.1	38	0.31	0.25
120	B	4016	2	308LSi	156.0	22.6	0.6	10	0	710	7.1	37	0.28	0.22
121	B	4016	2	430LNb	170.4	22.2	0.6	10	0	710	7.1	38	0.30	0.24
123	B	4003	2	409Nb	161.1	23.3	0.6	12	20	855	7.1	34	0.29	0.23
124	B	4003	2	409Nb	156.5	23.2	0.7	13	20	855	7.1	35	0.28	0.22
126	B	4003	2	409Nb	170.3	23.4	0.8	12	20	855	7.1	37	0.31	0.25
132	B	4003	2	409Nb	187.3	23.5	0.6	12	20	855	8.1	37	0.34	0.27
134	B	4003	2	409Nb	182.7	23.6	0.7	12	20	855	8	37	0.32	0.26
135	B	4003	2	409Nb	176.7	23.0	0.6	12	20	855	7.8	25	0.30	0.24
136	B	4003	2	409Nb	179.3	22.7	0.6	12	20	855	7.8	25	0.30	0.24
137	B	4003	2	409Nb	178.3	22.8	0.6	12	20	855	7.8	25	0.31	0.25
149	B	4016	2	430LNb	164.5	22.3	0.4	12	20	855	7.6	18	0.33	0.26
150	B	4016	2	430LNb	160.5	22.5	0.5	12	20	855	7.5	38	0.33	0.26

## Appendix 1. Welding parameters

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151	B	4016	2	430LNb	163.2	22.1	0.5	12	20	855	7.5	38	0.33	0.26
152	B	4016	2	430LNb	159.2	22.8	0.5	12	20	855	7.5	38	0.32	0.26
154	B	4016	2	430LNb	157.6	22.7	0.5	13	20	855	7.3	29	0.32	0.26
156	B	4016	2	430LNb	156.3	22.5	0.5	13	20	855	7.3	26	0.32	0.26
160	B	4016	2	430Ti	150.1	22.9	0.5	12	5	710	7.1	37	0.32	0.26
161	B	4016	2	430Ti	149.5	22.9	0.5	12	5	710	7.1	37	0.32	0.26
162	B	4016	2	430Ti	137.6	22.9	0.5	12	5	710	7.1	37	0.30	0.24
163	B	4016	2	430Ti	144.8	22.6	0.5	12	5	710	7.1	38	0.30	0.24
164	B	4016	2	430Ti	144.8	22.2	0.5	12	5	710	7.1	38	0.30	0.24
166	B	4016	2	430Ti	145.5	21.7	0.5	12	5	710	7.1	18	0.31	0.25
167	B	4016	2	430Ti	149.5	22.6	0.5	12	5	710	7.1	38	0.31	0.25
168	B	4016	2	430Ti	151.8	23.0	0.5	12	5	710	7.1	38	0.32	0.26
169	B	4016	2	430Ti	150.0	22.9	0.5	12	5	710	7.1	37	0.32	0.26
170	B	4016	2	430Ti	149.8	22.3	0.5	12	5	710	7.1	38	0.30	0.24
171	B	4016	2	430Ti	143.5	22.3	0.5	13	5	710	7.1	38	0.29	0.23
172	B	4016	2	430Ti	142.7	22.4	0.5	13	5	710	7.1	37	0.30	0.24
173	B	4016	2	430Ti	143.2	22.4	0.5	13	5	710	7.1	37	0.30	0.24
174	B	4016	2	430Ti	142.3	22.4	0.5	13	5	710	7.1	37	0.30	0.24
175	B	4016	2	430Ti	144.3	22.6	0.5	13	5	710	7.1	38	0.30	0.24
176	B	4016	2	430Ti	146.4	22.7	0.5	13	5	710	7.1	37	0.31	0.25
177	B	4016	2	430Ti	144.0	22.6	0.5	13	5	710	7.1	38	0.30	0.24
178	B	4016	2	430Ti	143.2	22.1	0.5	13	5	710	7.1	14	0.31	0.25
179	B	4016	2	430Ti	146.7	22.6	0.5	13	5	710	7.1	37	0.31	0.25
182	B	4509	2	430Ti	146.2	22.3	0.5	13	5	710	7.1	26	0.30	0.24
183	B	4509	2	430Ti	143.3	22.5	0.5	13	5	710	7.1	38	0.30	0.24
184	B	4509	2	430Ti	150.2	23.3	0.5	13	5	710	7.1	38	0.32	0.26
185	B	4509	2	430Ti	139.3	20.8	0.5	13	5	710	7.1	38	0.27	0.22
186	B	4509	2	430Ti	139.9	21.2	0.5	13	15	710	7.1	38	0.28	0.22
187	B	4509	2	430Ti	131.6	20.5	0.5	13	15	710	7.1	18	0.27	0.22
188	B	4509	2	430Ti	132.7	21.5	0.5	13	15	710	7.1	18	0.29	0.23
191	B	4509	2	430Ti	131.0	20.9	0.3	13	0	710	7.1	18	0.27	0.22
192	B	4509	2	430Ti	135.1	20.7	0.3	13	0	710	7.1	18	0.27	0.22
193	B	4509	2	430Ti	135.3	21.5	0.6	13	0	710	7.1	38	0.28	0.22
194	B	4509	2	430Ti	137.7	21.4	0.5	13	0	710	7.1	37	0.28	0.22
195	B	4509	2	430Ti	137.8	21.4	0.5	13	0	710	7.1	38	0.28	0.22
196	B	4509	2	430Ti	138.9	21.4	0.5	13	0	710	7.1	38	0.28	0.22
197	B	4509	2	430Ti	139.0	21.4	0.5	13	0	710	7.1	38	0.28	0.22
198	B	4509	2	430Ti	137.6	21.4	0.5	13	0	710	7.1	38	0.28	0.22
201	B	4509	2	430Ti	140.2	21.3	0.5	13	0	710	7.1	38	0.28	0.22
202	B	4509	2	430Ti	134.9	21.2	0.5	13	0	710	7.1	38	0.27	0.22
203	B	4509	2	430Ti	133.6	21.1	0.5	13	0	710	7.1	35	0.27	0.22
204	B	4509	2	430Ti	132.1	20.8	0.5	13	0	710	7.1	19	0.27	0.22
205	B	4509	2	430Ti	138.8	21.4	0.5	13	0	710	7.1	38	0.28	0.22
206	B	4509	2	430Ti	137.7	21.0	0.5	13	0	710	7.1	23	0.28	0.22
207	B	4016	2	430Ti	137.9	21.4	0.5	13	0	710	7.1	39	0.28	0.22
208	B	4016	2	430Ti	137.3	21.4	0.5	13	0	710	7.1	36	0.28	0.22
209	B	4016	2	430Ti	138.7	21.4	0.5	13	0	710	7.1	38	0.28	0.22
216	B	4509	2	430LNb	143.7	21.6	0.4	11	5	710	7.1	24	0.29	0.23
217	B	4509	2	430LNb	148.4	22.3	0.4	11	5	710	7.1	37	0.31	0.25
224	B	4003	2	409Nb	179.8	22.0	0.5	11	5	855	7.4	37	0.30	0.24
225	B	4003	2	409Nb	184.2	22.2	0.5	11	5	855	7.6	37	0.31	0.25
226	B	4003	2	409Nb	182.8	22.2	0.5	11	5	855	7.6	37	0.31	0.25
227	B	4003	2	409Nb	188.9	21.9	0.5	11	5	855	7.5	36	0.31	0.25
228	B	4003	2	409Nb	179.9	22.0	0.5	11	5	855	7.5	37	0.30	0.24
229	B	4003	2	409Nb	179.2	22.0	0.5	11	5	855	7.5	38	0.29	0.23

### Welding parameters, continued

Weld # H-numbered	Mfr.	Base metal	Thickness [mm]	Filler metal	I [A]	U [V]	Air gap [mm]	Nozzle [mm]	Tilt [°]	Weld.speed [mm/min]	Wire feed [m/min]	Lenght [cm]	Energy [kJ/mm]	Heat input [kJ/mm]
2	B	4521	2	316LSi	125.5	22.9	0.5	11	0	710	7.1	37	0.27	0.22
3	B	4521	2	316LSi	123.1	22.6	0.5	11	0	710	7.1	36	0.27	0.22
4	B	4521	2	316LSi	123.2	22.6	0.5	11	0	710	7.1	35	0.27	0.22
5	B	4521	2	316LSi	124.6	22.5	0.5	11	0	710	7.1	37	0.26	0.21
6	B	4521	2	316LSi	125.3	22.7	0.5	11	0	710	7.1	35	0.27	0.22

