Stainless Steel in Fire

(RFCS, Contract Nr RFS-CR-04048)

WP 5: Bolts and welds at elevated temperatures

Task 5.3 Isothermal (steady-state) tests on butt-welded joints

DRAFT Final report

1. Executive Summary

Stainless steel welding is a complex mixture of metallurgy, chemistry, geometry and aesthetics. Austenitic stainless steels are generally easy to weld and a lot of information is available on connections between stainless steel members by welding. However, there are limited test data available on the behaviour of stainless steel welded connections in fire.

This report describes the testing program and results for materials properties of butt-welded joints at elevated temperatures. The main objective of the tests is to provide data for fire design guidance of welded joints.

Stress-strain relationships of butt-welded joints at elevated temperatures were determined with isothermal (steady-state) tensile tests for two austenitic stainless steel grades 1.4318 (Polarit 711) and 1.4571 (Polarit 761) produced in the annealed condition. The tests were performed by Outokumpu Stainless Oy at Tornio Research Centre.

The stress-strain relations of butt-welded joints for the both annealed stainless steel grades and their respective mechanical properties (strengths corresponding to proof strains of 0,2%, 1,0%) were compared with values of the same grades studied in the ECSC funded projects, *Development of the use of stainless steel in construction* (contract 7210-SA/842) and *Structural design of cold worked austenitic stainless steel* (contract 7210-PR-318). Following conclusions can be drawn on these comparisons:

- Strengths of butt-welded joints at elevated temperatures in both grades were at the same level as base material studied in the earlier ECSC funded projects.

- The results show that the design strength of a full penetration butt weld, for temperatures up to 1000 °C, should be taken as equal to the strength of the base material as verified in this study for the grades 1.4318 and 1.4571 in the annealed condition.

2. Contents

3. Introduction

The austenitic stainless steels have nominal 0,2% proof strengths of 230 ...350 N/mm^2 and tensile strengths of 550 ..850 N/mm^2 in the annealed condition. Table 3.5 of the Third Edition of the *Design Manual for Structural Stainless Steel* [5] gives the cold worked strength levels specified in EN 1993-1-4 [6] which are taken from the European material standard for stainless steel, EN 10088.

In Section 9 of EN 1993-1-4 are given: *For structural fire design, material properties at elevated temperatures in Annex C of EN 1993-1-2 should be used.* In Annex B.2 of EN 1993-1-4 (Stainless steel in the work hardened condition) are given: *The design rules given in this Part 1-4 are applicable for material up to grade C700 and CP350.*

For butt-welded connections of stainless steel the standard EN 1993-1-2, Annex D states: *The design strength of a full penetration butt weld, for temperature up to 700 °C, should be taken as egual to the strength of weaker part joined using appropriate reduction factors for structural steel. For temperatures >700 °C the reduction factors given for fillet welds can also be applied to butt welds.*

Austenitic stainless steels are generally easy to weld and a lot of information is available on connections between stainless steel members by welding. However, there are no test data available on the behaviour stainless steel welded connections in fire.

This report describes the testing program and results for materials properties of butt-welded joints at elevated temperatures. The main objective of the tests is to provide data for fire design guidance of welded joints. Stress-strain relationships of butt-welded joints at elevated temperatures were determined with isothermal (steady-state) tensile tests for two austenitic stainless steel grades 1.4318 (Polarit 711) and 1.4571 (Polarit 761) produced in the annealed condition. The tests were performed by Outokumpu Stainless Oy.

The stress-strain relations of butt-welded joints for the both annealed stainless steel grades and their respective mechanical properties (strengths corresponding to proof strains of 0,2%, 1,0%) were determined. These values were compared with values of the same grades presented in the ECSC funded projects, *Development of the use of stainless steel in construction* (contract 7210-SA/842) and *Structural design of cold worked austenitic stainless steel* (contract 7210-PR-318).

4. Objectives

The objective of this task was to find out the material properties of butt-welded joints at elevated temperatures for two austenitic stainless steel grades 1.4318 (Polarit 711) and 1.4571 (Polarit 761) produced in the annealed condition according to the standard EN 10088-2: 2005 [1].

The main objective of the tests is to provide data for fire design guidance of welded joints.

5. Experimental Work

5.1 Material

The main alloying elements of the grades 1.4318 and 1.4571 according to the standard EN 10088-2:2005 are given in Table 1.

Table 1: Chemical compositions in wt-% (EN 10088-2:2005).

Steel	**C (max.)**	**Si (max.)**	**Mn**	**Cr**	**Ni**	**N**	**Mo**	**Cu**
1.4318	<0,03	<1,00	<2,00	16,5 – 18,5	6,0 – 8,0	0,10 - 0,20	-	-
1.4571	<0,08	<1,00	<2,00	16,5 – 18,5	10,5 – 13,5	-	2,00 – 2,50	-

Requirements for mechanical properties of the grades 1.4318 and 1.4571 at room temperature in the solution annealed condition according to the EN 10088-2: 2005 are given in Table 2.

