Tensile and Low Cycle Fatigue Properties of Solution Annealed Type 316L Stainless Steel Plate and TIG Weld Exposed to 5 dpa at Low Temperature (42°C)

J.-L. Puzzolante, M. Scibetta,
R. Chaouadi, W. Vandermeulen *

Reactor Materials Research,
Belgian Nuclear Research Center,
SCK•CEN, Mol, Belgium.

(*) VITO, Mol , Belgium.

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Tensile and Low Cycle Fatigue Properties of Solution Annealed Type 316L Stainless Steel Plate and TIG Weld Exposed to 5 dpa at Low Temperature (42°C)[‡]

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ABSTRACT

The austenitic stainless steel type AISI 316L was selected as the main structural material of the next-step ITER fusion device, i.e., the first wall, blanket modules, and vacuum vessel components. Although this steel was extensively investigated under different aspects, most results concern irradiation temperatures above 300°C.

In the present work, tensile and fatigue specimens were irradiated in the BR2 materials testing reactor at 42°C up to a maximum neutron fluence of 8 10^{21} n/cm^2 (E>0.1 MeV), corresponding to 5 dpa. The European reference AISI 316L in the solution annealed condition and the TIG-metal deposit are tested in the baseline and irradiated conditions. The tensile specimens were tested at 25, 250 and 450°C while the low-cycle fatigue tests are performed at room temperature.

The tensile test results obtained in this work are consistent with published data: substantial radiation hardening combined with some reduction of elongation. No specimen orientation effect could be evidenced. The amount of hardening decreases with increasing test temperature. By contrast, the low cycle fatigue data show no or little effect of irradiation, independent from irradiation and testing conditions. No major difference is found between the plate and the weld metal.

1 INTRODUCTION

316L austenitic stainless steel in the solution annealed condition has been selected as a structural material for the first wall and blanket structures of the International Thermonuclear Experimental Reactor (ITER). The first wall and divertor components will be exposed to a high 14MeV neutron flux in the range of 1-3 $MWyr/m^2$ (corresponding to 10-30 dpa) in the temperature range of 100 to 400°C [1]. These structural components will be subjected to thermo-mechanical cyclic loading as a result of cyclic strains produced during burn and off-burn periods of the plasma. Therefore, evaluation of the low cycle fatigue properties is a very important issue as it can be the limiting lifetime parameter.

The 316L austenitic stainless steel was extensively investigated within the fusion community. However, most of the published data are in the range of 300 to 650°C [2-10]. By contrast, little is known on the LCF properties of this steel in the low temperature range, in particular after irradiation.

Chung and al. [11] reported some data on the EC 316L steel in the unirradiated condition over the range 20-200°C. They found that for a total strain range $\varepsilon<1\%$, the fatigue life is temperature independent. However, for total strain ranges above 1%, the fatigue life tends to decrease in the neighborhood of 50°C. Above this temperature, the fatigue life becomes again temperature independent. The authors [11] suggested that this is probably due to the temperature sensitivity of the mobility of interstitial carbon atoms in the crystal.

Josefsson and Bergenlid [12] have published data on the tensile and low cycle fatigue properties of the 316L plate and TIG-metal deposit weld material tested at 75, 250 and 450 °C, irradiated at 35°C up to 0.3 dpa to simulate the start-up of the ITER reactor life. The tensile properties have shown that the irradiation to 0.3 dpa has caused a considerable material hardening.

The present work was initiated in order to provide supplementary data on tensile and low cycle fatigue after neutron irradiation near room temperature. Tensile as well as fatigue specimens of EC 316L austenitic stainless steel (plate and TIG-metal deposit weld) were irradiated in the BR2 materials testing reactor at 42°C to a maximum neutron exposure of about 5 dpa. Tensile specimens are tested at 25, 250 and 450°C while fatigue tests are performed at room temperature. Although the above mentioned irradiation conditions are not fully representative of fusion reactors, it is interesting to know how the fatigue properties will be affected by neutron exposure at low temperature.

2 MATERIALS AND IRRADIATION CONDITIONS

Two materials are investigated here, plate and weld. First, the plate material is the CEC Reference AISI 316L-167 SPH stainless steel, heat 12879. It was solution annealed at 1100°C for 30 min, followed by a water quench, according to the ASTM standards A240 and A480, and following the technical specification MTG/88/N052 of the NET Team. This plate was delivered by JRC-ISPRA but manufactured by Creusot-Loire Industrie, Usine du Creusot – France. The chemical composition of the 316L performed by Creusot-Loire is given in Table 1 [13].