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9	B	4521	2	316LSi	118.5	22.6	0	11	0	480	7.1	36	0.38	0.30
10	B	4521	2	316LSi	117.9	22.8	0	11	0	480	7.1	36	0.37	0.30
11	B	4521	2	316LSi	104.8	21.5	0	11	0	480	7.1	36	0.32	0.26
12	B	4521	2	316LSi	111.9	23.4	0	11	0	480	6.0	36	0.36	0.29
13	B	4521	2	316LSi	117.1	25.2	0	11	0	480	6.0	27	0.41	0.33
14	B	4521	2	316LSi	111.6	23.8	0	11	0	480	6.0	9	0.38	0.30
15	B	4521	2	316LSi	110.9	23.5	0	11	0	480	6.0	37	0.36	0.29
16	B	4521	2	316LSi	115.6	21.9	0.5	11	0	1040	7.1	36	0.17	0.14
17	B	4521	2	316LSi	129.8	22.8	0.5	11	0	1040	8.0	35	0.19	0.15
18	B	4521	2	316LSi	127.0	21.8	0.5	11	0	1040	8.2	35	0.18	0.14
19	B	4521	2	316LSi	138.2	23.1	0.5	11	0	1040	9.0	36	0.21	0.17
20	C	4016	2	308LSi	124.7	22.5	0.5	11	0	710	7.1	26	0.27	0.22
21	C	4016	2	308LSi	124.3	22.5	0.5	11	0	710	7.1	27	0.27	0.22
22	C	4016	2	308LSi	122.7	22.5	0.5	11	0	710	7.1	26	0.26	0.21
23	C	4016	2	308LSi	124.8	22.5	0.5	11	0	710	7.1	26	0.26	0.21
24	C	4509	2	308LSi	123.4	23.5	0.5	11	0	710	7.1	34	0.27	0.22
25	C	4509	2	308LSi	123.3	23.6	0.5	11	0	710	7.1	36	0.28	0.22
26	C	4509	2	308LSi	123.5	23.6	0.5	11	0	710	7.1	36	0.28	0.22
27	C	4509	2	308LSi	122.2	23.5	0.5	11	0	710	7.1	36	0.28	0.22
28	C	4509	2	308LSi	122.9	23.6	0.5	11	0	710	7.1	36	0.27	0.22
29	C	4509	2	308LSi	132.4	24.0	0.5	11	0	1040	8.0	33	0.20	0.16
32	C	4509	2	308LSi	134.3	24.0	0.5	11	0	1040	8.0	36	0.20	0.16
33	C	4509	2	308LSi	133.5	24.0	0.5	11	0	1040	8.0	36	0.20	0.16
34	C	4016	2	316LSi	113.5	21.6	0.5	11	0	710	7.1	27	0.25	0.20
35	C	4016	2	316LSi	116.0	22.4	0.5	11	0	710	7.1	26	0.26	0.21
36	C	4016	2	308LSi	121.1	22.4	0.5	11	0	710	7.1	26	0.27	0.22
37	C	4016	2	308LSi	121.4	22.6	0.5	11	0	710	7.1	26	0.27	0.22
38	C	4016	2	308LSi	113.3	22.5	0.5	11	0	710	7.1	26	0.25	0.20
39	A	4509	3	308LSi	124.5	22.2	0.5	11	0	710	9	29	0.27	0.22
40	A	4509	3	308LSi	118.3	22.4	0.8	11	0	710	9			
41	A	4509	3	308LSi	139.0	24.3	1.2	11	0	710	9			
42	A	4509	3	308LSi	141.1	24.8	1.2	11	0	525	9	27	0.46	0.37
43	A	4509	3	308LSi	140.5	24.8	1.2	11	0	600	9	27	0.41	0.33
44	A	4509	3	308LSi	141.7	24.7	1.2	11	0	600	9	27	0.40	0.32
45	A	4509	3	308LSi	144.7	24.8	1.2	11	0	600	9	27	0.42	0.34
46	A	4509	3	308LSi	144.1	24.7	1.2	11	0	600	9	26	0.41	0.33
47	A	4509	3	308LSi	143.7	24.7	1.2	11	0	600	9	27	0.40	0.32
48	A	4509	3	308LSi	141.8	24.6	1.2	11	0	600	9	26	0.40	0.32
49	A	4509	3	308LSi	141.1	24.6	1.2	11	0	600	9	27	0.39	0.31
50	C	4016	3	308LSi	144.6	24.7	1.2	11	0	600	9	25	0.42	0.34
51	C	4016	3	308LSi	147.8	24.6	1.2	11	0	600	9	27	0.42	0.34
52	C	4016	3	308LSi	148.7	24.7	1.2	11	0	600	9	27	0.42	0.34
53	C	4016	3	308LSi	146.9	24.6	1.2	11	0	600	9	26	0.41	0.33
54	C	4016	3	308LSi	144.4	24.6	1.2	11	0	600	9	27	0.40	0.32
55	C	4016	3	308LSi	144.2	24.6	1.2	11	0	600	9	27	0.40	0.32
56	C	4509	3.5	308LSi	153.3	25.4	1.2	11	0	600	9.5			
57	C	4509	3.5	308LSi	152.4	25.5	1.5	11	0	600	10			
58	C	4509	3.5	308LSi	159.4	25.9	1.5	11	0	600	10.5	27	0.46	0.37
59	C	4509	3.5	308LSi	163.6	25.3	1.5	11	0	600	11	26	0.49	0.39
60	C	4509	3.5	308LSi	161.4	25.0	1.5	11	0	600	11	27	0.49	0.39
61	C	4509	3.5	308LSi	163.4	24.9	1.5	11	0	600	11	28	0.47	0.38
62	C	4509	3.5	308LSi	170.4	25.3	1.5	11	0	600	12	28	0.51	0.41
63	C	4509	3.5	308LSi	169.0	25.4	1.5	11	0	600	12	28	0.50	0.40
64	C	4509	3.5	308LSi	167.0	25.7	1.5	11	0	600	12	28	0.50	0.40
65	C	4509	3.5	308LSi	172.2	26.1	1.5	11	0	600	12	28	0.51	0.41
66	C	4509	2	308LSi	116.9	22.3	0.5	11	0	710	7.1	28	0.26	0.21
67	B	4521	2	316LSi	112.7	2.9	0.5	11	0	710	7.1	16	0.25	0.20

TIG-welds (Nozzle = Nozzle distance to workpiece / Electrode distance to workpiece). Shielding gas Ar 7l/min, root gas Ar 10l/min.

85	C	4016	2	-	71.9	9.3	-	4/3	0	106	-	30	0.38	0.23
86	C	4016	2	-	71.9	9.0	-	4/3	0	106	-	29	0.39	0.23
87	C	4016	2	-	71.7	9.0	-	4/3	0	106	-	28	0.40	0.24
88	C	4016	2	-	71.9	9.2	-	4/3	0	106	-	29	0.40	0.24
89	C	4016	2	-	71.9	9.1	-	4/3	0	106	-	28	0.39	0.23
90	C	4016	2	-	71.8	8.7	-	4/2	0	106	-	22	0.38	0.23
91	C	4016	2	-	65.9	8.5	-	4/2	0	106	-	28	0.36	0.22
92	C	4509	2	-	68.9	9.3	-	4/2	0	106	-	30	0.39	0.23
93	C	4509	2	-	69.9	9.4	-	4/2	0	106	-	30	0.39	0.23
94	C	4509	2	-	68.9	9.4	-	4/2	0	106	-	30	0.38	0.23
95	C	4509	2	-	68.9	9.4	-	4/2	0	106	-	30	0.39	0.23
96	C	4509	2	-	68.9	9.3	-	4/2	0	106	-	28	0.38	0.23
97	C	4509	2	-	68.9	9.3	-	4/2	0	106	-	28	0.38	0.23
99	B	4509	2	-	68.9	8.9	-	4/2	0	106	-	29	0.38	0.23