Table 2: Requirements for mechanical properties of the grades 1.4318 and 1.4571 at room temperature.

Steel grade	**$R_{p0,2}$ N/mm^2 (min.) *)**	**R_m N/mm^2**	**A5 %**	**Hardness HB (max.)**
1.4318	350	650 - 850	40	-
1.4571	240	540 - 690	40	-

*) for thickness < 8 mm.

5.2 Experimental

Stress-strain relationships at elevated temperatures were determined with steady-state tensile tests by Outokumpu at Tornio Research Centre. The tensile tests were carried out by means of ZWICK Z250/SW5A material testing machine at the crosshead speed according to the standard SFS-EN 10 002-5.

The metal active gas welding (MAG) technique was used so that the wire electrode AVESTA 308L/MVR (G 19 9 L, X2CrNiN18-7) for the grade 1.4318 and AVESTA 318/8kNb (G 19 12 3 Nb, X6CrNiMoTi17-12-2) for the grade 1.4571 was used.

The wire electrode AVESTA 308L/MVR is designed for welding austenitic stainless steel type 19 Cr 10 Ni or similar and a typical chemical composition of the 308L/MVR welding fire is 0,2C, 0,40Si, 20,0Cr, 10,0Ni and 1,7Mn. The wire electrode AVESTA 318/8kNb is used for welding titanium and niobium stabilized stainless steel of type 17 Cr 11 Ni 2.5 Ti and a typical chemical composition of this welding fire is 0,04C, 0,85Si, 19,0Cr, 12,0Ni, 1,3Mn, 2,6Mo and Nb > 12xC.

Figure 1 shows schematic representation of the basics of MAG welding.

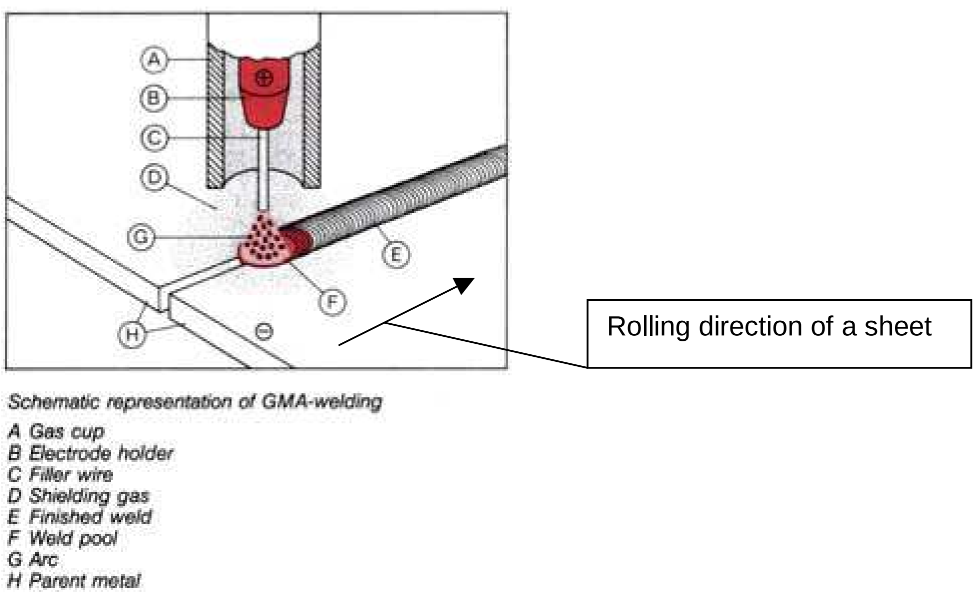


Figure1: Basics of MAG welding [8].

After welding (parallel to the rolling direction) test coupons were cut from a stainless steel sheet of nominal thickness 6 mm transversely to the rolling direction. All welded seams were grinded to the level of the surface of the base material.

Steady-state tests were carried out at temperature intervals of 100 ºC up to a temperature of 600 ºC and beyond which the interval was 50 ºC up to a maximum temperature 1100 ºC. Each test was duplicated and, in the event of a significant difference between results, a third test was performed. Tensile tests at room temperature were also carried out to determine the mechanical properties at room temperature.

5.3 Results

The test results for the mechanical properties of welded joints for weld material of the grades 1.4318 and 1.4571 at elevated temperatures are shown in Figures 2 and 3.

