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for Cogeneration of
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Test report with determination of creep weld coefficients

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An intermediate heat exchanger for future (Very) High Temperature Reactors was tested as part of the ARCHER EU Project, that ran over the period of 2011-2015. This document details the testing programme on laser weldments of thin sheets (~3mm) of the material Alloy 800H, which was conducted within the work package WP43 "Intermediate Heat Exchanger". The specified work by Alstom of creep and tensile testing of Alloy800H was to investigate the high temperature behaviour of the weldments and to measure any strength reduction factors that may occur due to the welding process. The ARCHER Project name of this deliverable, D43.55, is "Test report with determination of creep weld coefficients" [1].
The testing programmes at both MPA Stuttgart and Alstom include tensile tests at different strain rates and temperatures, and creep up to 850°C. Two batches of laser-welded material prepared by Alfa Laval were tested. The first batch had technical issues with the laser welding process and the integrity of the weld created, so a second batch of Alloy800H weldments was produced using modified (laser) welding parameters. This second batch was deemed by Alfa Laval to have been a successful welding process.
For the D43.55 deliverable Alstom has worked closely with MPA Stuttgart, not least in gaining the parent material results of thin-section Alloy800H to compare with weldment results in order to obtain weld strength factors (WSF). Analysis of whether thin-section Alloy800H is weaker than non-thin section Alloy800H is a key requirement for the need within the ARCHER project. This analysis is based on the testing results from both D43.55 (Alstom's deliverable on weld coefficients) and D43.53 (MPA Stuttgart' deliverable on parent material tests). The weldment test matrix has progressed well, though some weldment and parent metal creep tests are still underway - largely because the material is stronger than expected. Loss of tensile strength (UTS

Approval

Date	By
16/02/2015	Derek BUCKTHORPE
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The weldment test matrix has progressed well, though some weldment and parent metal creep tests are still underway - largely because the material is stronger than expected. Loss of tensile strength (UTS) of the weldment is noted at 750°C and 850°C compared to various published property data on parent metal (though this is possibly due to different strain rates). Creep weld strength factors have been estimated, taking into account the longer than expected lifetimes. Some higher applied stress weldment creep tests failed below the benchmark lifetimes of non-thin section Alloy 800H data. However, weldment creep tests at lower stresses failed with lifetimes close to, or - where presently still running – have lifetimes approaching the durations in published property data such as the ECCC datasheet on non thin-section Alloy800H data.

<u>Revision History</u>
April 2014 Initial – Preliminary D43.55 deliverable
January 2015 Revision A – Final D43.55 deliverable with updated results and strength reduction factors.

Project Information

The work has been performed as part of the ARCHER EU FP7 Project, according to the requirements of ARCHER EU Programme: 269892 Description of Work 6th Submission [2]. The mechanical testing was undertaken by Alstom at its Rugby facility under internal Programme References: CPM00236-T04 and ET0-006022. Background information on the ARCHER EU project can be found at the ARCHER website www.archer-project.eu.

Materials

Alloy800H material was obtained by Alfa Laval, who are members of the ARCHER program, from the original producers Thyssen-Krupp in the form of 4mm thick hot-rolled sheet. To produce the compact cross-flow heat exchanger, each sheet is machined to shape and reduced to about 3mm thickness. A central portion is then machined from one side to about 1.6mm thickness, leaving a thin rim of 3mm material around the perimeter, The plates are stacked and clamped, the rims are laser welded together from the outside. After welding, the weldments are not able to be trimmed of “flash” or skimmed to remove sharp contours, they cannot be post weld heat treated, and it is difficult to inspect them from the outside and impossible to inspect from the inside. Similarly, a repair weld cannot be effected. Therefore, the development of the laser welding parameters to produce a high quality weld is a crucial.

For the purposes of testing the laser welded material, Alstom and Alfa Laval, developed test specimens that are representative of the weldments in the compact cross-flow intermediate heat exchanger, Fig. 1a (N.B. single holes rather than double holes were used. The objective was to test as much weldment material within a single sample as possible, whilst retaining similar conditions to that in manufacture of the heat exchanger. A stack of six plates, each with a central machined region and a 3 mm thick rim, together with end-plates located against the rims and perpendicular to the plane of the stack (to later form the “head” and “shoulders” of the test piece) was then laser welded using the developed laser welding parameters.

- The test specimens were then machined similar to the outlines shown in Fig. 1a.
- The end plates (left at 4mm thickness further away from the weldment) were used to prepare the shoulders and grips and are shown in Fig. 1b.
- The central “sandwich” of ~3mm laser welded regions in the middle of the gauge length of the test specimen, and ~1.6mm thick sheet similar to the heat exchange surfaces are shown in Fig. 1c.

No test certification, composition data was delivered with plate section of Alloy 800H. N.B. Alloy 800H material has ~33% Ni, ~21% Cr, ~0.07%C Fe-balance composition.

General assembly of delivered plates with laser welded sandwich. Outlines of testpieces are indicative only.

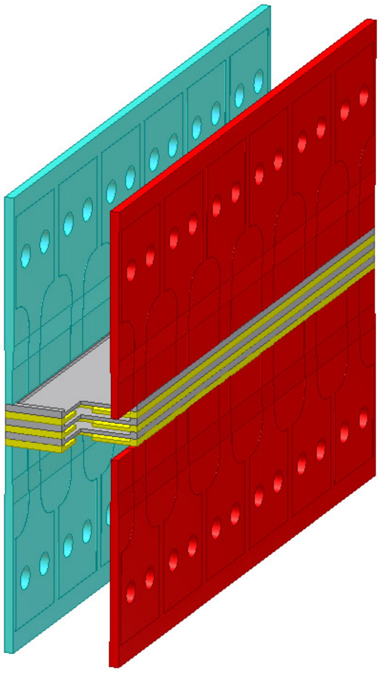
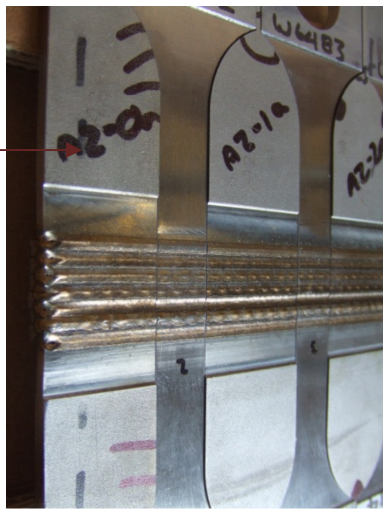


Fig. 1a Details of the welding trials / specimen manufacture (Source: Alfa Laval)

4mm end pieces welded onto the welded sandwich to make up the rest of the specimen area



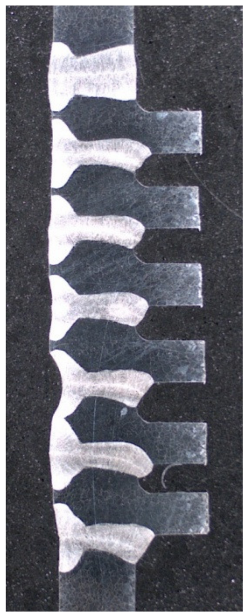


Fig. 1b Plates with gauge length smoothed for the specimens. The weld was kept unsmoothed for a few tensile tests.

Fig. 1c Laser weld regions between the plates: Mixed acid reagent etch.

Testing Programmes

Specimen Design

The weldment of Alloy 800H was produced by Alfa Laval with multiple ('bundle') welded plates to form the central area of the gauge length for specimens (Fig. 1). This represents the welding of the heat exchanger plates in the full size heat exchanger built in order for CAE to start the heat exchanger rig testing, which is a key part of the ARCHER program. The weldment area was smoothed flush for the creep tests to avoid any possible stress concentration effect. For the tensile testing, both smoothed flush and also weld left unsmoothed with fins from the plates left attached (see Fig. 2), were tested.

Creep and tensile test matrices were defined for testing [3], see section 4, at MPA Stuttgart and at Alstom (Rugby). Rugby carried out tensile and creep tests, using specimens from the weldment (see Fig. 1) Alloy 800H thin sheet.

A first set of specimens of "batch 1" welded material supplied were seen by Alfa Laval to contain many large cracks at the edge of the weld and into the Heat Affected Zone (HAZ). However, these large cracks were not observed during Alstom's own microstructural investigations of this material in the plates we received, although smaller cracks were present (mainly at the edge of the wedge or in the HAZ). Alfa Laval then made some changes to their welding procedure, and a second weldment was supplied (forming "batch 2"). The presence of small cracks is also the case in the second batch of Alloy 800H plates provided to both MPA Stuttgart and Alstom (mainly at the edge of the weld). Both batch 1 and 2 were used for creep tests. With some batch 1 tests already loaded (longer creep duration - 30k hrs) it was decided to keep these running; no adverse effects of weldment cracking during manufacture have been seen in the failed samples to date.

The weld in the gauge length is a cross-weld and is not longitudinal along the gauge length. The reason for the cross-weld was that it replicated the welded plate heat exchanger (rig) design. The Alstom drawing (see Appendix 1) differs in two main regards to the MPA Stuttgart creep drawing: 1/ the size of the end-hole and 2/ a ridge present where the gauge length smoothing starts. These differences should not affect the creep results but were noted as part of a cross-checking process.

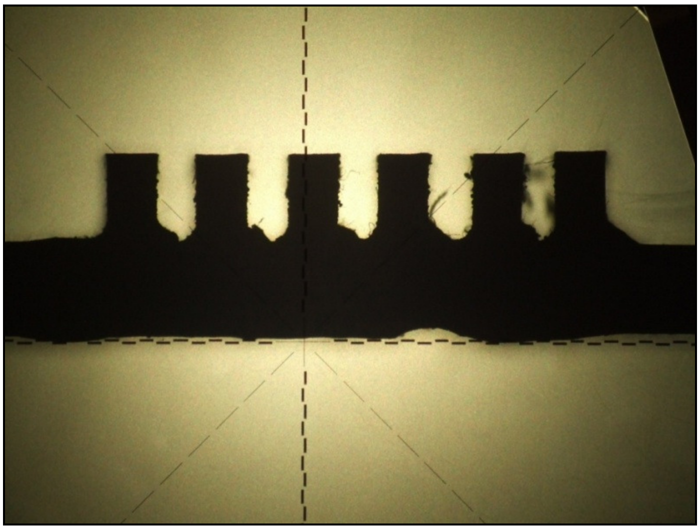


Fig. 2 Image of mid-section gauge length (unsmoothed) showing topography. Positioned on an x-y machine.

Test Matrices

Tensile Testing

An additional 2 tensile tests to those shown in Table 1 below were done at room temperature. The elevated temperature tests listed in the Table are in ℃, strain rates are min^{-1}.

Table 1. Tensile Testing Matrix – Alloy 800H Sheet Weldment – Cross Weld Samples (Where indicated, test conditions and particularly strain rate, conform to the full requirements of ISO 6892)

a) Tests on samples with weldment flash machined away:

Temperature	650	650	750	750	850	850
Strain rate	1.00E-04	1.00E-05	1.00E-04	1.00E-05	1.00E-04	1.00E-05
	"ISO 6892"		"ISO 6892"		"ISO 6892"	

b) Tests on samples with weldment flash left in place:

Temperature	650	650	750	750	850	850
Strain rate	1.00E-04	1.00E-05	1.00E-04	1.00E-05	1.00E-04	1.00E-05
	"ISO 6892"		"ISO 6892"		"ISO 6892"	

N.B. This original tensile matrix shown above comes from the ARCHER document [3]. The tensile testing has been completed.