Table 1. Chemical composition of NET reference plate 316L and automatic TIG-metal deposit (wt.%).

	C	Ni	Cr	Mn	Cu	Mo	Si	Co	S	P	Ta	N	B
plate	0.019	12.2	17.2	1.75	0.07	2.3	0.35	0.08	0.0007	0.0195	0.002	0.074	0.0009
weld ‡	0.045	9	17	2.5	0.1	2.5	0.5	0.25	0.02	0.025	--	--	--

‡ nominal composition.

Second, the Metal Deposit blocks n° NET 805-19 and NET 805-21 were produced at the Danish Welding Institute with an automatic TIG-welding machine and provided to SCK•CEN for testing. The blocks were approximately 1 meter long and 35 mm thick. The nominal chemical composition of the metal deposit is given in Table 1.

Fatigue and tensile specimens (plate and weld) were neutron irradiated in the BR2 Reactor (SCK•CEN) in the rigs Lotion 1 and 2, respectively. The specimens were cooled by the BR2 primary water (~42°C). The accumulated maximum neutron exposure is 5.4 dpa, which corresponds to a maximum fluence of 8 10^{21} n/cm^2 (E>0.1 MeV) for the fatigue specimens and 5.2 dpa (7.7 10^{21} n/cm^2, E>0.1 MeV) for the tensile specimens. Helium production was estimated to be 88.6 and 82.5 appm He, respectively. Figure 1 shows the axial distribution of the neutron dose for both Lotion 1 and 2 irradiations.

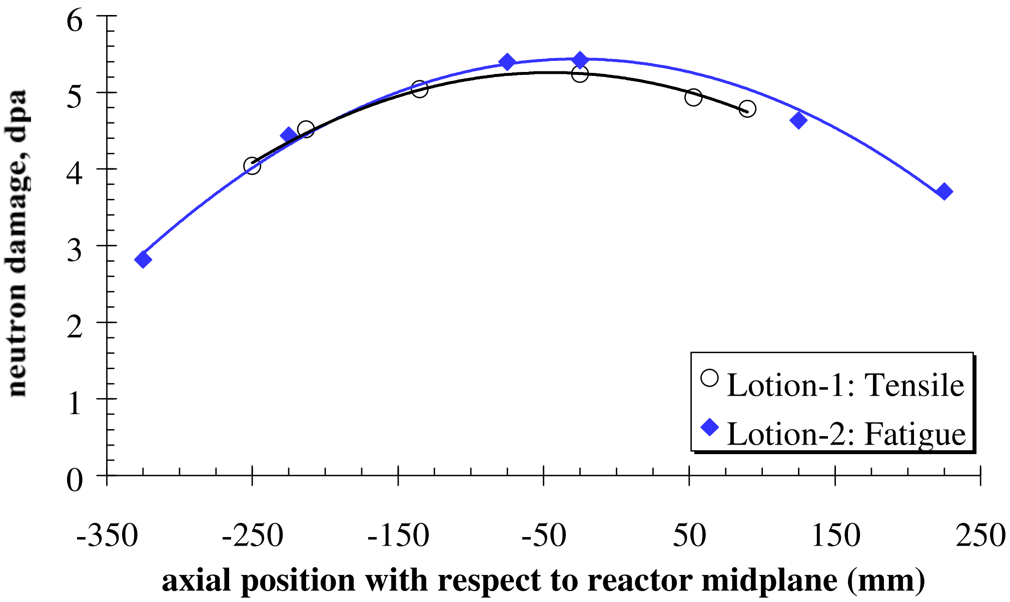

Fig. 1. Axial neutron exposure distribution in the irradiation rigs Lotion-1 and 2.

3 TEST RESULTS AND DISCUSSION

3.1. Tensile tests

The tensile tests on non-irradiated materials were performed at the Flemish Institute for Technological Research (VITO) using a 100 kN electromechanical test frame INSTRON type 1195. The same type of machine was used to test irradiated materials in the hot-cells at SCK•CEN. The specimen geometry is cylindrical with a cross section of 3 mm diameter and the gauge length is 15 mm. The tests were performed according to ASTM E8 standard under controlled displacement of 0.5 mm/min, corresponding to a strain rate of 5 10^{-4} s^{-1}, at three different temperatures (25°C, 250°C, 450°C) in the three orientations (L, T, S). Details on the tensile tests are given elsewhere [14]. The test results are summarized in Tables 2 and 3 for the plate and TIG weld materials, respectively.