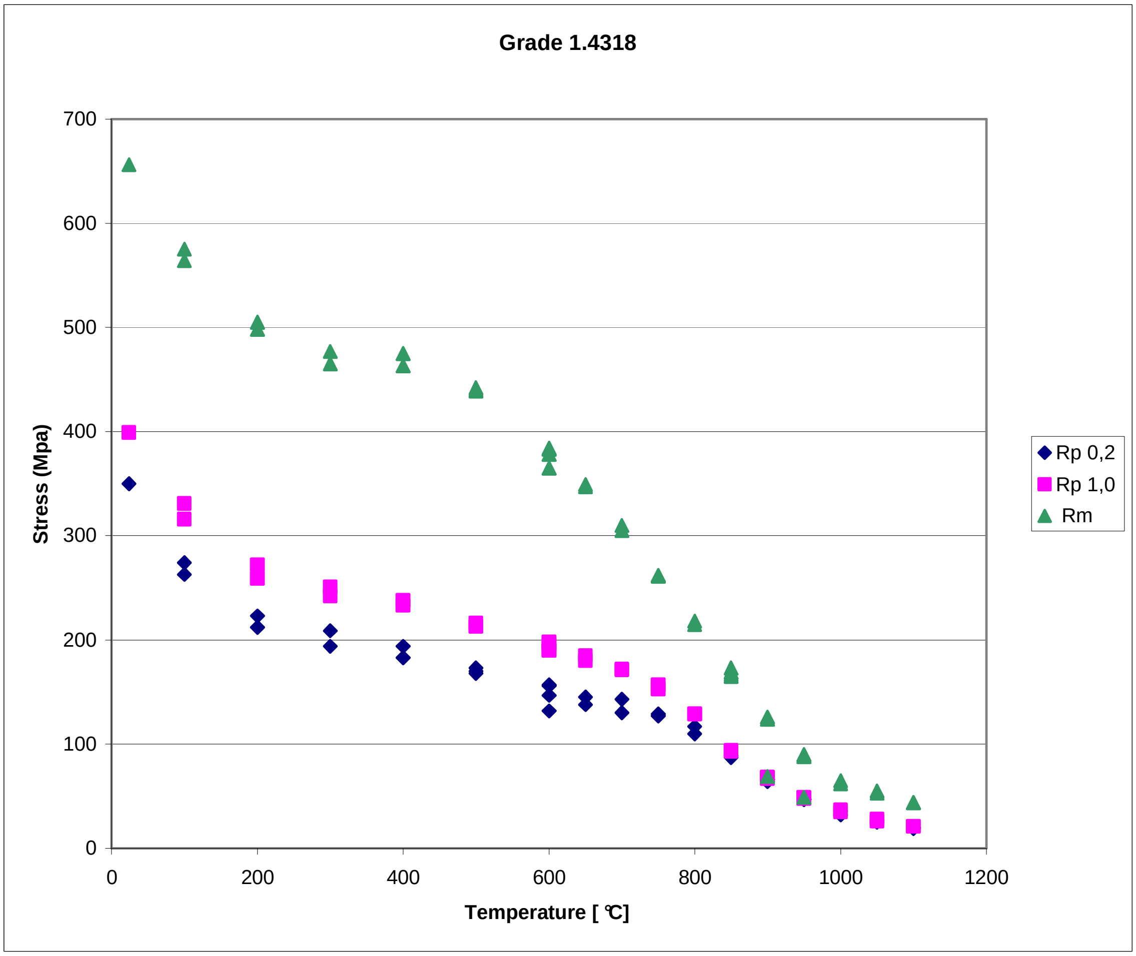


Figure 2: Tensile test results of butt welded joints for the grade 1.4318.

Data of the stress-strain values (strengths corresponding to proof strains of 0,2 %, 1,0 % and to the tensile strength) are given in Appendix 1.

Fracture points for the butt-welded joints of the grade 1.4318 are shown in Appendix 2.