Creep Testing

Temperature (℃)	650	650	750	750	750	850	850	850
Stress (MPa)	93	106	44	50	75	21	24	40
Expected Duration (h)	20,000	10,000	20,000	10,000	3,000	20,000	10,000	3,000
Test time (years)	2.3	1.1	2.3	1.1	0.3	2.3	1.1	0.3
Test status	in progress	in progress	in progress	in progress	completed	in progress	in progress	loaded March 2014

Alstom conducted the above test matrix on the cross-weld specimens of Alloy 800H. In parallel MPA Stuttgart is conducting the same test matrix on the parent material of Alloy 800H. Comparison on the results from the two test series (after completion) have enabled weld coefficients to be derived for the D43.55 deliverable. 850℃ 40MPa short term test (3000hrs failure due ~4.5 months) test was the final creep test in Alstom to be loaded.

Cross-check matrix of creep and stress relaxation testing

Extra cross checks (creep and additional short term creep tests) were done; also an additional stress relaxation test is underway on weldment material at MPA Stuttgart. The cross-checking tests were done in order to understand the primary creep behaviour difference between the parent material and the weldment in some of the tests (see Appendix 3). The differences in results especially the primary creep region are minimal but are maybe to do with testing parameters or dimensions of test pieces e.g. the minor differences in hole size in the endpieces of specimens etc. Stress relaxation tests on parent material sent from MPA Stuttgart was also done at Alstom as part of a cross-check to validate the strength drop results on the parent material by MPA Stuttgart (part of the D43.53 deliverable).

<u>MPA Stuttgart (2 spot check tests & an additional test proposed to be done)</u>

- Stress relaxation test at 750℃, a strain of 0.4% fixed, on welded material from Alfa Laval (supplied by Alstom) for 100 hrs. This particular test is not a cross-check but an additional test.
- Stress relaxation test at 850℃, a strain of 0.2% fixed, on welded material from Alfa Laval (supplied by Alstom) for 100 hrs.
- Creep test at 750℃, Stress of 48MPa applied for 150 hours only on welded material from Alfa Laval (supplied by Alstom).

<u>Rugby (3 spot check tests)</u>

- Stress relaxation test at 850℃, a strain of 0.2% fixed, on parent material specimen from Alfa Laval (supplied by Stuttgart) for 100 hrs, loaded March 2014.
- Creep test at 750℃, Stress 48MPa applied for 150 hours only, on parent material from Alfa Laval (supplied by Stuttgart).
- Repeat Creep test at 750℃, Stress 48MPa for 150 hours only, on welded material in order to check where elongation is occurring in the test sample.

Analysis of some of the spot checks are made in Appendix 2, e.g. elongation/strain% of the 150hrs creep tests.

Results

As-Received Metallographic Investigations

Areas of differing hardness (shown in blue in Fig. 3 and 4) discovered in the virgin Alloy 800H thin-section weldment material occur not just in the weld area. In fact the hardness changes inc. peaks can occur further away (see Fig. 3 purple lines) from the thin HAZ where the liquation lines were shown in metallography (see Fig. 7).

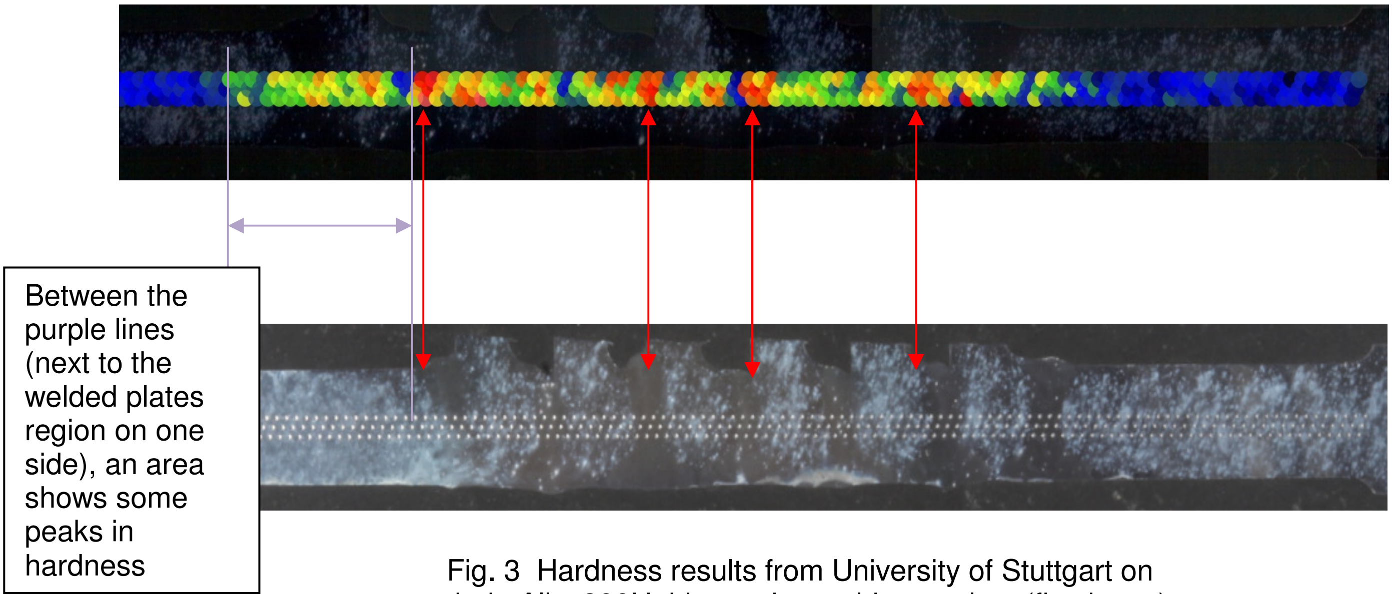


Fig. 3 Hardness results from University of Stuttgart on virgin Alloy800H thin-section weldment plate (fins intact)

Between the purple line, to the beginning of the weld, this area shows some hardness peaks. This correlates with the results from the hardness results from the University of Stuttgart.

This area could be accounted for by the local strain effect post-the last weld to be made.

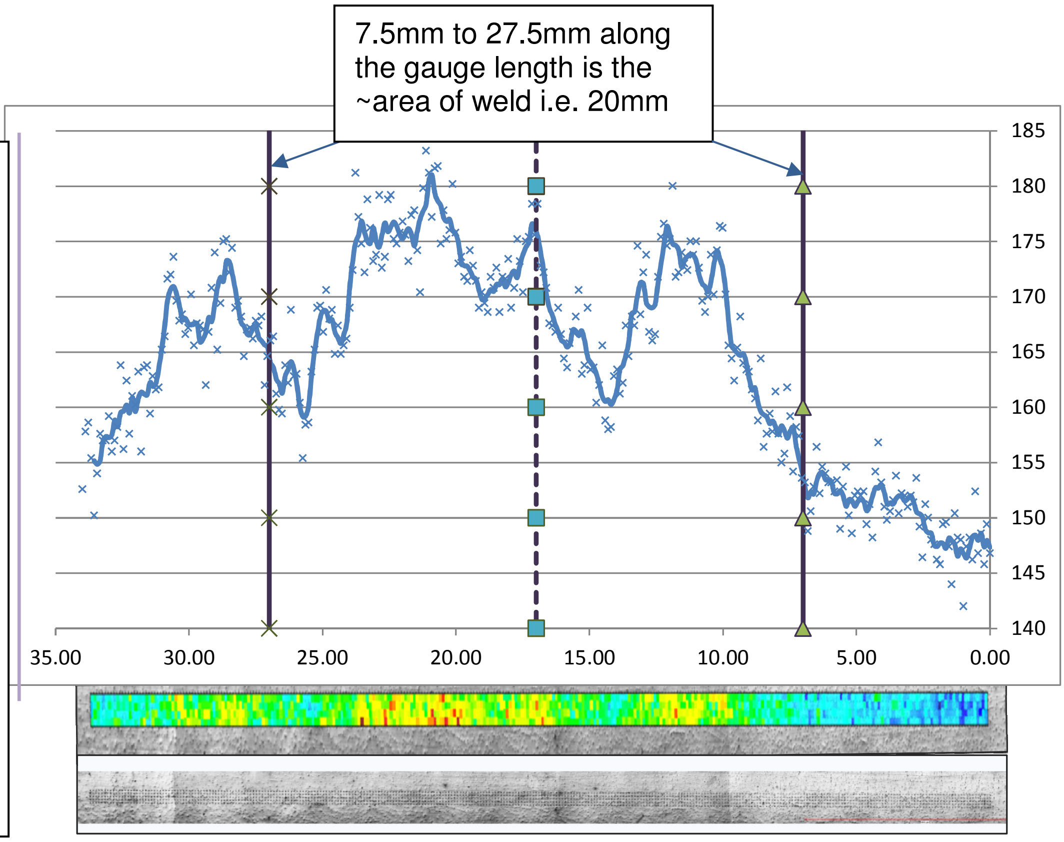


Fig. 4 Hardness results from Alstom, Rugby on virgin material Alloy800H thin-section weldment plate (fins machined off - smoothed).
[N.B. Variability in $Hv_{0.1}$ hardness result is usual as inclusions etc can cause scatter in values.]