3.1.1 Plate material

The test results on unirradiated and irradiated plate material are given in Table 2. As it can be seen, within the experimental scatter[†], there is no major difference between the three orientations. Therefore, similar symbols are used in Figures 2 and 3 for the three orientations. In Figure 2, the yield strength and ultimate tensile strength (UTS) in both unirradiated and irradiated conditions are compared. After irradiation, a drastic increase of the yield strength is observed associated with a significant decrease of strain hardening capacity. The elongation is also affected by irradiation. Figure 3 shows the uniform and total elongation as a function of test temperature. As for stresses, no major difference in elongation was found between the three orientations.

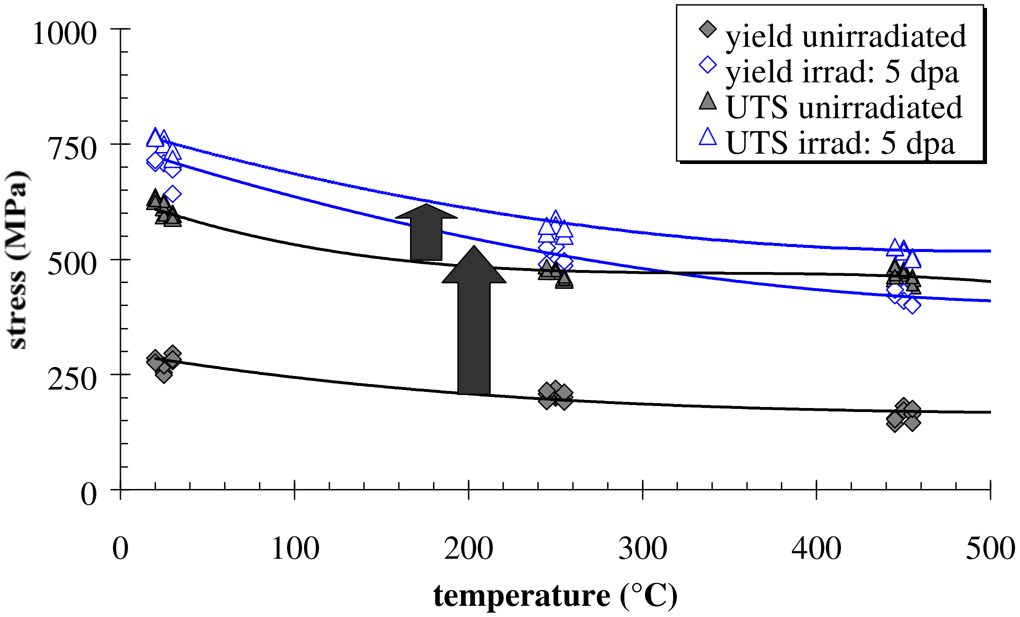

Fig. 2. Irradiation effects on the yield strength and UTS of the CEC Ref AISI 316L plate material.

3.1.2 TIG-weld

The test results are given in Table 3. As before, no specimen orientation effect can be evidenced. Therefore, no symbol distinction is made in Figure 4, which shows the yield strength and UTS as a function of test temperature.

The increase of the yield strength is modest in comparison to the plate material. However, in the baseline condition, the weld material exhibits higher stresses than the plate. Figure 5 shows how the uniform and total elongations are affected by irradiation.

[†] Note that if any effect exists, it should be consistently observed on the various parameters at the three test temperatures.