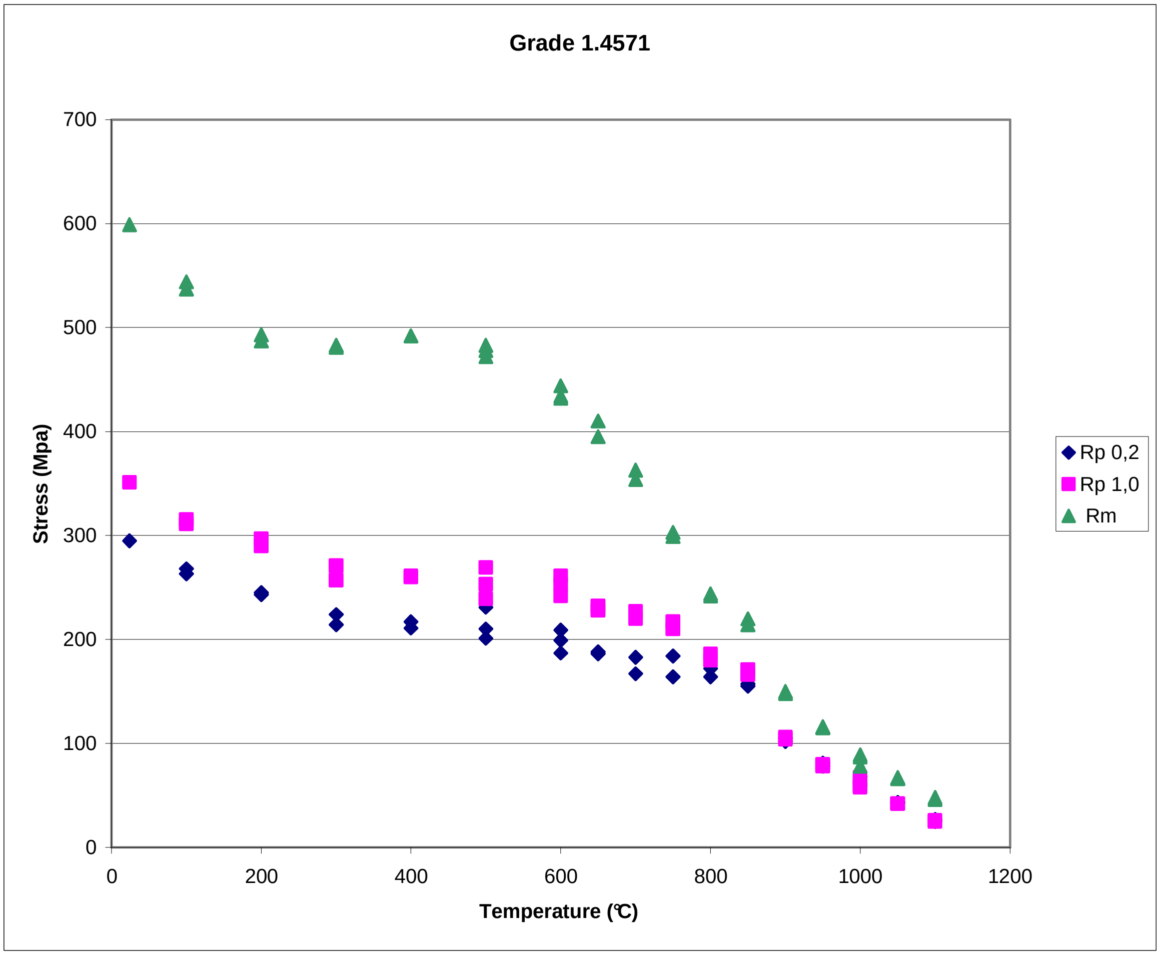


Figure 3: Tensile test results of butt-welded joints for the grade 1.4571

Data of the stress-strain values (strengths corresponding to proof strains of 0,2 %, 1,0 % and to the tensile strength) are given in Appendix 3.

Fracture points for the butt-welded joints of the grade 1.4571 are shown in Appendix 4.

The stress-strain relations of butt-welded joints for the both annealed stainless steel grades and their respective mechanical properties (strengths corresponding to proof strains of 0,2%, 1,0%) were compared to values of the same grades given in the ECSC funded projects, *Development of the use of stainless steel in construction* (contract 7210-SA/842) and *Structural design of cold worked austenitic stainless steel* (contract 7210-PR-318). The results are shown in Figures 4 and 5.