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100	B	4509	2	-	67.9	9.1	-	4/2	0	106	-	29	0.38	0.23
101	B	4509	2	-	68.9	8.9	-	4/2	0	106	-	29	0.38	0.23
102	B	4509	2	-	67.9	8.9	-	4/2	0	106	-	29	0.37	0.22
103	B	4521	2	-	67.9	8.5	-	4/2	0	106	-	40	0.36	0.22
104	B	4521	2	-	67.9	9.0	-	4/2	0	106	-	40	0.37	0.22
105	B	4521	2	-	67.9	9.2	-	4/2	0	106	-	39	0.38	0.23
106	B	4521	2	-	67.9	9.0	-	4/2	0	106	-	39	0.38	0.23
107	B	4521	2	-	67.9	9.1	-	4/2	0	106	-	40	0.37	0.22
108	B	4509	2	-	67.9	8.6	-	4/2	0	106	-	30	0.36	0.22
109	B	4509	2	-	67.8	8.6	-	4/2	0	106	-	29	0.35	0.21
110	B	4509	2	-	67.9	8.7	-	4/2	0	106	-	30	0.35	0.21
111	B	4509	2	-	67.9	8.6	-	4/2	0	106	-	29	0.36	0.22
112	B	4016	2	-	68.9	8.8	-	4/2	0	106	-	39	0.39	0.23
113	B	4016	2	-	68.9	8.8	-	4/2	0	106	-	40	0.38	0.23
114	B	4016	2	-	68.9	8.8	-	4/2	0	106	-	40	0.37	0.22
115	B	4016	2	-	68.9	8.9	-	4/2	0	106	-	39	0.38	0.23
116	B	4016	2	-	68.9	8.9	-	4/2	0	106	-	39	0.38	0.23
117	B	4016	2	-	69.9	8.4	-	4/2	0	106	-	40	0.35	0.21
118	C	4016	2	-	69.9	8.9	-	4/2	0	106	-	30	0.38	0.23
119	B	4521	2	-	69.9	8.9	-	4/2	0	106	-	30	0.39	0.23
120	B	4521	2	-	69.9	8.9	-	4/2	0	106	-	29	0.39	0.23
121	C	4509	2	-	69.8	9.0	-	4/2	0	106	-	20	0.37	0.22
122	B	4016	2	-	69.9	8.6	-	4/2	0	106	-	39	0.37	0.22
123	B	4003	2	-	69.8	8.8	-	4/2	0	106	-	19	0.38	0.23
124	B	4003	2	-	69.8	8.9	-	4/2	0	106	-	19	0.38	0.23
125	B	4003	2	-	69.8	8.9	-	4/2	0	106	-	19	0.38	0.23
126	B	4003	2	-	69.8	8.9	-	4/2	0	106	-	20	0.36	0.22
127	B	4003	2	-	69.8	8.6	-	4/2	0	106	-	19	0.36	0.22
128	C	4509	1	-	68.7	9.2	-	4/2	0	270	-	28	0.18	0.11
129	C	4509	1	-	68.6	10.0	-	4/2	0	360	-	28	0.14	0.08
130	C	4509	1	-	68.5	10.0	-	4/2	0	455	-	28	0.11	0.07
131	C	4509	1	-	68.5	9.8	-	4/2	0	455	-	27	0.11	0.07
132	C	4509	1	-	68.5	9.8	-	4/2	0	455	-	27	0.11	0.07
133	B	4509	1	-	68.5	8.5	-	4/2	0	455	-	24	0.10	0.06
141	C	4509	1	-	68.5	8.5	-	4/2	0	455	-	29	0.10	0.06
142	C	4016	1	-	67.6	9.0	-	4/2	0	455	-	29	0.10	0.06
143	C	4016	1	-	68.5	9.0	-	4/2	0	455	-	27	0.10	0.06
144	C	4016	1	-	69.5	8.7	-	4/2	0	455	-	28	0.10	0.06
145	C	4016	1	-	69.5	9.0	-	4/2	0	455	-	29	0.10	0.06
146	B	4521	1	-	69.5	9.2	-	4/2	0	455	-	28	0.10	0.06
147	B	4521	1	-	66.6	9.3	-	4/2	0	455	-	28	0.10	0.06
148	B	4521	1	-	66.5	9.2	-	4/2	0	455	-	28	0.10	0.06
149	B	4521	1	-	66.5	9.4	-	4/2	0	455	-	29	0.10	0.06
150	B	4521	1	-	66.5	9.6	-	4/2	0	455	-	28	0.10	0.06
151	B	4521	1	-	66.5	9.6	-	4/2	0	455	-	29	0.10	0.06
152	B	4509	1	-	66.5	9.5	-	4/2	0	455	-	28	0.10	0.06
153	B	4509	1	-	66.5	9.5	-	4/2	0	455	-	28	0.10	0.06
154	B	4509	1	-	66.5	9.4	-	4/2	0	455	-	28	0.10	0.06
155	B	4509	1	-	66.5	9.4	-	4/2	0	455	-	28	0.10	0.06
156	B	4509	1	-	66.5	9.6	-	4/2	0	455	-	28	0.10	0.06
157	C	4509	1	-	66.5	9.5	-	4/2	0	455	-	28	0.10	0.06
158	B	4003	1	-	66.5	9.4	-	4/2	0	455	-	27	0.10	0.06
159	C	4509	1	-	66.5	9.4	-	4/2	0	455	-	27	0.10	0.06
160	C	4509	1	-	66.5	9.4	-	4/2	0	455	-	28	0.09	0.05
161	B	4003	1	-	66.5	8.9	-	4/2	0	455	-	29	0.09	0.05
162	B	4003	1	-	66.5	9.3	-	4/2	0	455	-	28	0.09	0.05
163	B	4003	1	-	66.5	9.2	-	4/2	0	455	-	29	0.09	0.05
164	B	4003	1	-	69.5	9.1	-	4/2	0	455	-	28	0.10	0.06
MMA welds. V-type configuration for 4 to 6mm materials.														
270	B	4003	4	308L	53.9	21.2	2.3	-	-	-	-	9	0.72	0.58
271	B	4003	4	308L	54.2	20.5	2.3	-	-	-	-	7	0.76	0.61
272	B	4003	4	308L	55.2	20.5	2.3	-	-	-	-	7	0.65	0.52
303	B	4003	4	308L	55.5	20.5	2.3	-	-	-	-	9	0.69	0.55
304	B	4003	4	308L	55	20.7	2.3	-	-	-	-	9	0.72	0.58
305	B	4003	4	308L	55.5	20.5	2.3	-	-	-	-	8	0.75	0.60
306	B	4003	4	308L	55.3	20.9	2.3	-	-	-	-	8	0.78	0.62
313	B	4003	4	308L	66.8	20.4	2.3	-	-	-	-	9	0.67	0.54
317	B	4003	4	308L	69.5	21.1	2.3	-	-	-	-	11	0.75	0.60
318	B	4003	4	308L	68.9	21.2	2.3	-	-	-	-	14	0.76	0.61
321	B	4003	4	308L	68.7	21	2.3	-	-	-	-	14	0.75	0.60

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322	B	4003	4	308L	69.1	21.1	2.3	-	-	-	-	14	0.75	0.60
325	B	4003	4	308L	69.2	21.1	2.3	-	-	-	-	14	0.80	0.64
326	B	4003	4	308L	69	21.3	2.3	-	-	-	-	15	0.75	0.60
332	B	4003	4	308L	69.5	20.9	2.3	-	-	-	-	12	0.77	0.62
333	B	4003	4	308L	68.8	21.3	2.3	-	-	-	-	13	0.76	0.61
336	B	4003	4	308L	69.9	21	2.3	-	-	-	-	9	0.75	0.60
337	B	4003	4	308L	69.1	21.5	2.3	-	-	-	-	13	0.91	0.73
340	B	4509	4	308L	66.3	21.1	2.3	-	-	-	-	13	0.89	0.71
341	B	4509	4	308L	66.4	21	2.3	-	-	-	-	13	0.85	0.68
345	B	4509	4	308L	66.1	21.1	2.3	-	-	-	-	12	0.93	0.74
347	B	4509	4	308L	66.1	21.1	2.3	-	-	-	-	12	0.88	0.70
352	B	4509	4	308L	66.4	21	2.3	-	-	-	-	13	0.86	0.69
353	B	4509	4	308L	66.3	20.8	2.3	-	-	-	-	13	0.88	0.70
356	B	4509	4	308L	66	21	2.3	-	-	-	-	10	0.90	0.72
357	B	4509	4	308L	66.3	21	2.3	-	-	-	-	13	0.87	0.70
360	B	4509	4	308L	66.7	20.8	2.3	-	-	-	-	13	0.87	0.70
361	B	4509	4	308L	66.4	20.9	2.3	-	-	-	-	13	0.86	0.69
364	B	4509	4	308L	66.5	20.9	2.3	-	-	-	-	13	0.86	0.69
365	B	4509	4	308L	66.3	21.2	2.3	-	-	-	-	13	0.88	0.70
368	B	4003	6	308L	67.2	20.3	2.3	-	-	-	-	14	0.73	0.58
370	B	4003	6	308L	92.3	21.8	2.3	-	-	-	-	12	0.98	0.78
380	B	4003	6	308L	65.2	21.1	2.3	-	-	-	-	14	0.67	0.54
381	B	4003	6	308L	95.3	21.9	2.3	-	-	-	-	13	1.06	0.85
384	B	4003	6	308L	71.3	20.5	2.3	-	-	-	-	16	0.74	0.59
385	B	4003	6	308L	73.9	21	2.3	-	-	-	-	14	0.62	0.50
386	B	4003	6	308L	99.1	22	2.3	-	-	-	-	14	1.00	0.80
387	B	4003	6	308L	99.1	22	2.3	-	-	-	-	13	1.01	0.81
390	B	4003	6	308L	70.5	20.5	2.3	-	-	-	-	16	0.62	0.50
391	B	4003	6	308L	70.1	20.7	2.3	-	-	-	-	12	0.64	0.51
392	B	4003	6	308L	98.7	22.1	2.3	-	-	-	-	13	1.07	0.86
393	B	4003	6	308L	98.9	22.2	2.3	-	-	-	-	13	1.05	0.84
409	B	4003	6	308L	70.6	21.6	2.3	-	-	-	-	12	0.78	0.62
410	B	4003	6	308L	68	20.6	2.3	-	-	-	-	13	0.78	0.62
411	B	4003	6	308L	99.4	21.9	2.3	-	-	-	-	12	1.11	0.89
412	B	4003	6	308L	99.3	21.9	2.3	-	-	-	-	12	1.07	0.86
417	B	4003	6	308L	68.2	20.9	2.3	-	-	-	-	12	0.66	0.53
418	B	4003	6	308L	97.4	21.9	2.3	-	-	-	-	12	1.06	0.85
419	B	4003	6	308L	97.2	21.7	2.3	-	-	-	-	12	1.10	0.88
420	A	4509	3	308L			1.8	-	-	-	-	15	0.43	0.34
422	A	4509	3	308L	59.9	21	1.8	-	-	-	-	13	0.45	0.36
424	A	4509	3	308L	61.1	20.4	1.8	-	-	-	-	26	0.44	0.35
426	A	4509	3	308L	60.7	21.3	1.8	-	-	-	-	19	0.46	0.37
433	C	4509	2	308L	51.7	20.7	0	-	-	-	-	13	0.27	0.22
442	B	4509	2	308L	73.4	21.8	0	-	-	-	-	13	0.32	0.26
443	B	4509	2	308L	79.2	22.4	0	-	-	-	-	13	0.37	0.30
444	B	4509	2	308L	79.9	22	0	-	-	-	-	14	0.38	0.30
446	C	4509	3.5	308L	54.3	20	2.5	-	-	-	-	12	0.49	0.39
448	C	4509	3.5	308L	56	20.5	2.5	-	-	-	-	12	0.45	0.36
501	C	4016	1	-	69.1	9.8	-	4/2	-	455	-	15	0.11	0.07
502	C	4016	1	-	69	9.4	-	4/2	-	455	-	14	0.10	0.06
503	C	4016	1	-	69.1	9.6	-	4/2	-	455	-	14	0.11	0.07