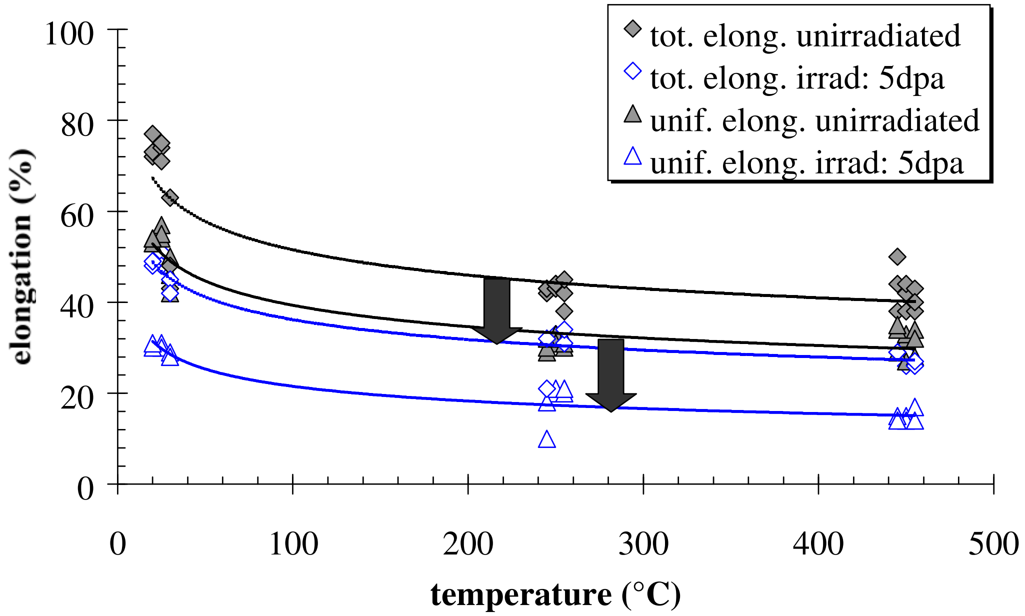

Fig. 3. Effect of irradiation on the uniform and total elongations of the 316L plate material.

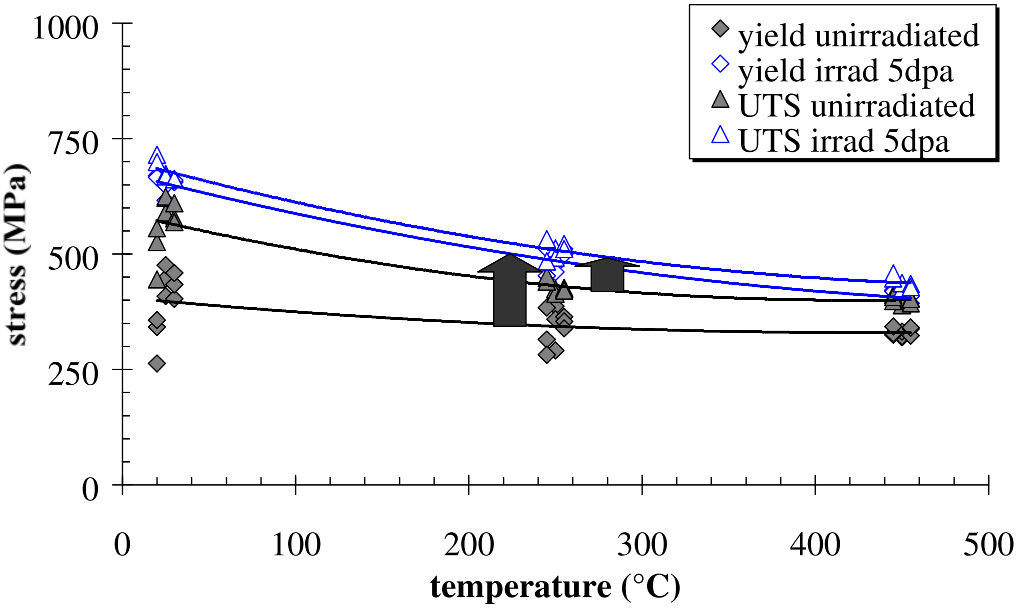

Fig. 4. Yield strength and UTS of the TIG weld material in the baseline and irradiated conditions.