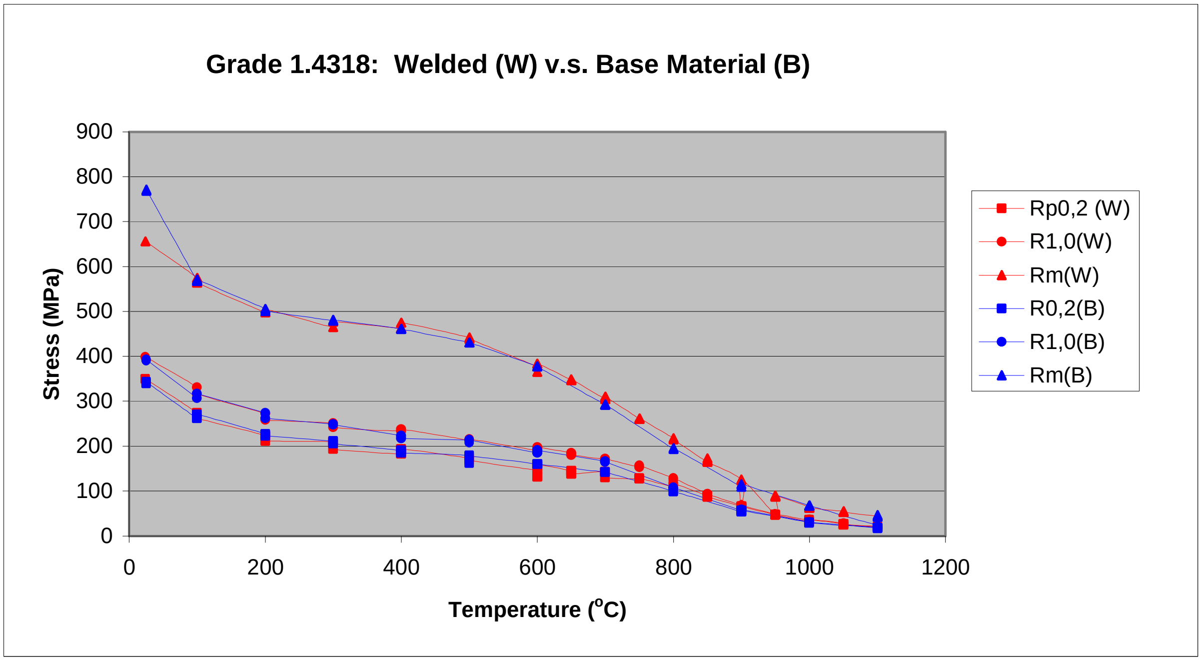


Figure 4: Tensile test results on weld materials for the grade 1.4318

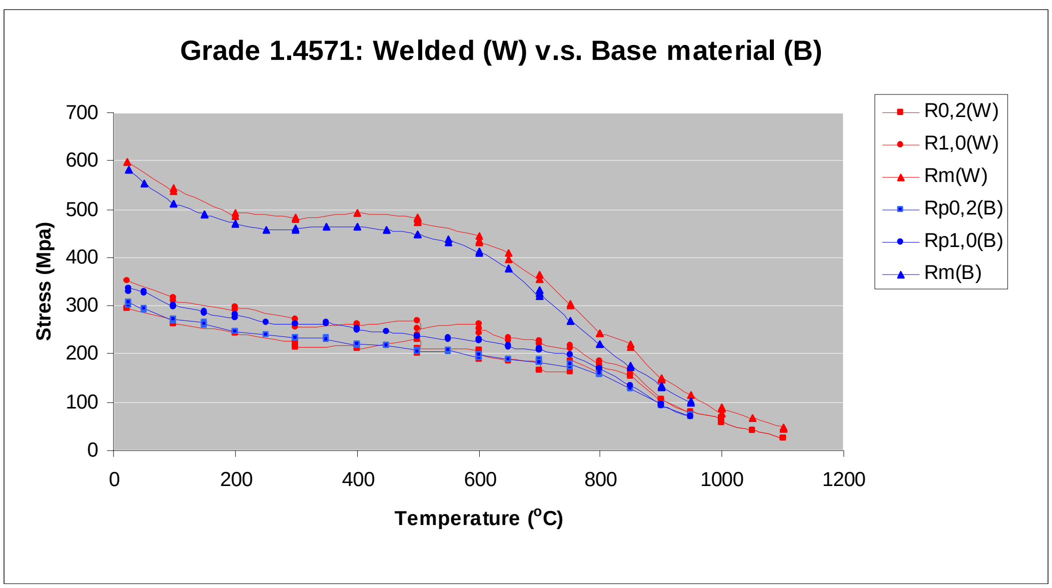


Figure 5: Tension test results on weld materials for the grade 1.4571

5.4 Discussion

Welding causes a heating and cooling cycle in the area surrounding the welded joint. Critical areas in the welded connection are HAZ and weld metal. At normal temperature the joint area is supposed to be most critical for failure, but at elevated temperature the joint behaviour might be different because the material is heat-treated all over [3]. In this study the fractures were mostly locating in the weld due to reason that the welds were ground to the level of the surface of the base material. Nevertheless, typically in case of the unground welds a fracture of the joint is located in the HAZ or in the base material.

According to the steady-state tensile tests performed in this study, the strength of butt-welded joints at elevated temperatures is not a restrictive detail. The same conclusion was drawn in the study of Ala-Outinen T. el al [3].

6. Development of design guidance

The stress-strain relations of welded joints for the both annealed stainless steel grades and their respective mechanical properties (strengths corresponding to proof strains of 0,2%, 1,0%) were compared with values of the same grades presented in the ECSC funded projects,

The results show that the design strength of a full penetration butt weld, for temperatures up to 1000 °C, should be taken as equal to the strength of the base material as verified in this study for the grades 1.4318 and 1.4571 in the annealed condition.