Tensile Testing

TESTPIECE DETAILS					TEST DATA										
TEST i.d.	SPECIMEN TYPE (or Drg No.)	STRAIN RATE (pre-yield) % / min	CROSSHEAD SPEED (post-yield) mm / min	TEST TEMP. (t) °C	YOUNG'S MODULUS E @ ROOM TEMP. GPa	YOUNG'S MODULUS E @ TEST TEMP. GPa	0.1% PROOF STRESS ($Rp_{0.1}$) MPa	0.2% PROOF STRESS ($Rp_{0.2}$) MPa	0.5% PROOF STRESS ($Rp_{0.5}$) MPa	UTS (Rm) MPa	ELONG'N (A) %	R.o.A. (Z) %	FRACTURE SITE	M/C No.	DATE TESTED
W6486	weld ground flush	0.60	0.474	24	192.4	185.5	247.3	**265.4**	288.8	**502.0**	25.1	22	In the weld	1	27-Apr-12 Fri
W6482	weld with fins	0.60	0.474	24	225.2	181.5	250.5	**265.2**	288.6	**542.0**	33.0	50	In the parent metal	1	17-Apr-12 Tue
W6487	weld ground flush	0.60	0.474	650	189.7	108.1	151.4	**161.8**	171.6	**368.0**	22.6	21	In the weld	1	08-May-12 Tue
W6483	weld with fins	0.60	0.474	650	223.2	151.2	143.0	**154.2**	192.0	**396.0**	26.8	26	In the weld	1	03-May-12 Thu
W6525	weld with fins	0.06	0.474	650	203.4	161.5	156.4	**170.1**	192.9	**370.0**	recheck	44	In the parent metal	1	04-Jul-12 Wed
W6529	weld ground flush	0.06	0.474	650	187.5	125.2	146.2	**161.6**	182.2	**326.0**	12.2	17	In the weld	1	09-Jul-12 Mon
W6484	weld with fins	0.60	0.474	750	204.4	137.3	168.6	**182.1**	204.5	**226.0**	34.1	61	In the parent metal	1	09-May-12 Wed
W6526	weld with fins	0.06	0.474	750	219.1	165.3	157.9	**170.4**	182.5	**189.0**	26.0	56	In the parent metal	1	05-Jul-12 Thu
W6530	weld ground flush	0.06	0.474	750	148.9	110.5	155.9	**162.9**	165.4	**167.0**	26.7	53	In the parent metal	1	10-Jul-12 Tue
W6532	weld ground flush	0.60	0.474	750	232.0	120.0	162.5	**175.6**	193.1	**212.0**	13.3	29	In the weld	1	12-Jul-12 Thu
W6485	weld with fins	0.60	0.474	850	194.6	121.5	127.6	**131.6**	135.3	**138.0**	45.0	66	In the parent metal	1	10-May-12 Thu
W6527	weld with fins	0.06	0.474	850	141.8	86.7	107.4	**108.0**	106.4	**110.0**	29.1	55	In the parent metal	1	06-Jul-12 Fri
W6531	weld ground flush	0.06	0.474	850	195.4	125.9	99.0	**101.6**	102.7	**105.0**	27.9	56	In the parent metal	1	11-Jul-12 Wed
W6533	weld ground flush	0.60	0.474	850	229.5	145.0	N/A	**N/A**	N/A	**N/A**	N/A	N/A	N/A	1	16-Jul-12 Mon
W6533a	weld ground flush	0.60	0.474	850	229.5	133.7	131.6	**134.4**	136.2	**138.0**	40.5	65	In the parent metal	1	16-Jul-12 Mon

Table 3. Tensile tests results of weldment Alloy800H.

A data collation from Oak Ridge laboratory [4] and a large collation of Alloy 800H data from KTA, The Nuclear Safety Standards Commission (Kerntechnischer Ausschuss - KTA) who produced design data points (mean and min) as a datasheet / standard [5] are shown in the plots (Figure 4 and 5). As shown in Table 3 there is lower elongation occurring when the break occurs in the weld, this is not unexpected as necking less likely in the weld due to the high strength sandwich laser weld of the 6 plates. The weldment tensile (Ultimate tensile strength) results compare closely with the ASME and the KTA UTS data when failure occurs in the welded plate area. There is a drop in the UTS at 750 and 850°C (see Fig. 6) when the break occurs away from the weld and the HAZ area, compared to the KTA data. Alstom's test results from the thin-section weldment specimens show a lower spread of UTS data at both 650°C and 750°C than the Oak Ridge non-thin section UTS results, though this is likely due to different strain rates involved with Oak Ridge tests compared to ARCHER tests. Weld with fins and weld without fins data in Table 3 show similar 0.2% proof stess at each temperature i.e. no notch effect of the unsmoothed (with fins) specimens causing lower proof stress results (Stress at 0.2% strain). There may be slight difference in UTS at room temperature between specimens with fins (notched) and smooth specimens, though further tests would be needed to show that this is the case, for it could be just (5-10%) which is normative.

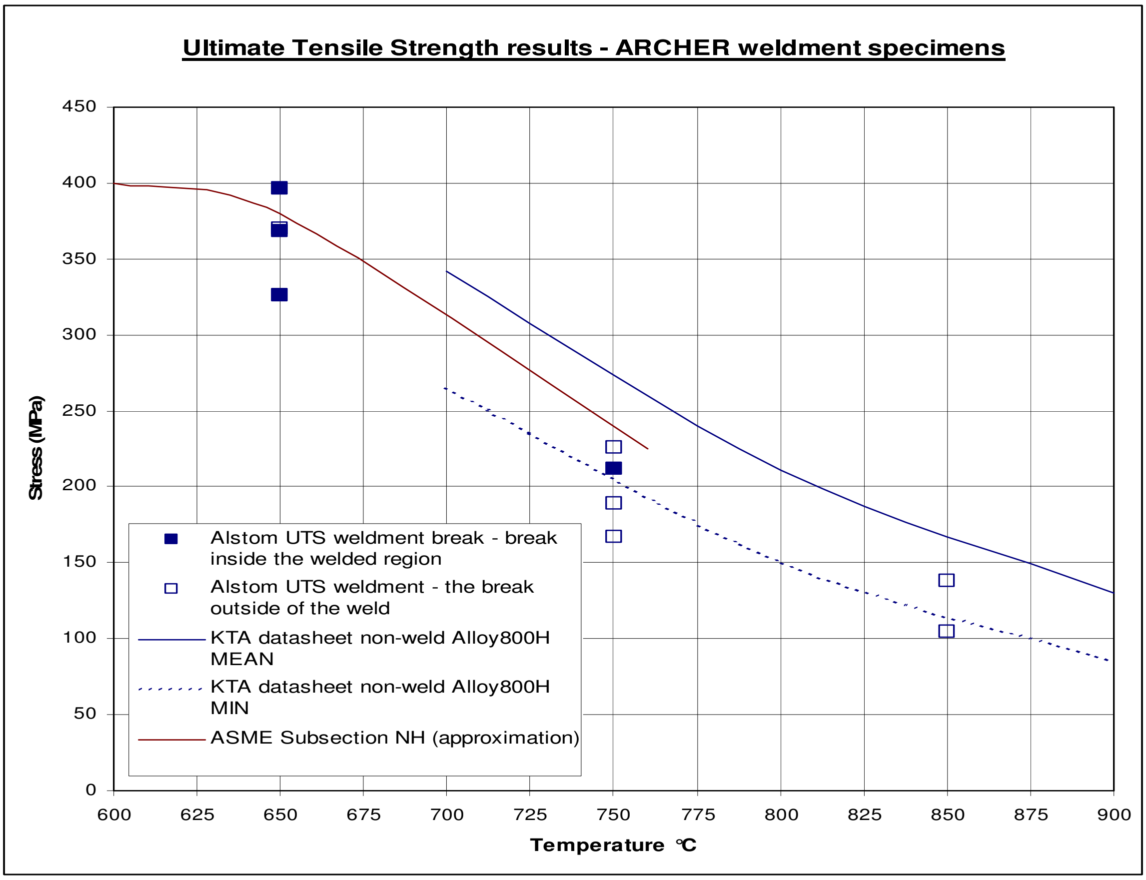


Fig. 5 Ultimate Tensile strength results from Table 3 tests compared to KTA data

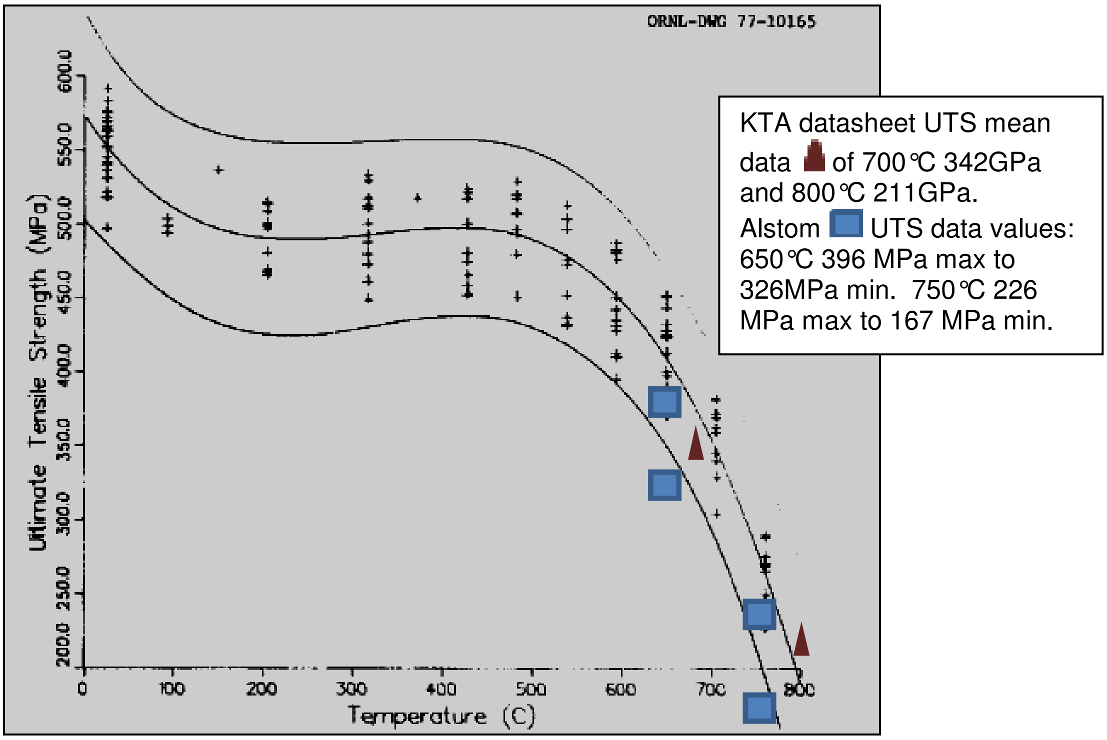


Fig. 6 UTS Tensile data (Oak Ridge National Laboratory) on Alloy 800H [4]

Creep Testing

The status of the creep testing program at the close of the ARCHER project done by both Alstom and the University of Stuttgart is shown below. The table also shows the times (hrs) to achieve specific % creep strain values in Alstom's weldment tests compared to that from the parent material tests done at MPA Stuttgart:-

Specimen Number	Temp (℃)	Stress (MPa)	Current or Final Duration (Hrs)	Time to % Creep Strain (hrs) 0.1	0.2	0.5	1.0	2.0	5.0	EL (%)	R in A (%)	Machine No	Life (Khrs)	Est. Comment
1ST BATCH ALSTOM														
R1790	650	93	15714	130	490	5820	9320	13000		5.0	14.4	MSP 06	20	Ruptured
MPA Stuttgart	650	94	12946	907	5702									
R1786	750	75	1048	3.4	27	140	290	500	880	10.1	18.2	MSP 05	3	Ruptured
R1783	750	44	20625	2120	6360	14500						MSP 07	20	On Test
MPA Stuttgart	750	43.6	16030	8118										On Test
R1787	850	21	13215	900	3380	8700	11100	12900		3.1	5.0	MSP 08	20	Ruptured
MPA Stuttgart	850	21.5	16622	3331	4819	6534	7949	9526	11726					On Test
2ND BATCH ALSTOM														
R1832	650	106	8529	95	200	2200	3900	5660	8180	5.5	13.4	MSP14	10	Ruptured
MPA Stuttgart	650	106	9946	187	1555	4063	5447	7196	8681	9.7	11.9			Ruptured
R1830	750	75	797	6.75	27	100	200	370	740	14.2	25.5	MSP16	1.5	Ruptured
R1855	750	75	680	1.4	7	55	140	270	520	6.5	27.9	MSP06	1.5	Ruptured
MPA Stuttgart	750	78	1812	194	328	586	943	1163	1459	12.0	7.8			Ruptured
R1831	750	50	12210	10.5	860	3340	5900	8620	12200	3.4	11.3	MSP15	10	Ruptured
MPA Stuttgart	750	48.8	16030	5320	10561									On Test
R1835	850	24	13194	340	2760	5960	7740	9060	10800	12.1	10.7	MSP16	10	Ruptured
MPA Stuttgart	850	24.3	16622	4465	5308	6671	7968	9537	11731	22.9	12.3			Ruptured
R1860	850	40	899	20	130	360	580	760		4.8	14.4	MSP 08	3	Ruptured
MPA Stuttgart	850	40	588	179	313	377	435	502	538	16	20			Ruptured

Table 2. Status of Creep Tests.
[Orange cells show Stress (MPa) applied values by MPA Stuttgart.
R1855 an extra test done due to spare specimen]

Weldment strength reduction factors compared to the parent material are best calculated using the failed tests, from both parent and weld material. Initial metallographic examination during the ARCHER program showed that the two failed weldment specimens at 750℃ have failed outside of the weld and also likely outside the HAZ (Heat affected zone) (fracture > 50 micron from weld). However, the HAZ cannot be clearly defined, as evidence using metallography alone is that it is no more than the region of 40 to 50 microns from the weld. For it is up to this 40-50 micron region that there is some metallographic evidence of liquation melt-lines along grain boundaries (see Fig. 7). Laser welding process has a concentrated heat source (high power density) and has high heating and cooling rates so the HAZ is narrow.