## Appendix 1. Welding parameters

6(6)

504	C	4016	1	-	69	9.3	-	4/2	-	455	-	13	0.11	0.07
507	C	4016	1	-	94.4	9.9	-	4/2	-	455	-	14	0.13	0.08
508	C	4016	1	-	94.1	10.1	-	4/2	-	455	-	14	0.13	0.08
509	C	4016	1	-	94.2	10	-	4/2	-	455	-	14	0.13	0.08
510	C	4016	1	-	94.4	9.7	-	4/2	-	455	-	14	0.12	0.07
512	C	4016	2	-	69.7	8.7	-	4/2	-	106	-	14	0.35	0.21
513	C	4016	2	-	69.9	8.7	-	4/2	-	106	-	14	0.37	0.22
514	C	4016	2	-	69.8	8.7	-	4/2	-	106	-	14	0.38	0.23
515	C	4016	2	-	69.9	8.8	-	4/2	-	106	-	14	0.38	0.23
533	C	4016	2	-	80	9.8	-	4/2	-	106	-	14	0.42	0.25
534	C	4016	2	-	79.9	9.4	-	4/2	-	106	-	14	0.40	0.24
535	C	4016	2	-	79.9	9.6	-	4/2	-	106	-	14	0.41	0.25
536	C	4016	2	-	79.9	9.6	-	4/2	-	106	-	14	0.41	0.25
538	B	4016	2	-	79.9	9.2	-	4/2	-	106	-	19	0.39	0.23
539	B	4016	2	-	79.9	9.6	-	4/2	-	106	-	19	0.42	0.25
540	B	4016	2	-	79.9	9.3	-	4/2	-	106	-	19	0.40	0.24
541	B	4016	2	-	79.9	9.3	-	4/2	-	106	-	19	0.38	0.23
543	B	4016	2	-	69.9	9	-	4/2	-	106	-	20	0.39	0.23
544	B	4016	2	-	69.9	9.1	-	4/2	-	106	-	20	0.39	0.23
545	B	4016	2	-	69.9	9.1	-	4/2	-	106	-	19	0.39	0.23
546	B	4016	2	-	69.9	9.1	-	4/2	-	106	-	20	0.38	0.23
548	C	4509	2	-	69.8	9.4	-	4/2	-	106	-	23	0.39	0.23
549	C	4509	2	-	69.9	9.5	-	4/2	-	106	-	22	0.41	0.25
550	C	4509	2	-	80	10	-	4/2	-	106	-	20	0.40	0.24
551	C	4509	2	-	80	9.9	-	4/2	-	106	-	20	0.40	0.24
552	C	4509	2	-	79.9	10	-	4/2	-	106	-	17	0.39	0.23
553	C	4509	2	-	80	10.1	-	4/2	-	106	-	14	0.41	0.25
554	B	4509	2	-	80	9.7	-	4/2	-	106	-	22	0.39	0.23
555	B	4509	2	-	80	9.3	-	4/2	-	106	-	22	0.38	0.23
556	B	4509	2	-	70	8.9	-	4/2	-	106	-	22	0.38	0.23
557	B	4509	2	-	69.9	9.1	-	4/2	-	106	-	22	0.39	0.23
579	C	4521	2	-	67.1	9.3	-	4/2	-	106	-	29	0.38	0.23
580	C	4521	2	-	67.9	9.4	-	4/2	-	106	-	29	0.37	0.22
581	C	4521	2	-	67.9	9.4	-	4/2	-	106	-	29	0.38	0.23
582	C	4521	2	-	67.9	9.5	-	4/2	-	106	-	30	0.39	0.23
583	C	4521	2	-	67.9	9.5	-	4/2	-	106	-	29	0.40	0.24
584	C	4521	2	-	67.9	9.6	-	4/2	-	106	-	29	0.40	0.24
585	C	4521	2	-	67.9	9.3	-	4/2	-	106	-	29	0.39	0.23
591	C	4521	2	316LSi	150.1	20.8	0.5	11	0	710	6.6	29	0.29	0.23
592	C	4521	2	316LSi	149.4	20.8	0.5	11	0	710	6.6	28	0.28	0.22
593	C	4521	2	316LSi	141.9	21.1	0.5	11	0	710	6.6	28	0.27	0.22
596	C	4521	2	316LSi	137.6	20.4	0.5	11	0	710	6.6	14	0.27	0.22
597	C	4521	2	316LSi	141.2	21.1	0.5	11	0	710	6.6	27	0.28	0.22
598	C	4521	2	316LSi	141.8	21.1	0.5	11	0	710	6.6	29	0.27	0.22
601	A	4621	1.5	316LSi	118	20.2	0.5	11	0	710	5	29	0.21	0.17
602	A	4621	1.5	316LSi	106	19.9	0.5	11	0	710	4.5	28	0.20	0.16
603	A	4621	1.5	316LSi	107.8	19.7	0.5	11	0	710	4.7	27	0.20	0.16
604	A	4621	1.5	316LSi	107.7	19.8	0.5	11	0	710	4.7	28	0.20	0.16
605	A	4621	1.5	316LSi	107.4	19.6	0.5	11	0	710	4.7	27	0.19	0.15
606	A	4621	1.5	316LSi	108.3	19.7	0.5	11	0	710	4.7	26	0.19	0.15
607	A	4621	1.5	316LSi	108	19.7	0.5	11	0	710	4.7	27	0.19	0.15
608	A	4621	1.5	316LSi	108.3	19.8	0.5	11	0	710	4.7	28	0.19	0.15
611	A	4621	1.5	-	46	9.6	-	4/2	0	106	-	28	0.28	0.17
612	A	4621	1.5	-	46	9.3	-	4/2	0	106	-	28	0.28	0.17
613	A	4621	1.5	-	47	9.7	-	4/2	0	106	-	29	0.26	0.16
614	A	4621	1.5	-	49	9.8	-	4/2	0	106	-	29	0.28	0.17
615	A	4621	1.5	-	49	10	-	4/2	0	106	-	29	0.28	0.17
616	A	4621	1.5	-	49	9.1	-	4/2	0	106	-	28	0.25	0.15
617	A	4621	1.5	-	49	9.2	-	4/2	0	106	-	29	0.26	0.16
618	A	4621	1.5	-	49	9	-	4/2	0	106	-	28	0.26	0.16

## Appendix 2. Grain sizes, width of the regions, and martensite measurements

1(2)

## Appendix 2. Grain sizes, width of the regions, and martensite measurements

Appendix 3. Hardness measurements

1(1)