7. Conclusions

This report describes the testing program and results for materials properties of butt-welded joints at elevated temperatures. The main objective of the tests is to provide data for fire design guidance of welded joints. Stress-strain relationships of welded joints at elevated temperatures were determined with isothermal (steady-state) tensile tests for two austenitic stainless steel grades 1.4318 (Polarit 711) and 1.4571 (Polarit 761) produced in the annealed condition. The tests were performed by Outokumpu Stainless Oy at Tornio Research Centre.

The stress-strain relations of welded joints for the both annealed stainless steel grades and their respective mechanical properties (strengths corresponding to proof strains of 0,2%, 1,0%) were compared with values of the same grades presented in the ECSC funded projects, *Development of the use of stainless steel in construction* (contract 7210-SA/842) and *Structural design of cold worked austenitic stainless steel* (contract 7210-PR-318). Following conclusions can be drawn on these comparisons:

- Strengths of butt welded joints at elevated temperatures in both grades were at the same level or even better as base material studied earlier projects.

- The results show that the design strength of a full penetration butt weld, for temperatures up to 1000 °C, should be taken as equal to the strength of the base material as verified in this study for the grades 1.4318 and 1.4571 in the annealed condition.

8. Recommendations for further work

The test results of this study are based on the limited amount of steel grades. Additional tests are needed in order to verify mechanical properties of butt-welded joints for all grades given in the Annex C of EN 1993-1-2 and in Table 7.1 of the Third Edition of the *Design Manual for Structural Stainless Steel* .

Besides, further studies are required in order to verify the test results for cold worked grade CP 350 and C700 and higher strength levels given in EN 1993-1-4 and in the Third Edition of the *Design Manual for Structural Stainless Steel.*

9. References

[1] EN 10088-2, Stainless steel - part 2: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes, CEN 2005

[2] Ala-Outinen, T
Fire resistance of austenitic stainless steels Polarit 725 (EN 1.4301) and Polarit 761 (EN 1.4571), VTT Research Notes 1760, Espoo, Finland, 1996

[3] Ala-Outinen, T and Oksanen, T
Stainless steel compression members exposed to fire, VTT Research Notes 1864, Espoo, Finland, 1997

[4] Baddoo, N et al.
Structural design of cold worked austenitic stainless steel, Final report, RFCS Project, Contract No 7210-PR/318, Report EU 21975 EN, 2006

[5] Design Manual for Structural Stainless Steel, Building series, 3rd edition, Euro Inox and the Steel Construction Institute, 2006

[6] SFS-EN 1993-1-4, Eurocode 3: Design of steel structures. Part 1.4: General rules. Supplementary rules for stainless steels structural fire design, CEN 2006

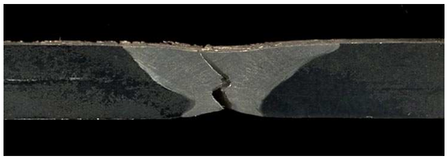
[7] EN 1993-1-2, Eurocode 3: Design of steel structures - Part 1.2: General rules - Structural fire design, CEN 2005

[8] Avesta Welding Manual, Practice and products for stainless steel welding, ISBN 91-631-5713-6, Avesta Welding AB, Avesta , Sweden, 2004

Appendix 1: Tensile test results of butt welds for the grade 1.4318

Tempera-Ture °C	Thickness [mm]	Width [mm]	0,2-proof stress [N/mm^2]	1,0%-proof stress [N/mm^2]	Tensile strength [N/mm^2]	Elongation after fracture A_5	Point of Fracture
24	5,69	9,94	350	399	656	27	Weld
100	5,59	9,74	274	331	575	32	Weld
100	5,67	9,64	263	316	564	34	Weld
200	5,63	9,66	223	272	498	30	Weld
200	5,72	9,66	212	259	505	34	Weld
300	5,54	9,62	209	251	465	27	Weld
300	5,69	9,78	194	242	477	33	Weld
400	5,76	9,83	183	233	463	31	Weld
400	5,74	9,7	194	238	475	35	Weld
500	5,74	9,63	173	213	442	35	Weld
500	5,75	9,68	170	213	440	32	Weld
500	5,56	9,87	168	216	439	31	Weld
600	5,71	9,87	147	190	378	28	Weld
600	5,78	9,79	156	190	384	26	Weld
600	5,56	9,85	132	196	365	22	Weld
600	5,43	9,85	157	198	383	26	Weld
650	5,71	9,71	145	185	347	25	Weld
650	5,72	9,75	138	180	349	25	Weld
700	5,75	9,72	143	171	305	28	Weld
700	5,84	9,73	130	172	310	27	Weld
750	5,7	9,85	127	153	261	28	Weld
750	5,62	9,94	129	157	262	30	Weld
800	5,56	9,74	110	129	218	24	Weld
800	5,71	9,99	117	129	215	27	Weld
850	5,7	9,9	89	94	165	25	Weld
850	5,61	9,9			173	24	Weld
850	5,67	9,9			169	24	Weld
850	5,73	9,78			167	20	Weld
850	5,58	9,89			169	18	Weld
850	5,77	9,94	87	93	165	21	Weld
900	5,72	9,78	66	68	124	14	Weld
900	5,71	9,87	64	67	69	8	Weld
900	5,5	9,94	66	68	126	14	Weld
950	5,69	9,79	47	48	49	6	Weld
950	5,79	9,87	47	48	88	11	Weld
950	5,75	9,85	47	49	90	12	Weld
1000	5,72	9,97	32	35	65	11	Weld
1000	5,65	9,81	36	37	62	8	Weld
1050	5,56	9,83	27	28	55	15	Weld
1050	5,73	9,8	25	26	53	16	Weld
1100	5,63	9,88	20	21	44	0	Weld
1100	5,64	9,78	19	21	44	13	Weld