However, using hardness mapping at the University of Stuttgart on a virgin specimen has shown that increases in hardness *can* occur > 50 microns, to around 4mm (4000micron) away from the weld area, albeit on one side only of the sandwich of welds. A Hardness transverse (across the weld) of untested (virgin) material, along the length of the gauge length, has taken place also at Alstom in Rugby. The hardness results from Rugby show a similar higher hardness on one side of the weldment compared to the other, for approx. 4-5mm.

The testpieces post-failure images (Fig. 8) show greater necking and elongation occurring outside of the weld and the HAZ and close to each end of the gauge length. We are able to evaluate elongation throughout all along the gauge length, as the specimens are sprayed black with very high temperature paint (Hycote 650C) over half the width. Marks were then made every 5mm along the parallel, away from the mid position with a vernier height gauge and surface plate. The marks were made across approximately across 70% of the width about the centre. The marks from the vernier are then measured accurately with a shadow graph. After the test the marks are re-measured with the shadow graph.

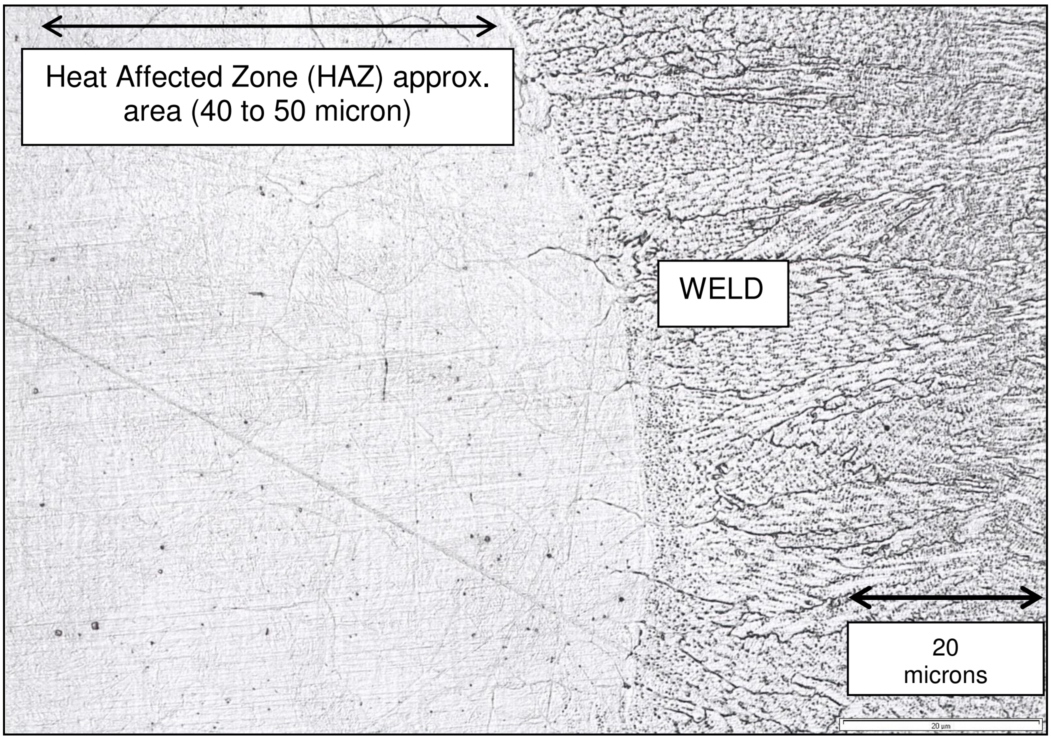


Fig. 7 Heat Affected zone (HAZ) area, mixed acid reagent etch: 100cm^3 of water, 85cm^3 of hydrochloric acid, 8g of copper chloride, 6g of ferric chloride, 15ml of nitric acid

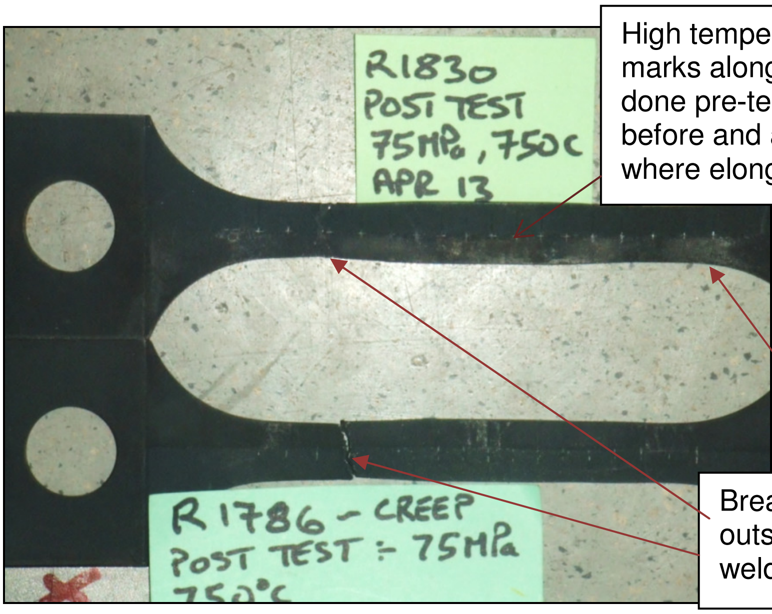


Fig. 8 Two 750°C failed tests on weldment Alloy800H
(750°C, 75MPa – Batch 1 & Batch 2)

Derivation of Weld Strength Factors

The standard WSF approach.

The standard WSF (weld strength factor) or strength reduction factor, is based on actual test results and / or extrapolated data to a higher number of hours e.g. 100k & 300k. This data can be put into publishable format such as the table shown in Fig. 9. This table shows the format that ASME use in their document subsection NH [6] to publish their strength reduction factors for Alloy800H welds. It is to be noted that the data presented for Alloy800H by ASME is not laser welded Alloy800H, but a more normal fusion weldment that uses the filler metal Inco 82.

2013 SECTION III, DIVISION 1 - NH

Table NH-I-14.10C-2
Stress Rupture Factors for Alloy 800H Welded with SFA-5.14 ERNiCr-3 (INCO 82)

U.S. Customary Units

Temp., °F	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
850-900	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
950	0.89	0.90	0.90	0.90	0.89	0.89	0.88	0.87	0.86	0.86
1,000	0.85	0.86	0.86	0.86	0.85	0.85	0.84	0.84	0.82	0.81
1,050	0.88	0.88	0.88	0.88	0.87	0.86	0.85	0.84	0.83	0.81
1,100	0.91	0.91	0.91	0.90	0.89	0.88	0.87	0.85	0.83	0.81
1,150	0.94	0.93	0.93	0.92	0.90	0.89	0.87	0.85	0.83	0.81
1,200	0.96	0.96	0.95	0.93	0.92	0.90	0.88	0.86	0.83	0.81
1,250	0.99	0.98	0.96	0.95	0.93	0.91	0.88	0.85	0.82	0.80
1,300	1.00	1.00	0.98	0.96	0.93	0.91	0.88	0.85	0.82	0.78
1,350	1.00	1.00	0.99	0.96	0.94	0.91	0.87	0.84	0.77	0.68
1,400	1.00	1.00	1.00	0.97	0.94	0.89	0.79	0.71	0.62	0.54

SI Units

Temp., °C	10 hr	30 hr	100 hr	300 hr	1,000 hr	3,000 hr	10,000 hr	30,000 hr	100,000 hr	300,000 hr
450-475	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	0.93	0.94	0.94	0.94	0.93	0.93	0.92	0.92	0.91	0.91
525	0.87	0.88	0.88	0.88	0.87	0.87	0.86	0.85	0.84	0.83
550	0.86	0.87	0.87	0.87	0.86	0.85	0.84	0.84	0.82	0.81
575	0.89	0.89	0.89	0.89	0.88	0.88	0.86	0.84	0.83	0.81
600	0.92	0.92	0.92	0.91	0.89	0.88	0.87	0.85	0.83	0.81
625	0.94	0.93	0.93	0.92	0.90	0.89	0.87	0.85	0.83	0.81
650	0.96	0.96	0.95	0.93	0.92	0.90	0.88	0.86	0.83	0.81
675	0.99	0.98	0.96	0.95	0.93	0.91	0.88	0.85	0.82	0.80
700	1.00	1.00	0.98	0.96	0.93	0.91	0.88	0.85	0.82	0.78
725	1.00	1.00	0.99	0.96	0.94	0.91	0.87	0.84	0.78	0.71
750	1.00	1.00	1.00	0.97	0.94	0.90	0.82	0.76	0.67	0.59

Fig. 9 ASME 2013 III Subsection NH Strength Rupture Factors (Alloy 800H welded)

Weld Strength factors (using ARCHER test results)
Using the results of the ARCHER creep testing programme for thin-section Alloy 800H for the parent and the weld material the following data results have been analysed.

a) 650℃.