Grade	Mfr	Thk	Method	Filler	Weld#	Sample	Distance from the weld centre [mm]																																			
							-8.4	-7.2	-6.8	-6.4	-6	-5.6	-5.2	-4.8	-4.4	-4	-3.6	-3.2	-2.8	-2.4	-2	-1.6	-1.2	-0.8	-0.4	0	0.4	0.8	1.2	1.6	2	2.4	2.8	3.2	3.6	4	4.4	4.8	5.2	5.6	6	6.4
4003	B	2	MAG	308LSi	D61	1	153	171	299	316	321	319	315	324	315	306	297	315	317	216	258	280	236	229	224	205	314	314	320	323	324	320	316	309	294	174	160	154				
4003	B	2	MAG	308LSi	D65	2	160	155	234	289	307	309	313	312	312	305	306	309	210	206	218	198	178	300	298	313	311	331	344	344	329	316	293	261	162	162						
4003	B	2	MAG	409LNb	D134	1	154	153	203	299	312	318	323	312	315	321	310	316	307	243	249	212	260	283	271	253	312	320	322	326	321	323	322	319	315	300	189	146	149			
4003	B	2	MAG	409LNb	D136	2	150	150	282	297	314	320	317	318	319	311	303	276	197	194	297	205	274	234	215	219	239	304	299	313	320	321	322	319	307	265	149	149				
4003	B	2	MAG	409LNb	D134	PWHT 1	144	145	140	142	143	146	150	150	147	145	149	159	186	214	209	204	224	227	187	149	144	144	149	145	143	138	140	136	135	141	146					
4003	B	4	MMA	308L	H336	1	155	148	152	147	190	298	302	302	309	307	305	310	303	299	310	288	302	288	286	301	296	298	300	298	304	299	296	252	162	174	185	188	180	184		
4003	B	6	MMA	308L	H370	1	138	131	136	136	277	296	297	309	296	303	308	308	308	308	306	272	300	308	299	300	304	297	307	307	299	303	296	294	265	142	141	138	140			
4016	B	2	MAG	308LSi	D87	1	153	153	155	155	160	201	203	197	216	186	198	194	213	220	226	222	223	215	202	184	190	201	251	207	225	187	168	158	154	152	152					
4016	B	2	MAG	308LSi	D90	2	159	162	157	157	188	209	215	204	219	211	194	196	213	241	234	232	227	233	234	194	211	230	208	215	210	207	170	161	158	150	161					
4016	B	2	MAG	430LNb	D149	1	153	153	162	195	215	201	216	203	224	194	196	190	197	192	189	192	195	196	194	196	201	223	192	218	204	226	207	210	173	149	149					
4016	B	2	MAG	430LNb	D154	2	150	154	154	187	221	212	220	198	205	228	240	207	183	191	190	188	190	186	185	196	203	209	187	188	211	212	222	191	159	154	151					
4016	B	2	MAG	430Ti	D166	1	158	155	159	165	185	195	219	197	212	200	201	197	196	198	210	190	201	209	198	191	208	204	220	217	212	201	166	165	159	153	154					
4016	B	2	MAG	430Ti	D170	2	156	160	162	163	208	205	228	192	193	231	201	204	198	195	197	191	196	193	197	182	213	179	200	207	213	189	160	160	159	156						
4016	B	2	MAG	430Ti	D168	PWHT 1	143	144	144	147	161	170	180	171	174	165	171	179	179	180	184	178	182	183	164	177	184	172	176	175	174	157	154	149	145	147	143					
4016	B	2	MAG	430Ti	D174	PWHT 2	147	151	143	145	147	145	166	179	178	176	180	174	175	176	173	173	178	184	184	182	179	180	184	176	179	168	149	144	145	147	147					
4016	C	2	MAG	308LSi	H38	1	153	157	150	150	153	157	166	197	199	196	180	202	189	188	184	203	194	201	199	201	178	173	185	191	202	199	206	187	160	154	153	155	153	161	159	
4016	C	2	MAG	308LSi	H38	2	154	157	154	151	152	158	185	187	187	191	193	187	185	185	201	188	204	195	204	194	187	209	181	185	205	204	207	195	171	160	152	155	150	152	155	155
4016	C	3	MAG	308LSi	H55	1	159	161	159	159	155	161	160	171	194	217	202	211	198	191	191	185	195	195	199	200	219	214	220	179	159	160	165	162	164	164	159					
4016	C	3	MAG	308LSi	H55	2	161	167	164	162	167	167	167	210	195	203	195	185	197	192	192	177	200	200	191	198	200	213	196	185	209	228	218	174	161	161	163	163	163	163		
4509	B	2	MAG	308LSi	D49	1	179	171	163	167	167	168	159	163	164	163	167	167	179	178	222	207	210	178	177	164	170	168	173	168	164	164	167	172	166	168						
4509	B	2	MAG	308LSi	D52	2	177	176	172	173	171	168	172	176	163	172	175	161	197	196	198	201	218	216	190	159	170	172	172	166	163	162	161	170	162	164	169					
4509	B	2	MAG	430LNb	D41	1	171	163	158	171	163	167	168	169	162	172	167	169	167	173	175	172	168	173	165	171	173	174	167	165	165	163	163	161	169	178	170					
4509	B	2	MAG	430LNb	D47	2	183	175	169	170	167	166	160	161	172	173	160	170	179	183	184	181	166	172	179	171	162	165	160	173	174	167	167	167	167	167	167	169	169	175		
4509	B	2	MAG	430Ti	D34	1	174	170	171	169	173	166	173	168	168	168	187	182	174	178	176	182	182	178	172	169	169	171	180	164	167	171	171	167	167	167	167	167	167			
4509	B	2	MAG	430Ti	D40	2	171	172	172	169	168	161	165	168	167	167	170	189	179	187	189	175	188	178	189	174	176	169	168	166	163	163	163	174	174	173	173	173	173			
4509	B	2	MAG	430Ti	D202	PWHT 1	155	152	159	159	154	153	157	155	160	162	162	163	161	167	168	168	165	167	169	171	181	177	173	163	164	156	152	154	154	156	156	157				
4509	C	2	MAG	308LSi	H29	1	165	167	163	177	168	161	162	163	159	164	167	165	162	172	171	171	205	214	212	171	157	165	164	168	159	154	165	163	163	168	168	166	154	162		
4509	C	2	MAG	308LSi	H29	2	169	172	172	172	164	159	160	156	162	158	164	159	165	169	172	173	212	203	212	217	165	168	166	164	157	159	160	163	162	163	163	163	167	164	157	
4509	A	3	MAG	308LSi	H43	1	162	155	163	159	159	151	152	144	151	158	152	154	162	185	204	192	195	195	165	164	154	157	151	152	157	152	156	148	151	154	157	153				
4509	A	3	MAG	308LSi	H43	2	171	166	170	163	161	164	163	155	162	171	168	164	157	167	173	202	196	198	205	200	170	165	156	156	151	155	158	160	165	161	155	155	158			
4509	C	3.5	MAG	308LSi	H58	1	195	194	179	183	173	171	171	168	167	161	162	159	165	167	199	198	210	197	211	207	169	161	152	167	151	155	163	168	168	166	154	162	160	180	185	180
4509	C	3.5	MAG	308LSi	H58	2	195	185	176	180	174	164	158</																													