Table 2[‡]. Tensile test results on the plate material.

dose (dpa)	T (°C)	orientation	Id.	σ_y (MPa)	σ_{UTS} (MPa)	ε_u (%)	ε_t (%)
0	25	L	L5-36	278	635	53	72
			L5-42	286	627	54	77
			L5-46	276	627	54	73
		T	T4-22	254	596	54	74
			T4-30	249	613	57	75
			T4-34	270	625	55	71
		S	S3-48	279	599	50	63
			S3-55	296	599	46	48
			S3-63	283	590	42	43
	250	L	L5-33	208	475	29	42
			L5-72	192	487	30	43
			L5-75	215	488	32	43
		T	T4-18	200	484	33	43
			T4-53	205	478	33	44
			T4-9	219	475	31	44
		S	S3-41	201	456	30	38
			S3-44	191	456	31	42
			S3-47	211	461	32	45
	450	L	L5-21	155	459	29	38
			L5-48	143	485	34	50
			L5-59	153	466	35	44
		T	T4-3	182	476	32	42
			T4-31	182	474	27	38
			T4-35	172	471	33	44
		S	S3-10	164	444	34	43
			S3-34	145	444	28	38
			S3-54	176	460	32	40
4.5	25	L	L35-5-1	709	768	30	48
5.2			L35-8-1	715	764	31	49
5.0		T	T35-10-1	724	763	31	51
4.0			T35-13-1	709	750	30	48
5.2		S	S30-11-1	695	736	29	45
4.8			S30-14-1	642	718	28	42
4.5	250	L	L35-5-2	525	556	10	21
5.2			L35-8-2	489	573	18	32
5.0		T	T35-10-2	527	589	20	32
4.0			T35-13-2	495	574	21	33
5.2		S	S30-11-2	486	551	20	31
4.8			S30-14-2	496	567	21	34
4.5	450	L	L35-5-3	422	526	15	29
5.2			L35-8-3	434	527	14	29
5.0		T	T35-10-3	429	523	15	29
4.0			T35-13-3	410	517	14	26
5.2		S	S30-11-3	402	505	17	26
4.8			S30-14-3	400	501	14	27

[‡] Legend: σ_y is the 0.2%-yield strength, σ_{UTS} is the tensile strength, ε_u is the uniform elongation and ε_t is the total elongation.

Table 3[‡]. Tensile test results on the TIG weld material.

dose (dpa)	T (°C)	orientation	Id.	σ_y (MPa)	σ_{UTS} (MPa)	ε_u (%)	ε_t (%)
0	25	L	MDL-15	342	526	28	39
			MDL-5	263	445	39	51
			MDL-8	357	556	38	47
		T	MDT-25	409	590	40	51
			MDT-27	447	622	38	51
			MDT-41	476	624	44	52
		S	MDS-13	403	577	27	43
			MDS-17	434	569	28	44
			MDS-6	459	610	41	51
	250	L	MDL-16	384	448	12	22
			MDL-17	315	440	13	25
			MDL-26	282	452	15	26
		T	MDT-1	387	420	13	23
			MDT-17	359	424	13	25
			MDT-32	291	414	9	21
		S	MDS-10	364	427	8	18
			MDS-11	354	424	11	23
			MDS-24	339	421	10	24
	450	L	MDL-23	325	398	15	27
			MDL-34	328	412	12	19
			MDL-41	343	407	14	19
		T	MDT-19	320	389	16	25
			MDT-31	322	399	16	29
			MDT-40	332	404	17	24
		S	MDS-22	338	405	12	21
			MDS-26	323	393	9	19
			MDS-4	341	403	13	21
5.2	25	L	MDL-35-9-1	670	715	27	40
4.4			MDL-35-12-1	666	699	20	29
4.1		T	MDT-35-4-1	648	673	25	34
5.0			MDT-35-7-1	616	668	26	36
4.8		S	MDS-30-3-1	656	663	26	42
5.2			MDS-30-6-1	660	662	23	38
5.2	250	L	MDL-35-9-2	511	532	11	22
4.4			MDL-35-12-2	453	484	10	19
4.1		T	MDT-35-4-2	476	512	9	16
5.0			MDT-35-7-2	461	492	7	16
4.8		S	MDS-30-3-2	511	522	8	24
5.2			MDS-30-6-2	499	511	9	20
5.2	450	L	MDL-35-9-3	422	447	5	16
4.4			MDL-35-12-3	419	458	9	19
4.1		T	MDT-35-4-3	395	423	6	19
5.0			MDT-35-7-3	399	437	8	18
4.8		S	MDS-30-3-3	393	435	6	19
5.2			MDS-30-6-3	409	428	5	17

[‡] Legend: σ_y is the 0.2%-yield strength, σ_{UTS} is the tensile strength, ε_u is the uniform elongation and ε_t is the total elongation.