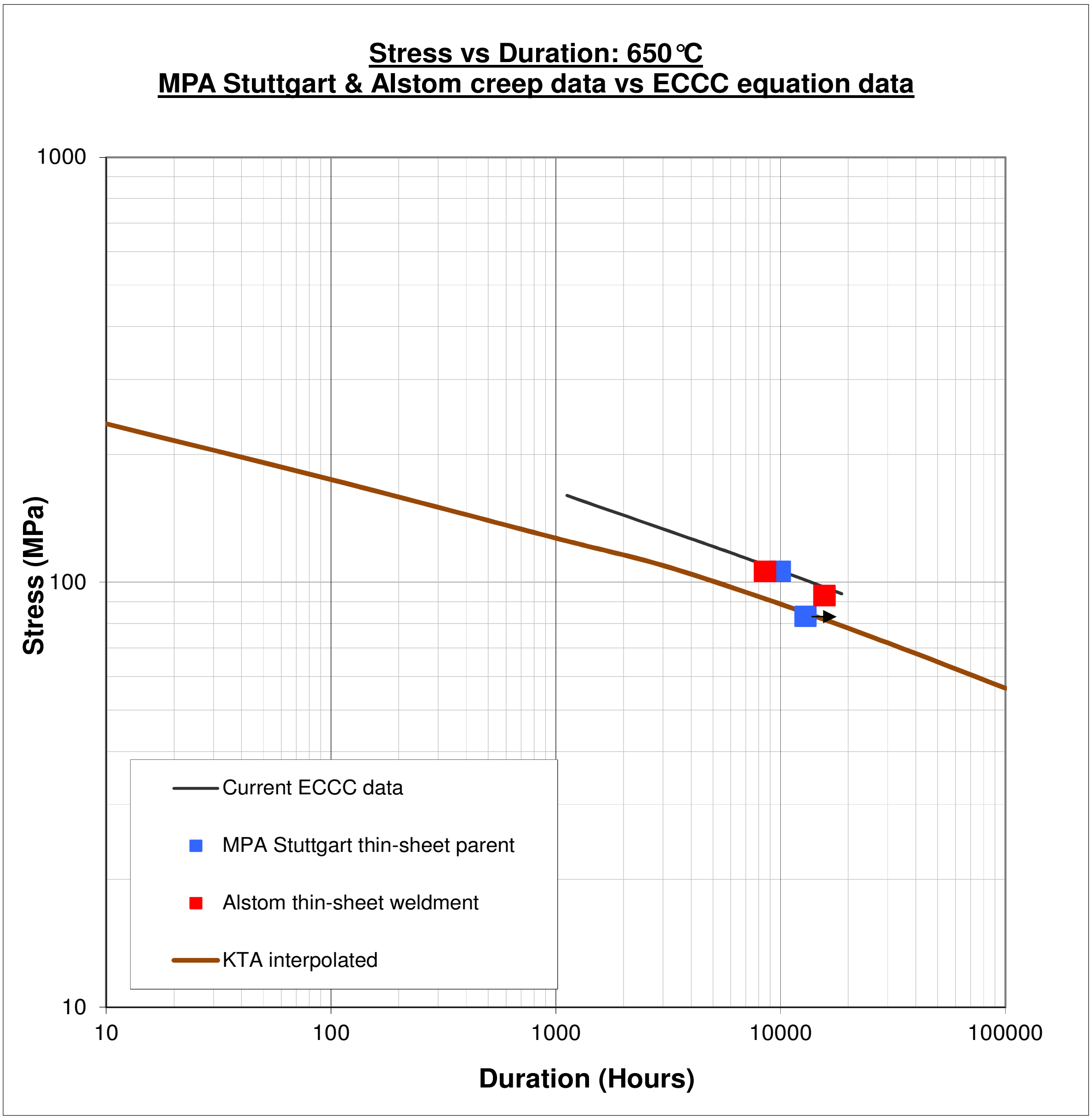


Fig. 10 650°C creep stress comparisons.

b) 750℃.

The 750℃ test at 10khrs for the weldment thin-section Alloy800H is close to the ECCC data equation [7]. The parent material (PM) testing is still ongoing, and outperforms the ECCC mean property line. Guideline weld strength factor for creep rupture strength is possible at 750℃ using a manual fit. An extra test done was at 75MPa (at Rugby), shown in Appendix 4, showing that there is scatter at higher stresses.

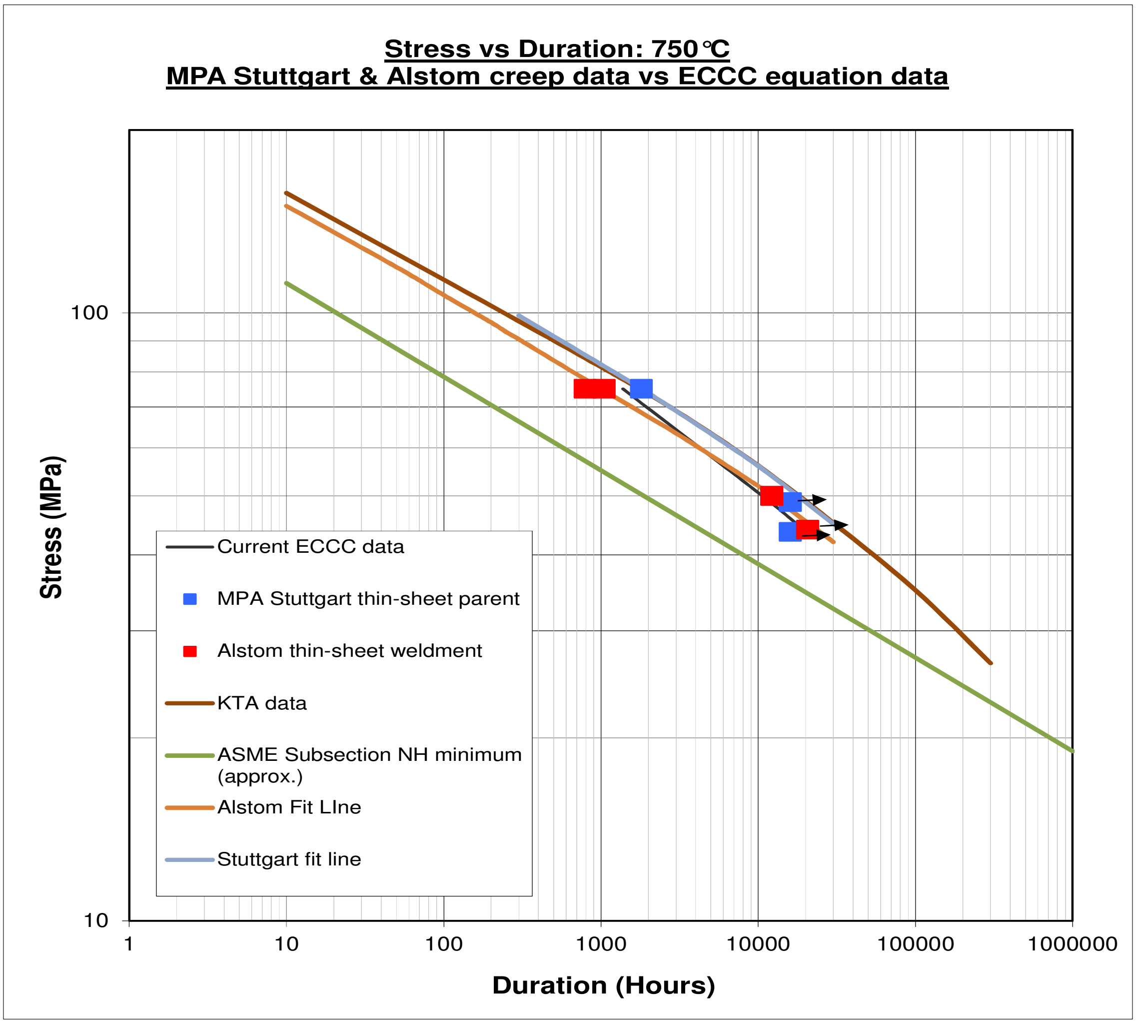


Fig. 11 750℃ creep stress comparisons.

Failed tests of both thin section parent material and thin-section weldment materials are recommended for future research at 30k hrs, 50khrs and 100k hrs for weld strength factors to be more comprehensively obtained for 750℃ .

c) 850℃.

The amount of outperformance of the 850℃ thin-section parent material to weldment material is unknown due to the Parent material tests not failing at this temperature. However it can be shown that a guideline WSF at ~10k hrs at this temperature can be given. There is a need for longer term tests to be able to publish WSF as a resource; as 50k to 100k tests are ideally needed until failure in order to get more comprehensive WSF for publication purposes.

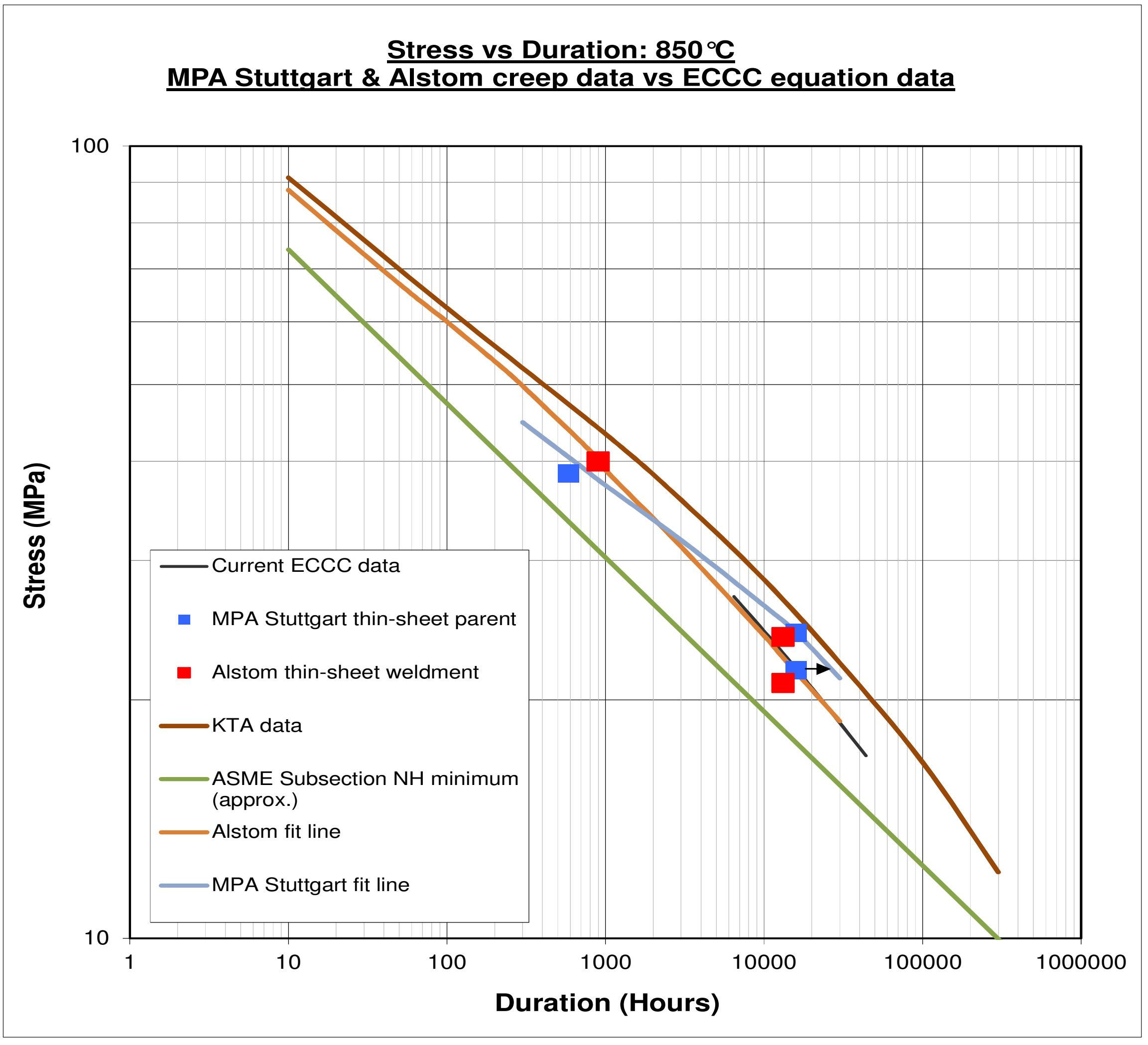


Fig. 12 850℃ creep stress comparisons.

d) WSF plot.