Grade	Mfr	Thk	Method	Filler	Weld#	Sample	Fracture	thickness (mm)	width (mm)	E-Modulus (kN/mm²)	Rp 0,1 (N/mm²)	Rp 0,2 (N/mm²)	Rp 1,0 (N/mm²)	Rm (N/mm²)	Ag (%)	A50 (%)	A80 (%)	A5 (%)	Test duration (s)
4003	B	1	Base	-	-	1	-	0.998	20.09	216	327	331	346	477	17.4		28	50	212.4
4003	B	1	Base	-	-	3	-	0.993	20.10	218	327	332	346	478	17.4		28	50	213.0
4003	B	1	Base	-	-	2	-	0.995	20.09	211	327	332	347	478	18.0		28	49	214.6
4003	B	1	Base	-	-	4	-	0.998	20.10	210	328	333	347	478	17.3		28	51	215.5
4003	B	1	TIG	Autog.	H164	2	b	1.001	20.15	198	325	331	351	476	14.9		23	42	207.3
4003	B	1	TIG	Autog.	H164	3	b	0.998	20.12	205	325	331	351	477	14.9		24	44	212.0
4003	B	1	TIG	Autog.	H164	4	b	0.998	20.12	207	326	332	352	477	14.9		23	41	210.1
4003	B	1	TIG	Autog.	H164	1	b	0.998	20.12	202	326	333	353	477	14.7		24	45	215.6
4003	B	2	Base	-	-	1	-	1.994	20.00	207	346	360	386	495	16.9		28	42	107.0
4003	B	2	Base	-	-	2	-	1.984	20.02	211	348	361	386	497	16.8		31	48	112.6
4003	B	2	MAG	409LNb	D134	1	b	1.959	20.02	210	349	362	392	501	13.3		20	28	89.5
4003	B	2	MAG	409LNb	D134	1	b	1.788	20.06	220	317	326	353	504	11.1		16	22	69.6
4003	B	2	MAG	409LNb	D134	2	b	1.838	20.03	215	366	380	414	524	11.0		17	25	81.1
4003	B	2	MAG	409LNb	D134	3	b	1.701	20.06	222	371	386	431	532	8.3		12	17	69.0
4003	B	2	MAG	409LNb	D134	4	b	1.729	20.03	227	375	391	431	539	9.7		15	22	75.6
4003	B	2	MAG	409LNb	D134	2	bh	1.973	20.02	200	298	299	326	476	13.9		19	26	79.3
4003	B	2	MAG	409LNb	D134	3	bh	1.659	20.05	235	320	334	367	509	8.9		13	19	63.7
4003	B	2	MAG	308LSi	D65	1	b	1.958	20.02	194	345	361	393	491	11.0		17	25	80.2
4003	B	2	MAG	308LSi	D65	2	b	1.910	20.01	212	353	368	401	502	11.2		16	22	78.7
4003	B	2	MAG	308LSi	D65	3	b	1.867	20.00	209	354	370	405	507	10.0		16	23	78.0
4003	B	2	MAG	308LSi	D65	4	b	1.808	20.02	215	365	379	416	517	9.8		16	23	76.2
4003	B	4	Base	-	-	1	-	4.015	12.13	223	399	436	490	583	10.2	19		22	75.2
4003	B	4	Base	-	-	2	-	4.007	12.15	196	416	444	491	580	9.7	13		14	76.7
4003	B	4	Base	-	-	3	-	4.094	12.13	236	388	425	476	567	10.5	18		20	74.6
4003	B	4	MMA	308L	H337	1	b	3.472	12.13	230	368	389	459	531	4.8	12		15	52.7
4003	B	4	MMA	308L	H337	2	b	3.523	12.16	211	353	371	430	509	5.9	13		16	53.0
4003	B	4	MMA	308L	H337	3	b	3.486	12.12	225	346	371	432	532	7.1	16		19	59.9
4003	B	6	Base	-	-	1	-	5.974	12.05	230	322	342	374	482	15.3	30		30	96.2
4003	B	6	Base	-	-	2	-	5.968	12.15	221	321	342	373	483	16.0	29		30	96.1
4003	B	6	Base	-	-	3	-	5.965	12.10	215	327	345	373	483	15.5	29		29	95.7
4003	B	6	MMA	308L	H380/381	1	b	5.636	12.13	220	324	347	390	492	10.0	19		20	72.2
4003	B	6	MMA	308L	H380/381	2	b	5.730	12.24	201	325	341	383	486	8.9	18		19	70.2
4003	B	6	MMA	308L	H380/381	3	b	5.761	12.22	222	319	338	380	485	9.3	18		19	68.9
4003	B	6	MMA	308L	H380/381	4	b	5.409	12.15	226	308	326	373	484	9.0	17		18	63.1
4003	B	6	MMA	308L	H380/381	5	b	5.673	12.19	192	327	345	385	491	9.7	19		19	69.6
4016	C	1	Base	-	-	3	-	1.006	20.08	215	346	344	348	516	17.8		27	47	204.8
4016	C	1	Base	-	-	2	-	1.000	20.10	224	349	347	349	519	18.1		26	44	203.4
4016	C	1	Base	-	-	1	-	1.000	20.08	218	349	346	349	519	18.0		28	50	208.5
4016	C	1	Base	-	-	4	-	1.000	20.06	223	349	346	350	521	18.1		27	45	201.4
4016	C	1	TIG	Autog.	H145	4	b	1.019	20.17	215	349	349	347	501	16.1		25	44	186.4
4016	C	1	TIG	Autog.	H145	3	b	1.020	20.16	213	348	347	348	501	16.5		24	41	185.0
4016	C	1	TIG	Autog.	H145	2	b	1.020	20.13	209	349	349	348	501	16.4		24	40	186.4
4016	C	1	TIG	Autog.	H145	1	b	1.016	20.14	205	348	349	350	503	16.6		26	45	187.5
4016	B	2	Base	-	-	1	-	1.959	20.04	193	347	356	380	488	16.0		29	45	106.8
4016	B	2	Base	-	-	2	-	1.961	20.03	204	346	357	381	488	16.7		31	49	113.3
4016	B	2	MAG	430LNb	D149	1	b	1.920	20.13	202	347	357	387	500	14.5		28	46	108.3
4016	B	2	MAG	430LNb	D149	2	b	1.919	20.12	208	346	357	387	499	14.5		26	42	105.9
4016	B	2	MAG	430LNb	D149	3	b	1.871	20.14	203	352	364	396	511	14.6		26	40	103.5
4016	B	2	MAG	430Ti	D170	1	b	1.840	20.09	204	365	378	409	521	14.6		26	42	109.0
4016	B	2	MAG	430Ti	D170	2	b	1.915	20.09	196	351	363	392	500	13.6		25	39	104.2
4016	B	2	MAG	430Ti	D170	3	b	1.906	20.14	206	353	364	393	500	14.1		25	39	99.6
4016	B	2	MAG	430Ti	D170	4	b	1.890	20.12	186	356	368	397	506	14.1		27	44	108.0
4016	B	2	MAG	430Ti	D176	1	b	1.840	20.07	207	301	305	336	502	14.1		21	31	82.9
4016	B	2	MAG	430Ti	D176	3	b	1.851	20.08	202	299	303	334	494	13.7		21	31	81.1
4016	B	2	MAG	430Ti	D176	2	w	1.888	20.07	207	296	295	328	490	14.8		21	29	83.6
4016	B	2	MAG	308LSi	D90	1	b	1.820	20.12	205	358	371	403	518	12.5		20	29	89.5
4016	B	2	MAG	308LSi	D90	2	b	1.827	20.14	211	358	371	403	519	12.9		18	25	87.9
4016	B	2	MAG	308LSi	D90	3	b	1.874	20.14	201	348	362	394	508	13.8		24	37	98.7
4016	B	2	MAG	308LSi	D90	4	b	1.835	20.17	188	357	370	401	513	13.1		20	29	88.5
4016	C	2	Base	-	-	1	-	1.980	20.14	221	336	344	366	496	16.1		27	42	106.7
4016	C	2	Base	-	-	2	-	1.979	20.13	216	336	344	366	496	16.1		27	40	106.5
4016	C	2	Base	-	-	3	-	1.979	20.13	217	337	345	367	496	15.7		29	45	109.4
4016	C	2	TIG	Autog.	H118	2	w	2.097	20.05	205	318	327	351	446	7.0		7	7	136.4
4016	C	2	TIG	Autog.	H118	3	w	2.020	20.06	198	329	338	363	445	4.9		5	5	125.9
4016	C	2	TIG	Autog.	H118	1	hw	1.976	20.06	207	341	350	374	496	13.5		14	14	174.8
4016	C	2	TIG	Autog.	H118	4	hw	1.974	20.06	215	341	349	375	457	4.9		5	5	126.7
4016	B	2	TIG	Autog.	H123	3	w	2.048	20.03	183	326	333	356	462	10.4		10	10	156.7
4016	B	2	TIG	Autog.	H123	2	b	1.948	20.07	214	344	352	376	490	13.2		23	35	208.8
4016	B	2	TIG	Autog.	H123	4	b	1.953	20.06	218	342	351	375	489	13.1		22	32	207.6
4016	C	2	MAG</td																

Appendix 4. Tension tests at room temperature

2(3)