Appendix 2: Fracture points of test samples in different temperatures for butt wels of the grade 1.4318.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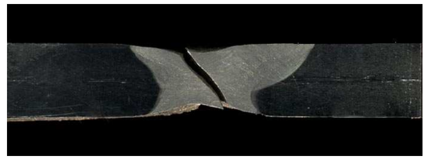
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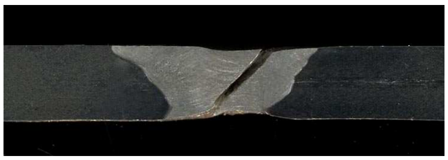
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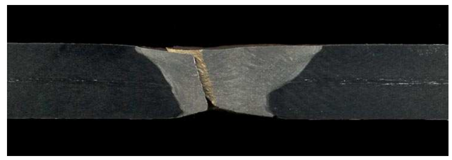
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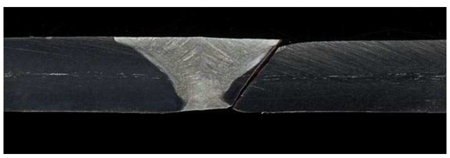
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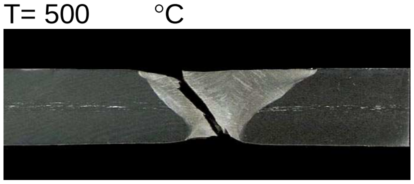
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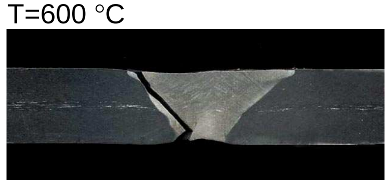
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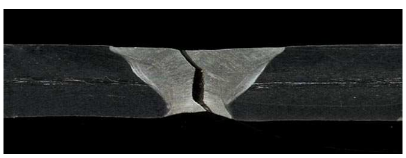
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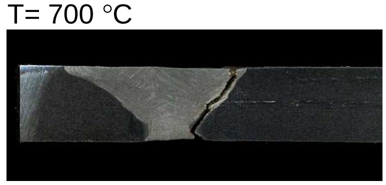
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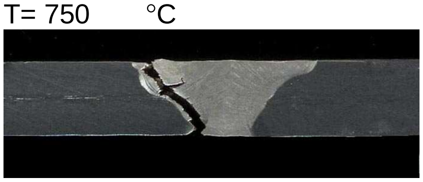
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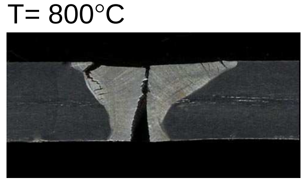
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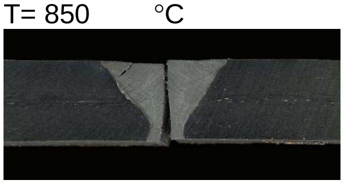
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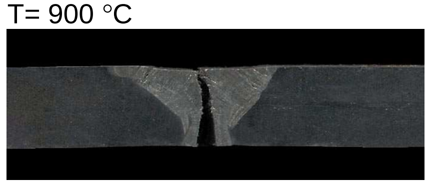
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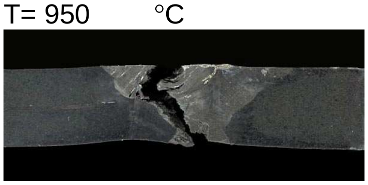
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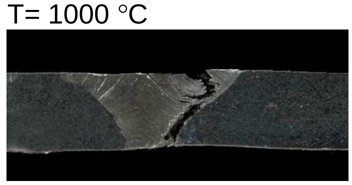
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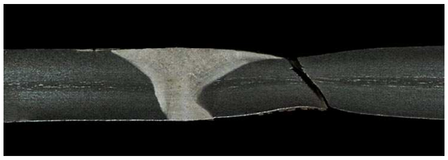
Appendix 3: Tensile test results of butt welds for the grade 1.4571