The plot for WSF (Fig. 13) for creep rupture is based on ARCHER test program data of PM and weldment material.

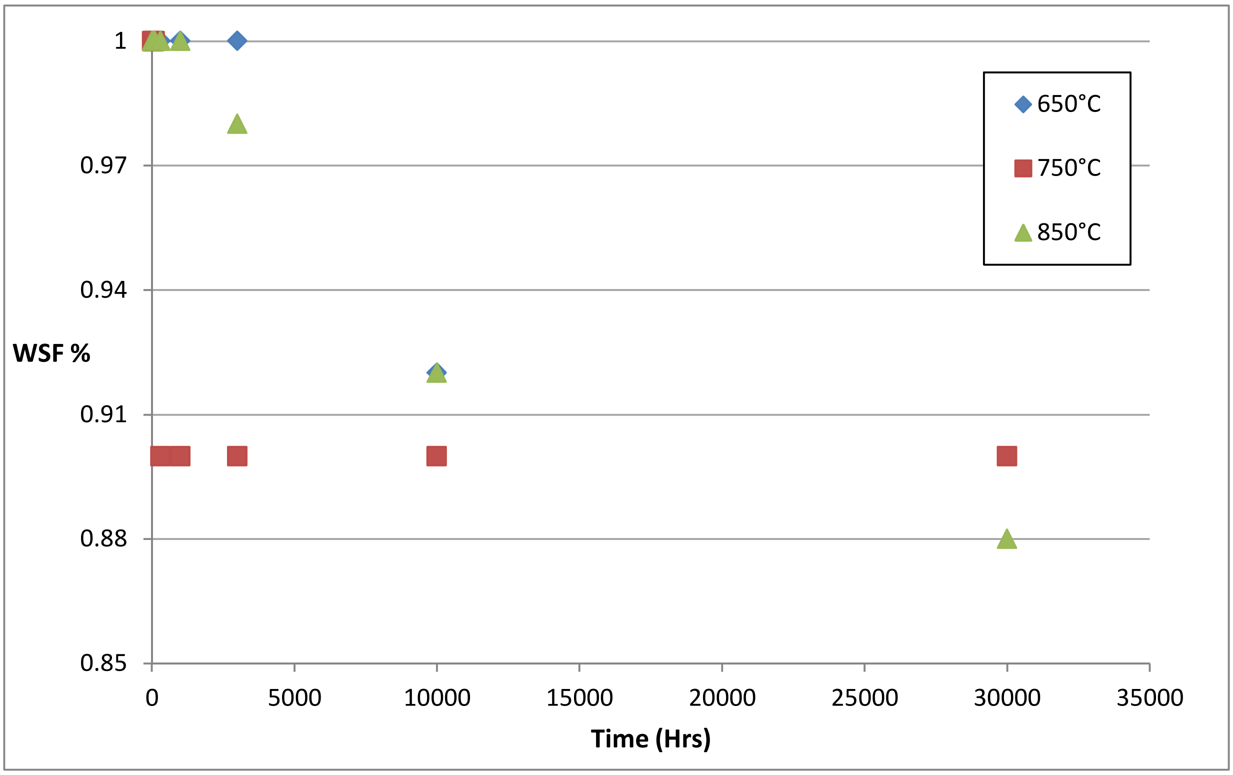


Fig. 13 WSF (Weld strength factor) at three elevated temperatures.

e) Strength Reduction Table

Temp °C	10 hr	30 hr	100 hr	300 hr	1000 hr	3000 hr	10000 hr	30000 hr	100000 hr	300000 hr
650	1.00	1.00	1.00	1.00	1.00	1.00	0.92			
750	1.00	1.00	1.00	0.90	0.90	0.90	0.90	0.90		
850	1.00	1.00	1.00	1.00	1.00	0.98	0.92	<0.88		

Fig. 14 Weld Strength Factors of Alloy800H thin-section material

3. How best to fill gaps in WSF to obtain publishable WSF data

There is a need for longer term tests to be able to publish WSF as a resource; as 50k to 100k tests are ideally needed until failure in order to get a higher accuracy of WSF for publication up to 100k hrs and above.

Conclusions and Recommendations

The test work on Alloy 800H laser weldments produced by the same welding process as used in the ARCHER IHX has shown that high integrity weldments can be produced, with good tensile and creep rupture properties, in relatively short term tests (<50k hrs). This is even though metallography and hardness traverses demonstrate a large amount of flash left behind on the interior surface, contours that could act as potential notches, and an elevated hardness (170-180Hv0.1 in the weldment, compared to 130-140Hv0.1 in the parent).

In tensile tests, the properties of the cross weld samples were similar to those expected from other Alloy 800H parent metal data, but were slightly lower at 650°C and 750°C, though some of this variance is likely linked to strain rates of the test procedure used. In the creep tests, it was notable that the weldment samples failed at only slightly shorter durations compared to tests on parent material, though some parent material tests are still ongoing. Moreover, both parent and weldment were close to the mean data produced by KTA and ECCC.

Weldment Strength Factors (WSFs) were calculated based on these preliminary results on one heat of Alloy 800H. With test data up to and including 30kh (with some tests still running at ARCHER completion) indicative WSF ranged from 1 at short durations (<1,000h) and dropped to 0.90 – 0.92, depending on temperature, at 30k hrs. Such factors exceed those in the ASME BPV tables for fusion welds, but must be considered as preliminary, awaiting further testing and, importantly, the derivation of minimum strength properties of weldments.

Therefore, based on this relatively small scale programme, laser welding of Alloy 800H without post weld heat treatment or inspection appears to be a viable technique, at least in manufacturing terms, for the IHX compact plate heat exchanger. Further work will be required to fully characterise the weld strength factors at longer durations (e.g.>50k hrs) including using published methods of extrapolation from test results [8]; and also to prove the reproducibility of the laser welded joints.

References

[1] SEVENTH FRAMEWORK PROGRAMME THEME [Fission-2010-2.3.1], R&D activities in support of the implementation of the Strategic Research Agenda of SNE-TP, Program Name: ARCHER, Description of Work, page 65 (D43.55 deliverable).

[2] ARCHER - Advanced Reactor for Cogeneration of Heat & Electricity R&D. Co-funded by the European Commission under the Euratom Research and Training Programme on Nuclear Energy within the Seventh Framework Programme. Grant Agreement Number: 269892. Description of Work, 6th Submission, Dec 2010.

[3] Materials Testing of Thin Section Alloy 800H, Weldments for Reactor Heat Exchanger Applications – Test Specification September 2011, Chris Bullough, released 2011/10/06.

[4] Survey of available creep and tensile data for Alloy 800H, M. K. Booker, V. B. Baylor, & B.L.P. Booker, Jan 1978, Oak Ridge National Laboratory, Union Carbide Corporation.

[5] KTA Werkstoffdatenblatt Alloy800H (X8NiCrAlTi 32 21 H), Stand: 1.7.1991, Section A5.

[6] STP-NU-020 Verification of Allowable Stresses in ASME section III subsection NH for Alloy 800H, prepared by R. W. Swindeman et al, 2008.

[7] ECCC creep equation, ECCC datasheets 2005, ECCC Management Committee, 5th Sept 2005.

[8] ECCC recommendations – Volume 5 Part IIb [Issue 1] Guidance for the assessment for Creep Rupture, Creep Strain and Stress Relaxation data, recommendations for the assessment of weld creep-rupture data, 0509/MC/102 [Issue 1], 1105/01.

Appendices

Appendix 1 - Test piece drawing

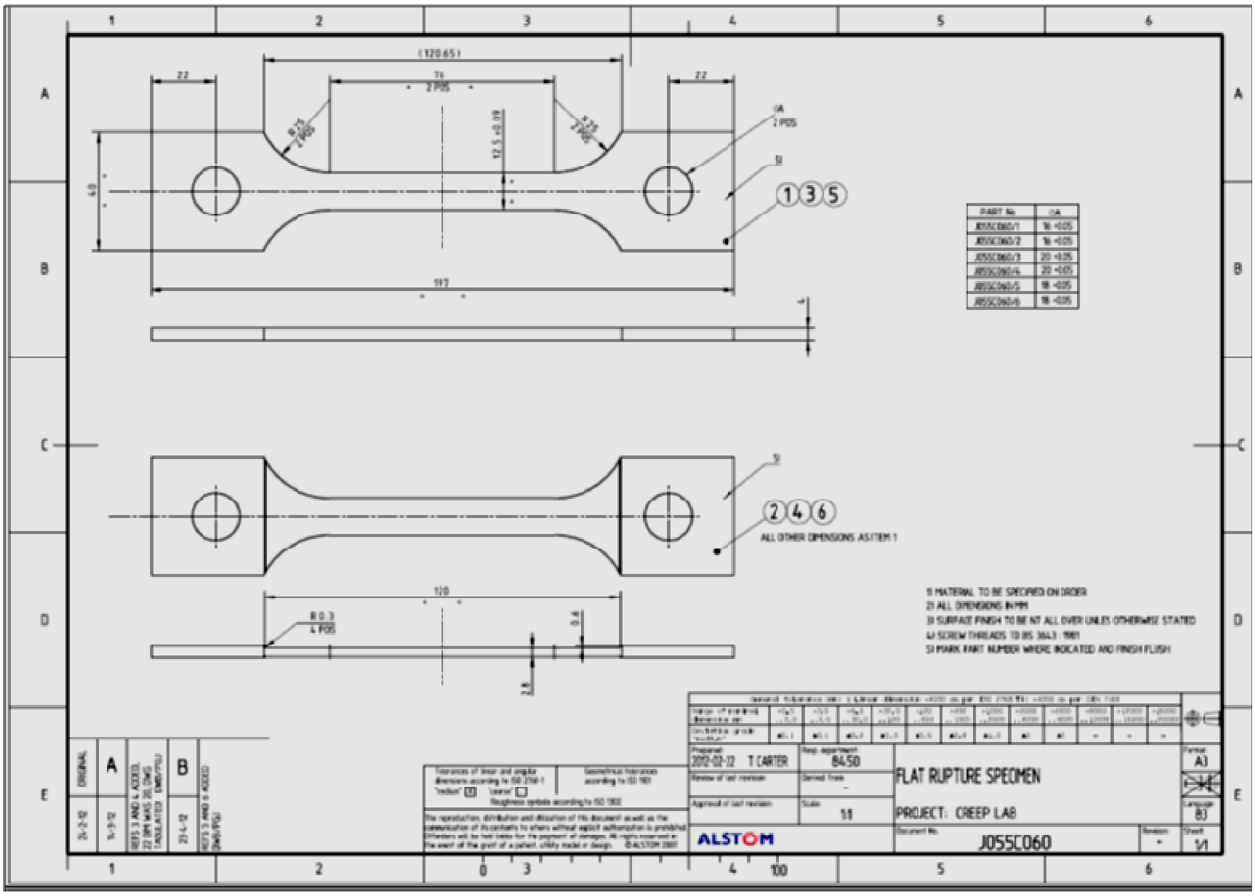


Fig. 15 Creep Specimen Drawing [3]

Appendix 2 - Strain measurements along gauge length of welded samples

To note the lower stresses 24MPa and 21MPa (longer term) creep tests failed within the weld area. The other tests that have so far failed have failed away from the weld but may be affected by a HAZ area (see section on hardness levels).