4509	B	1	TIG	Autog.	H155	4	b	1.006	20.14	227	365	373	392	484	16.8		27	48	992.1
4509	B	1	TIG	Autog.	H155	1	b	1.006	20.14	211	368	375	393	485	16.1		25	46	1008.7
4509	C	1	TIG	Autog.	H160	4	b	0.987	20.12	207	326	331	354	477	19.7		30	52	1130.1
4509	C	1	TIG	Autog.	H160	2	b	0.989	20.08	220	327	333	356	478	18.8		29	52	1114.6
4509	C	1	TIG	Autog.	H160	3	b	0.989	20.08	210	328	333	355	479	19.5		31	55	1175.0
4509	B	2	Base	-	-	1	-	1.984	20.07	218	394	399	412	496	14.6		29	46	109.8
4509	B	2	Base	-	-	2	-	1.986	20.05	208	394	399	413	497	14.6		30	48	117.1
4509	B	2	MAG	430Ti	D194	1	w	1.852	20.06	185	326	334	366	511	10.2		15	20	73.2
4509	B	2	MAG	430Ti	D194	2	w	1.912	20.03	192	323	329	361	521	12.8		19	27	84.6
4509	B	2	MAG	430Ti	D194	3	w	1.984	20.03	205	311	318	348	494	11.4		16	21	76.6
4509	B	2	MAG	430Ti	D40	1	f	1.815	20.02	207	388	400	438	500	6.7		11	17	73.4
4509	B	2	MAG	430Ti	D40	2	f	1.741	20.06	249	397	410	452	514	6.4		11	18	65.0
4509	B	2	MAG	430Ti	D40	3	f	1.861	20.01	222	387	401	433	501	8.0		13	19	80.0
4509	B	2	MAG	430Ti	D40	4	f	1.684	20.01	196	407	420	468	519	5.1		9	14	64.0
4509	B	2	MAG	430LnB	D41	1	f	2.026	20.04	233	368	381	403	479	10.4		15	21	69.0
4509	B	2	MAG	430LnB	D41	3	f	1.919	19.99	218	378	392	420	490	8.2		13	19	84.1
4509	B	2	MAG	430LnB	D41	4	f	1.853	19.98	222	382	396	432	499	7.3		11	17	65.1
4509	B	2	MAG	430LnB	D41	2	w	2.035	20.01	198	367	378	400	477	11.4		20	30	102.8
4509	B	2	MAG	308LSi	D49	1	b	1.918	20.00	215	385	394	416	495	11.1		18	26	82.2
4509	B	2	MAG	308LSi	D49	3	b	1.744	19.99	225	392	403	436	510	8.9		13	20	83.2
4509	B	2	MAG	308LSi	D49	4	b	1.736	19.95	217	385	398	432	498	7.2		14	24	76.4
4509	B	2	MAG	308LSi	D49	2	bh	1.747	19.95	220	396	408	440	510	7.7		14	23	84.7
4509	C	2	Base	-	-	1	-	1.975	20.11	222	344	351	369	489	16.2		29	44	109.1
4509	C	2	Base	-	-	2	-	1.976	20.11	222	344	352	370	490	16.4		29	44	109.3
4509	C	2	Base	-	-	3	-	1.976	20.12	220	343	350	368	489	16.6		29	45	109.4
4509	B	2	TIG	Autog.	H111	4	b	1.999	20.07	182	360	370	390	480	17.2		28	41	1045.9
4509	B	2	TIG	Autog.	H111	1	b	1.994	20.07	186	361	371	390	483	16.4		24	32	1024.9
4509	B	2	TIG	Autog.	H111	3	b	1.996	20.08	185	363	372	393	482	16.2		26	39	1019.3
4509	B	2	TIG	Autog.	H111	2	b	1.994	20.06	202	362	373	394	482	16.5		28	41	1048.7
4509	C	2	TIG	Autog.	H121	1	b	1.983	20.05	201	344	353	374	482	17.8		29	44	1150.8
4509	C	2	TIG	Autog.	H121	2	b	1.983	20.05	217	346	354	375	481	17.4		25	35	1120.9
4509	C	2	TIG	Autog.	H121	4	b	1.982	20.02	221	345	353	374	482	17.6		27	39	1101.8
4509	C	2	TIG	Autog.	H121	3	b	1.985	20.06	192	347	354	376	481	17.8		29	43	1110.6
4509	C	2	MAG	308LSi	H24	1	b	1.713	20.11	222	377	393	428	510	8.2		13	21	78.8
4509	C	2	MAG	308LSi	H24	2	b	1.736	20.13	232	370	386	420	506	9.5		15	23	83.0
4509	C	2	MAG	308LSi	H24	3	b	1.779	20.12	227	367	382	414	503	10.0		15	21	82.3
4509	C	2	MAG	308LSi	H24	4	b	1.787	20.11	228	366	382	414	502	9.7		14	20	79.5
4509	A	3	MMA	308L	H420	1	b	2.794	12.15	223	336	353	386	469	13.6	24	30		195.1
4509	A	3	MMA	308L	H420	2	b	2.607	12.15	205	341	354	385	470	13.0	25	31		180.3
4509	A	3	MMA	308L	H420	3	b	2.698	12.14	226	340	355	389	468	13.9	26	32		218.4
4509	A	3	MMA	308L	H420	4	b	2.691	12.13	203	347	360	389	478	14.2	25	31		194.7
4509	A	3	MMA	308L	H420	5	b	2.789	12.13	231	330	346	379	465	15.2	28	34		214.0
4509	A	3	MMA	308LSi	H43	3	b	2.541	12.14	225	347	359	393	486	10.1	20	27		159.9
4509	A	3	MMA	308LSi	H43	4	b	2.610	12.13	226	332	342	371	474	12.8	23	29		161.3
4509	C	3.5	MMA	308L	H448	1	h	3.266	12.17	222	393	417	484	534	5.9	12	15		94.4
4509	C	3.5	MMA	308L	H448	2	h	3.251	12.17	233	384	409	475	523	4.8	8	9		61.7
4509	C	3.5	MMA	308L	H448	3	h	3.123	12.15	213	400	421	482	531	5.4	6	6		57.2
4509	C	3.5	MMA	308L	H448	4	h	2.778	12.17	246	400	422	487	542	5.8	11	14		79.7
4509	C	3.5	Base	-	-	1	-	3.552	12.12	227	500	512	524.0	579	8.3		20	18	98.0
4509	C	3.5	Base	-	-	2	-	3.553	12.13	226	502	513	525.0	579	7.9		19	18	97.6
4509	C	3.5	Base	-	-	3	-	3.552	12.13	241	504	513	524.0	578	8.1		20	18	97.8
4509	C	3.5	MAG	308LSi	H61	1	h	3.072	12.13	195	416	446	499	549	5.0	10	13		101.6
4509	C	3.5	MAG	308LSi	H61	2	h	3.130	12.16	220	415	445	495	552	7.7	14	17		121.0
4509	C	3.5	MAG	308LSi	H61	3	h	3.105	12.13	249	445	469	522	574	5.6	12	14		110.1
4509	C	3.5	MAG	308LSi	H61	4	h	3.156	12.06	241	419	442	498	554	5.8	11	14		108.1
4509	B	4	Base	-	-	1	-	3.926	12.18	227	385	401	425	495	14.7	29	33		95.9
4509	B	4	Base	-	-	2	-	3.922	12.12	226	386	401	424	495	14.7	29	33		95.4
4509	B	4	Base	-	-	3	-	3.940	12.15	231	383	401	426	493	14.6	29	33		96.1
4509	B	4	MMA	308L	H340	1	b	3.749	12.18	231	357	379	419	502	12.8	25	29		210.6
4509	B	4	MMA	308L	H340	2	b	3.663	12.12	221	359	379	419	497	10.9	21	25		167.1
4509	B	4	MMA	308L	H340	3	b	3.584	12.20	237	345	368	412	500	11.8	23	26		173.5
4521	B	1	Base	-	-	3	-	0.983	20.11	223	439	426	424	583	17.2		27	48	210.8
4521	B	1	Base	-	-	2	-	0.984	20.10	226	442	428	425	585	17.0		27	48	211.2
4521	B	1	Base	-	-	4	-	0.977	20.12	225	442	424	424	585	17.0		27	48	209.6
4521	B	1	Base	-	-	1	-	0.971	20.11	224	443	426	425	588	16.4		27	50	209.4
4521	B	1	TIG	Autog.	H148	4	w	1.038	20.14	214	411	412	409	554	15.5		21	33	165.7
4521	B	1	TIG	Autog.	H148	2	w	1.036	20.14	210	414	415	408	555	15.3		21	32	170.3
4521	B	1	TIG	Autog.	H148	1	w	1.022	20.15	211	421	420	414	564	16.2		22	35	177.5
4521	B	1	TIG	Autog.	H148	3	wb	0.985	20.14	223	435	436	427	581	13.8		20	33	164.6
4521	B	2	MAG	316LSi	H2	1	b	1.779	20.14	225	429	444	483	579	9.1		14	20	80.6
4521	B	2																	