Temperature °C	Thickness [mm]	Width [mm]	0,2-proof stress [N/mm²]	1,0%-proof stress [N/mm²]	Tensile strength [N/mm²]	Elongation after fracture A_5	Point of fracture
24	5,55	9,85	295	351	599	41	Weld
100	5,65	9,72	268	315	537	46	Base
100	5,67	9,62	263	311	544	41	Base
200	5,47	9,71	245	290	487	33	HAZ
200	5,71	9,78	243	297	493	33	HAZ
300	5,83	9,76	224	271	483	32	Base
300	5,8	9,64	214	257	481	36	Base
400	5,69	9,83	217	261	492	35	Base
400	5,71	9,67	211	260	492	34	Base
500	5,42	9,88	231	269	483	28	Weld
500	5,75	9,74	201	239	478	31	Base/HAZ
500	5,47	9,8	210	253	472	28	Weld
600	5,6	9,79	209	261	444	30	Weld
600	5,52	9,78	187	242	434	26	Weld
600	5,4	9,81	199	253	432	24	Weld
650	5,7	9,91	186	228	410	27	Weld
650	5,53	9,75	188	232	395	21	Weld
700	5,59	9,79	183	227	354	20	Weld
700	5,67	9,8	167	220	363	25	Weld
750	5,74	9,76	164	210	299	32	Weld
750	5,65	9,82	184	217	303	31	Weld
800	5,65	9,7	164	180	242	35	Weld
800	5,67	9,76	172	186	244	36	Weld
850	5,38	9,74	157	171	220	23	Weld
850	5,4	9,81	155	166	214	26	Weld
900	5,94	9,75	102	104	148	76	Base
900	5,9	9,86	105	106	150	69	Base
950	5,97	9,73	78	78	115	71	Base
950	5,92	9,83	81	80	116	78	Base
1000	5,42	9,83	68	67	78	45	Weld
1000	5,98	9,8	61	60	89	71	Base
1000	5,95	9,85	59	58	87	69	Base
1050	5,94	9,74	43	42	67	75	Base
1050	5,94	9,79	43	42	66	83	Base
1100	5,92	9,78	27	26	48	75	Base
1100	5,91	9,85	25	25	46	115	Base

Appendix 4: Fracture points of test samples in different temperatures for butt wels of the grade 1.4571.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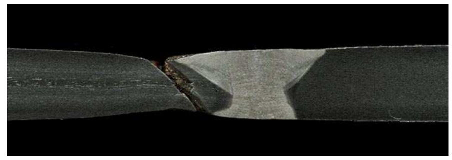
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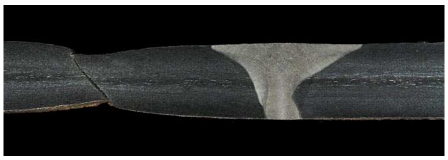
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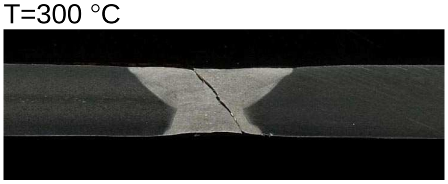
T=400 °C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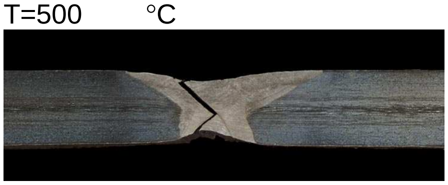
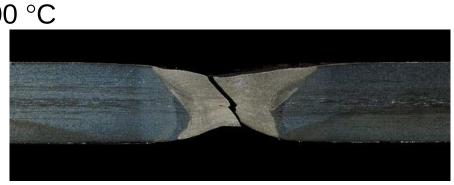
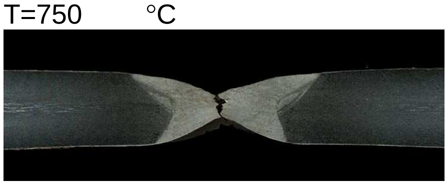
T=600 °C

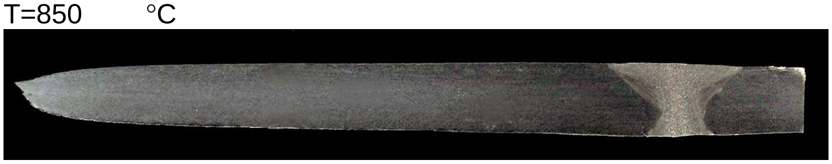

T=650 °C


T=700 °C


T=750 °C


T=800 °C


T=850 °C


T=900 °C


T=950 °C