	R1835 smooth 24 MPa 850 deg C		R1831 smooth 50 MPa 750 deg C		R1855 smooth 75 MPa 750 deg C		R1786 smooth 75MPa 750 deg C		R1830smooth 75MPa 750 deg C	
Nominal mark on parallel length	Pre test measure	Post test	Pre test measure	Post test	Pre test measure	Post test	Pre test measure	Post test	Pre test measure	Post test
mm	mm	mm	mm	mm	mm	mm	mm	mm	mm	mm
Hole to Zero										
			27.314	27.581	27.837	28.2	27.731	27.862	27.491	27.957
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	5.008	5.761	5.017	5.521	4.988	6.171	5.002	5.500	5.010	5.913
10	9.966	11.635	10.001	12.067	9.994	14.360	9.995	11.658	10.020	13.816
15	14.968	17.492	14.998	17.747	14.996	20.622	14.999	18.908	15.014	20.337
20	19.985	23.375	20.002	23.217	19.986	26.506	19.993	25.308	19.986	26.148
25	24.963	28.831	54.992	28.283	24.984	31.906	25.002	30.795	25.005	31.380
30	29.970	34.242	29.997	33.326	29.990	36.927	29.984	35.869	30.013	36.491
35	34.985	39.428	34.990	38.288	34.988	41.944	34.982	40.855	35.013	41.510
40	39.998	44.662	40.027	43.349	40.001	46.956	39.983	45.888	40.025	46.480
45	44.994	50.760	44.985	48.270	44.986	51.931	44.983	50.873	45.022	51.512
50	49.979	56.817	49.980	53.346	49.985	56.945	49.974	55.873	49.998	56.451
55	54.993	62.729	54.996	58.344	54.988	61.973	54.982	60.899	55.008	61.564
60	59.990	68.585	60.025	63.507	59.993	67.050	59.978	66.220	60.015	66.748
65	65.002	74.281	65.006	68.727	64.983	72.265	64.970	71.352	64.997	72.580
70	69.985	79.971	70.005	73.935	69.987	77.527	69.963	76.615	70.025	78.948
75	74.981	85.695	74.995	79.301	74.994	82.865	74.964	82.175	75.011	84.938
80	79.980	91.495	84.848	84.476	79.978	88.023	79.966	87.677	80.018	90.819

	R1787smooth 21MPa		R1860 smooth 40MPa 850 deg C		R1832 smooth 106MPa @650C		R1790 smooth 93Mpa 650 deg C	
Nominal mark on parallel length	Pre test measure	Post test	Pre test measure	Post test	Pre test measure	Post test	Pre test measure	Post test
mm	mm	mm	mm	mm	mm	mm	mm	mm
Hole to Zero								
	27.666	27.796?	27.824	27.95	27.407	27.615	27.779	27.825
0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	4.991	5.030	4.996	5.672	5.021	5.439	4.996	5.163
10	9.994	10.108	9.979	12.285 ??	9.972	11.165	9.988	10.468
15	14.993	15.198	14.974	18.303	14.982	17.873?	14.996	15.715
20	19.994	20.280	19.988	23.647	19.991	23.700	19.995	20.970
25	24.980	25.397	24.973	28.692	24.992	29.025	24.986	26.106
30	29.979	30.478	29.971	33.719	29.993	34.056	29.990	31.132
35	34.972	35.513	34.969	38.730	34.972	39.040	34.979	36.137
40	39.985	41.110	39.985	43.781	40.000	44.079	39.990	41.146
45	44.975	46.310	44.979	48.781	45.001	49.123	44.994	46.156
50	49.969	51.421	49.974	53.803	49.996	54.107	50.002	51.165
55	54.970	56.579	54.993	58.832	55.016	59.069	54.994	56.191
60	59.957	61.671	59.945	63.810	60.005	64.397	60.002	61.413
65	64.969	66.911	64.970	68.847	65.008	69.874	64.995	66.751
70	69.967	72.071	69.956	73.883	70.031	75.299	69.994	72.174
75	74.972	77.200	74.964	78.889	74.999	80.782	74.992	78.385
80	79.963	82.298	79.954	83.924	80.000	86.112	79.986	83.385

Fig. 16 Position of failure cracks (shown in red)

	R1835 smooth 24 MPa 850 deg C		R1831 smooth 50 MPa 750 deg C	R1855 smooth 75 MPa 750 deg C	R1786 smooth 75MPa 750 deg C	R1830smooth 75MPa 750 deg C
	0.753		0.504	1.183	0.498	0.903
	0.916		1.562	3.183	1.165	2.893
	0.855		0.683	1.26	2.246	1.527
	0.866		0.466	0.894	1.406	0.839
	0.478		0.076	0.402	0.478	0.213
Area in or right next to the weld	0.404		0.038	0.015	0.092	0.103
	0.171		-0.031	0.019	-0.012	0.019
	0.221	<< Double	0.024	-0.001	0.032	-0.042
	1.102	fracture	-0.037	-0.01	-0.015	0.035
	1.072	<< in weld	0.081	0.015	0.009	-0.037
	0.898		-0.018	0.025	0.018	0.103
	0.859		0.134	0.072	0.325	0.177
	0.684		0.239	0.225	0.14	0.85
	0.707		0.209	0.258	0.27	1.34
	0.728		0.376	0.331	0.559	1.004
	0.801		-4.678	0.174	0.5	0.874

	R1787smooth 21MPa		R1860 smooth 40MPa 850 deg C	R1832 smooth 106MPa @650C	R1790 smooth 93Mpa 650 deg C
	0.039		0.676	0.418	0.167
	0.075		1.63	0.775	0.313
	0.091		1.023	1.698	0.239
	0.081		0.33	0.818	0.256
Area in or right next to the weld	0.131		0.06	0.324	0.145
	0.082		0.029	0.03	0.022
	0.042		0.013	0.005	0.016
	0.584	<<fracture	0.035	0.011	-0.002
	0.21	in weld	0.006	0.043	0.006
	0.117		0.027	-0.011	0.001
	0.157		0.01	-0.058	0.034
	0.105		0.026	0.339	0.214
	0.228		0.012	0.474	0.345
	0.162		0.05	0.402	0.424
	0.124		-0.002	0.515	1.213
	0.107		0.045	0.329	0.006

Fig. 17 Changes (in mm) to regularly spaced gauge length markings.
[Within each specimen higher mm elongations are shown in orange and lower elongations shown in yellow when the specimen broke in the weld region.]

At any given temperature there is little strain in the weldment region at highest stresses, but in the lower stress tests it is the other way around. However, more tests will need to be carried out at lower stresses and differing temperatures to confirm this conclusion. It is important to note that the lower stress creep tests of the R1835 specimen (24 MPa) and the R1787 specimen (21 MPa) fractured within the weld.

These fractures occurred next to or in an area of lower elongation. This is not surprising as welds often show lower elongation. Whether low elongation provokes brittle fracture when Alloy800H weldment is in a low stress environment needs to be further analysed by doing further creep tests at low stress. It should be noted that where fracture has occurred away from the weld this does not mean that the weld has greater elongation.

Those tests shown in Fig. 16/17 failing outside of the weld show regions or a region of low elongation within the weld area, it is just that failure has not occurred there.

Fig. 18 The length of the weld mid-section gauge length.
Note in this picture it exceeds 20mm and is ~22mm.

Failures of Tensile and Creep specimens that occur outside the weld / HAZ area possibly show areas of rupture/performance issues where the HAZ area may have extended on one side of the weld (see Hardness results Fig. 3 and 4). The hardness results (Fig. 3 & 4) therefore show an extension of hardness peaks on one side away from the weld area and therefore hard to soft transition areas can occur away from the weld/HAZ area. This evidence is not shown by metallography alone where liquation lines show a very limited HAZ area. These transition areas of differing hardness (Fig. 4) may encourage cracks to form here during elongation under creep stress at elevated temperature. The weld area is approximately 20mm. The area can be larger than this e.g. 22mm (see Fig. 18).

Appendix 3 – Primary creep – end hole elongation?