4521	C	2	TIG	Autog.	H586	2	w	2.024	20.14	212	389	397	422	538	13.2		16	19	76.3
4521	C	2	TIG	Autog.	H587	3	w	2.064	20.18	205	381	388	413	530	15.6		21	28	90.3
4521	C	2	TIG	Autog.	H588	4	w	2.043	20.16	212	386	394	419	534	13.5		18	23	80.2
4621	A	1.5	Base	-	-	4	-	1.488	20.21	212	385	393	408	478	15.7		29	49	102.9
4621	A	1.5	Base	-	-	3	-	1.487	20.16	208	386	395	410	479	15.1		28	49	102.7
4621	A	1.5	Base	-	-	2	-	1.488	20.15	206	387	395	410	479	15.1		29	52	104.6
4621	A	1.5	Base	-	-	1	-	1.486	20.15	208	387	395	410	480	15.0		29	52	104.0
4621	A	1.5	MAG	316LSi	H607	1	b	1.401	20.17	209	377	391	421	482	9.1		17	29	69.2
4621	A	1.5	MAG	316LSi	H607	2	b	1.395	20.22	207	380	395	423	487	10.6		19	33	74.4
4621	A	1.5	MAG	316LSi	H607	4	b	1.336	20.22	219	394	406	438	499	8.3		15	27	64.6
4621	A	1.5	MAG	316LSi	H607	3	b	1.315	20.21	222	403	418	448	515	9.6		15	25	66.8
4621	A	1.5	TIG	Autog.	H618	1	b	1.487	20.16	219	373	385	408	483	14.3		27	46	101.7
4621	A	1.5	TIG	Autog.	H618	2	b	1.501	20.15	215	369	382	404	478	14.5		27	47	102.5
4621	A	1.5	TIG	Autog.	H618	3	b	1.510	20.17	212	368	380	402	476	13.7		25	43	98.3
4621	A	1.5	TIG	Autog.	H618	4	b	1.504	20.16	215	370	382	404	477	13.9		26	45	99.5

#### Appendix 5. Impact toughness tests at temperatures -40 ... +20 °C

1(2)

Grade	Mfr.	THK [mm]	Energy [kJ/mm]	Filler	Notch	Temperature Sample No.	U[cm <sup>2</sup> ]																		Individual means		Combined HTHAZ									
							-40			-40			-40			-20			-20			0			0			20		20		20				
							16	17	18	19	20	11	12	13	14	15	6	7	8	9	10	1	2	3	4	5	-40	-20	0	20						
14003	B	2	-	-	Base	162	145	154	156	157	167	160	159	137	146	163	153	158	159	157	158	155	162	150	158											
14003	B	2	-	PWHT	Base	113	133	123	122	113	131	146	182	129	120	137	142	138	138	151	156	146	137	143	121	142	139	147								
14003	B	2	0.23	308 LSI	HTHAZ	18	92		122	94	184	118	160	15			166		89	175	187		168	81	119	166	155	53	109	150	167					
14003	B	2	0.25	409Nb	HTHAZ	14	53	15	34	36	141	141	20	95	183	108	136	156		210		145	208	155	30	99	146	179								
14003	B	2	0.24	PWHT 409Nb	HTHAZ	66	28	36	69	49	39	92	92	60	83	88	102	113	141	72	110	133	119	127	50	73	103	122								
14003	B	2	0.23	308 LSI	WM	65	93	103	99	100	99	123	102	109	83	74	111	89	103	102	81	78	87	105	94	90										
14003	B	2	0.25	409Nb	WM	13	14	12	11	86	13	27	10	73	67	60	65	71	127	105	119	12	42	66	100											
14003	B	2	0.24	PWHT 409Nb	WM	74	14	11	19	11	158	28	16	149	227	21	148	213	201	169	171	258	187	30	53	151	197									
14003	B	4	-	-	Base	106	124	111	128	121	113	161	144	120	124	127	133	132	133	161	144	149	163	184	162	118	133	137	160							
14003	B	4	0.61	308L	HAZ	22	54	28	36	18	29	18	55	38	87	64	75	62	62	81	89	85	68	32	35	72	81									
14003	B	4	0.61	308L	WM	85	77	60	83	91	82	90	79	77	102	101	96	101	109	115	98	112	79	82	100	107										
14003	B	6	-	-	Base	13	133	95	135	8	154	155	155	133	27	177	193	146	191	136	187	203	152	196	185	77	125	168	184							
14003	B	6	0.55+0.85	308L	HAZ	89	34	37	91	101	89	111	129	46	104	208	122	143	110	135	166		160	165	63	95	137	157								
14003	B	6	0.55+0.85	308L	WM	79	81	79	80	67	96	87	84	96	88	82	88	86	122	92	103	107	116		77	90	94	109								
14016	C	2	-	-	Base	97	96	100	99	102	114	100	106	110	115	109	123	109	109	120	118	118	123	126	122	99	109	114	122							
14016	C	2	0.23	TIG	HTHAZ	14	13	13	15	12	13	14	17	13	14	23	19	23	16	17	15	18	14	15	17	13	14	20	16	15	15	19	19			
14016	C	2	0.22	308 LSI	HTHAZ	15	19	15	19	18	15	15	14	14	16	17	21	21	17	24	18	22	21	27	17	15	18	22								
14016	C	2	0.22	308 LSI	WM																															
14016	C	2	0.23	TIG	WM	13	13	12	11	12	12	14	12	11	14	12	13	13	12	17	15	15	16	14	12	12	15									
14016	C	2	0.23	Gleeble	HTHAZ																															
14016	C	2	0.23	Gleeble	HTHAZ																															
14016	B	2	-	-	Base	15	140	18	116	116	151	152	134	142	149	162	172	156	166	140	162	159	158	81	146	159	160									
14016	B	2	-	PWHT	Base	142	156	125	152	151	135	153	158	165	149	120	141	154	155	144	136	145	145	153	150	142										
14016	B	2	0.23	TIG	HTHAZ	12	18	14	13	11	16	14	12	19	19	12	12	13	14	18	20	16	14	16	13	16	15	17	17							
14016	B	2	0.23	308 LSI	HTHAZ	18	15	13	11	11	16	17	15	17	20	18	13	18	17	14	15	21	20	16	14	16	17	17								
14016	B	2	0.26	430 LNB	HTHAZ	10	13	10	13	11	13	14	15	14	32	15	14	18	18	15	18	16	16	18	19	12	14	18	16							
14016	B	2	0.24	430 Ti	HTHAZ	12	13	13	13	12	17	15	15	18	15	15	12	14	13	18	19	15	16	18	16	14	17	16	18							
14016	B	2	0.25	PWHT 430Ti	HTHAZ	11	17	11	58	46	15	48	62	59	27	54	60	62	60	60	60	60	60	60	60	12	24	36	50	42						
14016	B	2	0.23	TIG	WM	12	7	9	10	10	9	10	9	9	11	10	11	11	15	10	11	11	10	12	9	12	11									
14016	B	2	0.23	308 LSI	WM	17														70																
14016	B	2	0.26	430 LNB	WM	10	13	12	11	11	13	26	12	12	12	13	13	13	18	30	11	9	18	25		12	15	19	16							
14016	B	2	0.24	430 Ti	WM	10	10	10	9	9	10	11	10	11	10	14	15	11	16	12	10	10	10	10	10	10	10	12	14	12						
14016	B	2	0.25	PWHT 430Ti	WM	39	11	12	8	9	48	9	37	15	19	58	11	51	91	71	96	95	98	16	26	40	90									
14016	B	2	0.23	Gleeble	HTHAZ																															
14016	B	2	0.23	Gleeble	HTHAZ																															
14016	C	3	-	-	Base	12	13	13	13	14	18	36	73	64	91	82	90	66	90	97	111	104	101	110	104	13	56	85	106							
14016	C	3	0.33	308 LSI	HTHAZ	13	11	16	15	12	11	15	16	13	17	15	14	11	14	13	15	19	15	19	19	13	14	13	17	12	13	18				
14016	C	3	0.35	308L	HTHAZ	9	10	10	10	11	11	13	9	13	11	12	13	15	13	14	24	22	13	19	17	10	12	13	19							
14016	C	3	0.33	308 LSI	WM																															
14509	C	2	-	-	Base	19	20	76	19	18	80	126	110	119	13	138	128	131	146	139	140	139	127	139	136	30	90	136	136							
14509	C	2	0.23	TIG	HTHAZ	13	13	11	11	14	15	15	12	12	12	90	72	126	96	124	100	103	113	12	94	111	15	39	98	114						
14509	C	2	0.22	308 LSI	HTHAZ	15	16	19	17	15	86	96	21	72	21	105	102	100	109	80	108	124	121	116	16	59	99	117								
14509	C	2	0.23	TIG	WM	48	48	17	11	21	61	80	15	78	13	114	64	102	69	102	90	147	108	77	66	106	32	69	83							
14509	C	2	0.22	308 LSI	WM	160	27	86	115	156	105	24	134	18	186							110	66	102	83	84	15	16	41	89						
14509	C	2	0.1	Gleeble	HTHAZ																															
14509	C	2	0.23	Gleeble	HTHAZ																															
14509	C	2	0.4	Gleeble	HTHAZ																															
14509	B	2	-	-	Base	16	20	12	15	13	103	97	112	92	100	119	126	113	111	125	112	120	124	130	15	101	114	122								
14509	B	2	-	PWHT	Base	10	40	9	10	25	46	34	40	40	49	34	16	48	48	68	61	60	57	56	19	35	39	61								

#### Appendix 5. Impact toughness tests at temperatures -40 ... +20 °C

2(2)