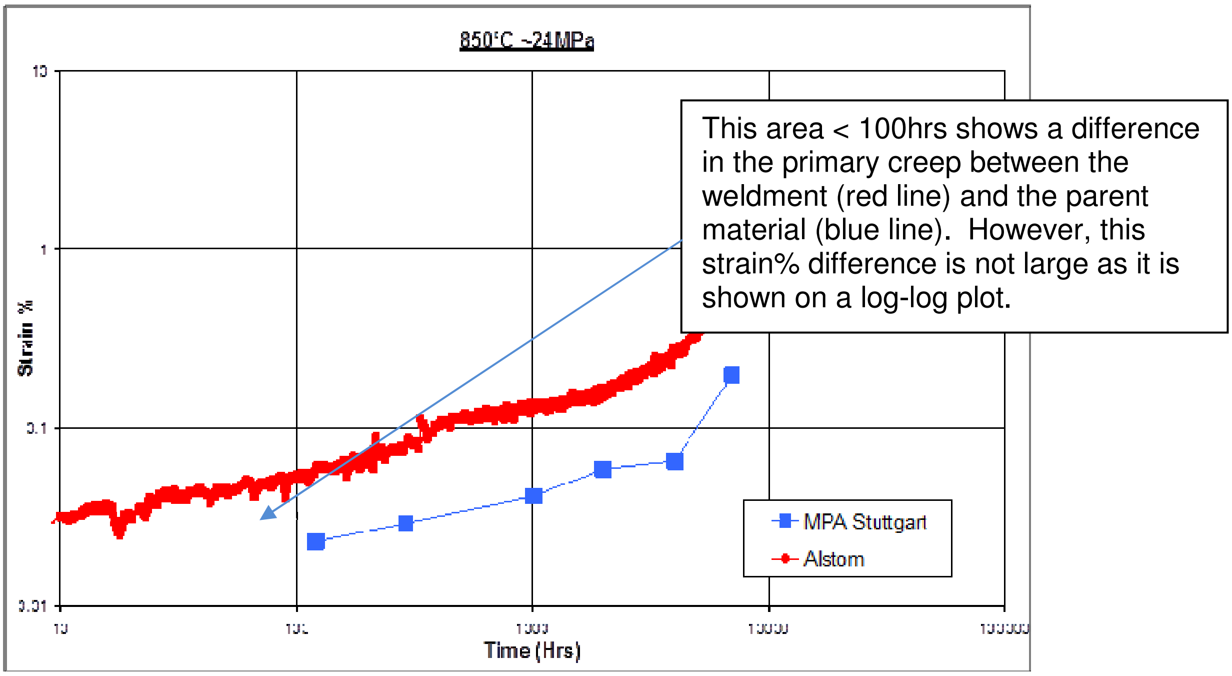


Fig. 19 Interlaboratory Comparison – Measurement of Strain

Creep Strain vs Time plot, test condition: 850℃ ~24MPa

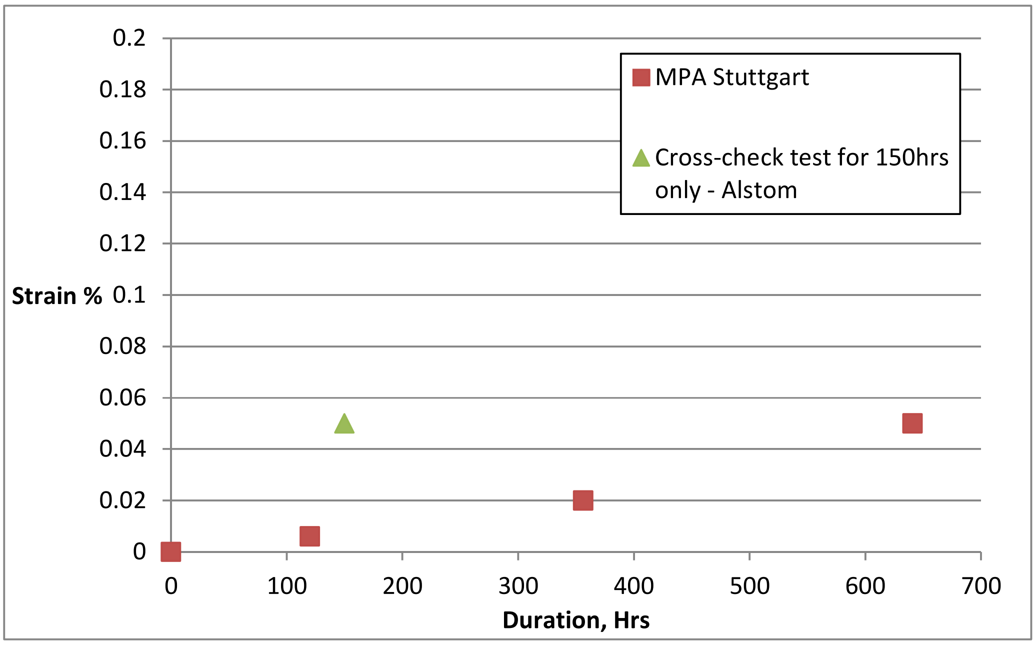
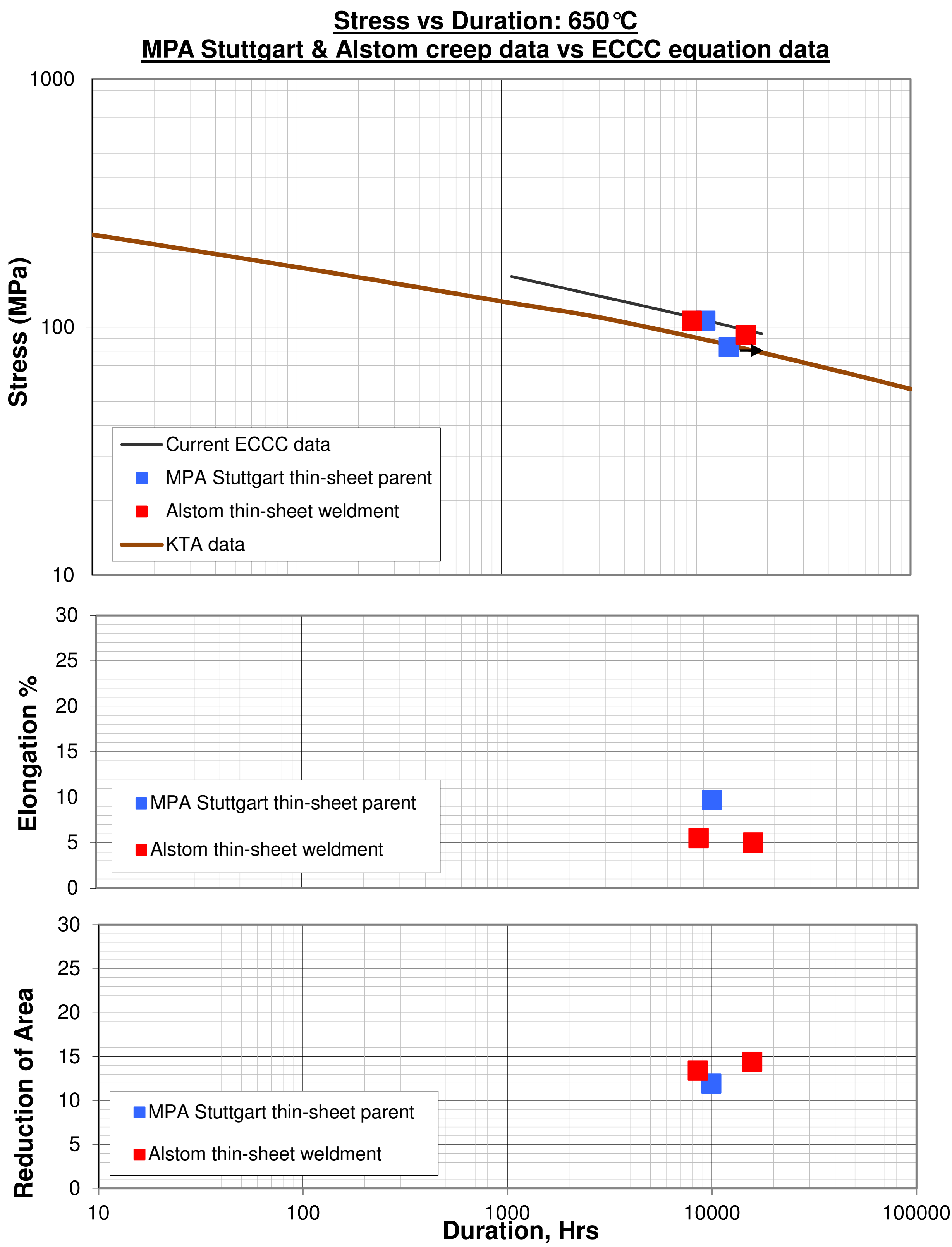
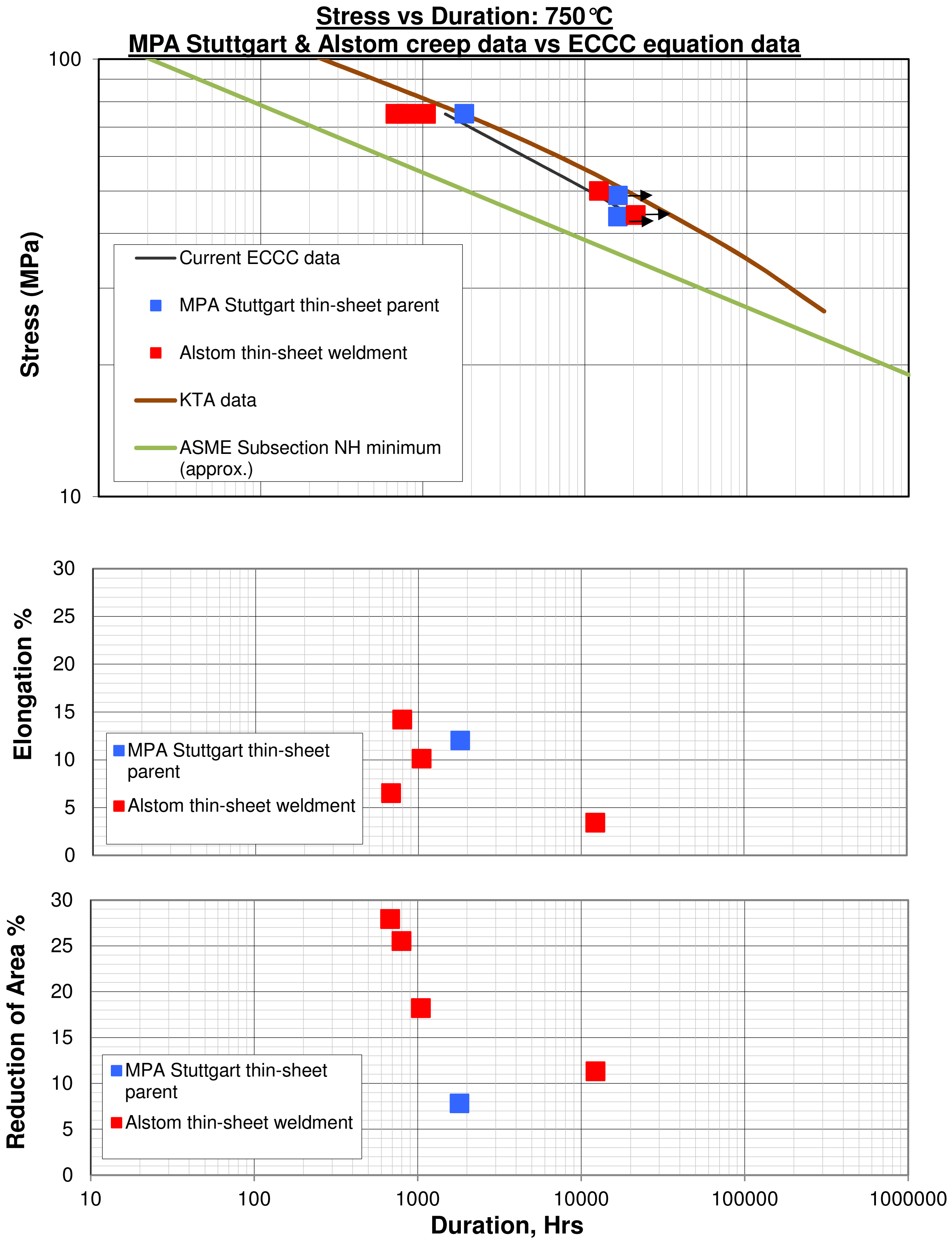


Fig. 20 750℃ 48 MPa, parent material (cross-check done at Alstom)

The Alstom R1856 sample had its end-holes measured and the 0.029 (very approximate) extension in end-holes during the first 150hrs means that of the 0.05% strain experience at 150hrs ~58% of the primary could be due to end-hole elongation. The 0.029 extension could explain therefore explain >50% of the difference occurring when cross-checking with MPA Stuttgart's data.

Appendix 4 – Creep 3-part graphs




Stress vs Duration: 750℃
MPA Stuttgart & Alstom creep data vs ECCC equation data
100
10
Stress (MPa)
Current ECCC data
MPA Stuttgart thin-sheet parent
Alstom thin-sheet weldment
KTA data
ASME Subsection NH minimum (approx.)
Elongation %
30
25
20
15
10
5
0
MPA Stuttgart thin-sheet parent
Alstom thin-sheet weldment
Reduction of Area %
30
25
20
15
10
5
0
MPA Stuttgart thin-sheet parent
Alstom thin-sheet weldment
10
100
1000
10000
100000
1000000
Duration, Hrs

ALSTOM	Revision: -	Doc. Type: TN	Language: en	Page: 25/25	TN14/0672

Stress vs Duration: 850°C
MPA Stuttgart & Alstom creep data vs ECCC equation data