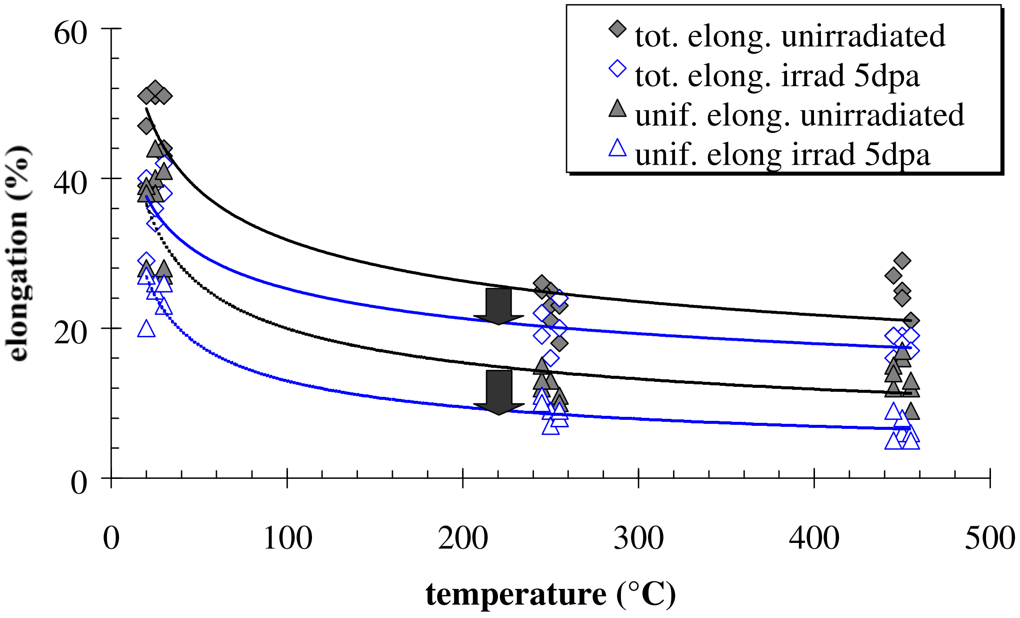

Fig. 5. Irradiation effects on the ductility of the 316L TIG-metal deposit material.

3.1.3 Discussion

As other laboratories also investigated this plate, it is interesting to compare the tensile properties obtained in this work with those found in the literature [7,12-13,15-17]. Figure 6 compares the data in terms of yield and ultimate stresses as a function of test temperature. A very good agreement between the various data is found. Similar consistency is found on the TIG weld material in comparison with the STUDSVIK data [12] in the test temperature range up to 450°C.

In the irradiated condition, Figure 7 compares our results with the few data found in literature. Of course, much more data were published but the conditions of irradiation are very different. At 5 dpa, there is a good agreement between our data and ECN data [16]. Note that the most of the hardening damage occurs already at a very low neutron dose level, as found by other investigators [18-21].

The increase of the yield strength which reflects the strengthening induced by irradiation decreases with elevating test temperature. Similar trend was reported by Wiffen and Maziasz [21]. Although irradiated in identical conditions, the increase of yield strength is higher in the plate than in the weld. This can be associated with the strain hardening capacity of the materials. Indeed, if the yield strength increase is plotted as a function of the difference between the UTS and the yield strength in the baseline condition, the strengthening is found to correlate very well with the initial strain hardening capacity. In other words, the yield strength increase is limited by the initial work hardening capacity of the material. This is also observed with cold-worked stainless steels for which the yield increase becomes almost negligible for high cold-working levels [5,21]. This is also consistent with the saturation of yield strength [18]. Note that an appropriate parameter reflecting the irradiation damage would be the strain hardening capacity but expressed in terms of stress rather than uniform elongation.

As shown in Figure 7, the yield strength drastically increases already at very low neutron dose levels. It is known that the yield strength after irradiation saturates with increasing fluence at a value independent of the initial condition of the alloy [18]. In Figure 8, tensile test data at low irradiation and test temperature (25 to 80 °C) show clearly the decreasing hardening with neutron exposure. It also clearly shows the loss of hardening capacity with increasing neutron dose. This is also reflected by the TIG-metal deposit, which shows less hardening than the plate, the yield strength values before irradiation being higher for the weld. One can suggest that the yield increase (irradiation hardening) is proportional to the difference between the tensile and yield strength (work hardening). This is illustrated by Figure 9 for two different conditions of testing and irradiation.

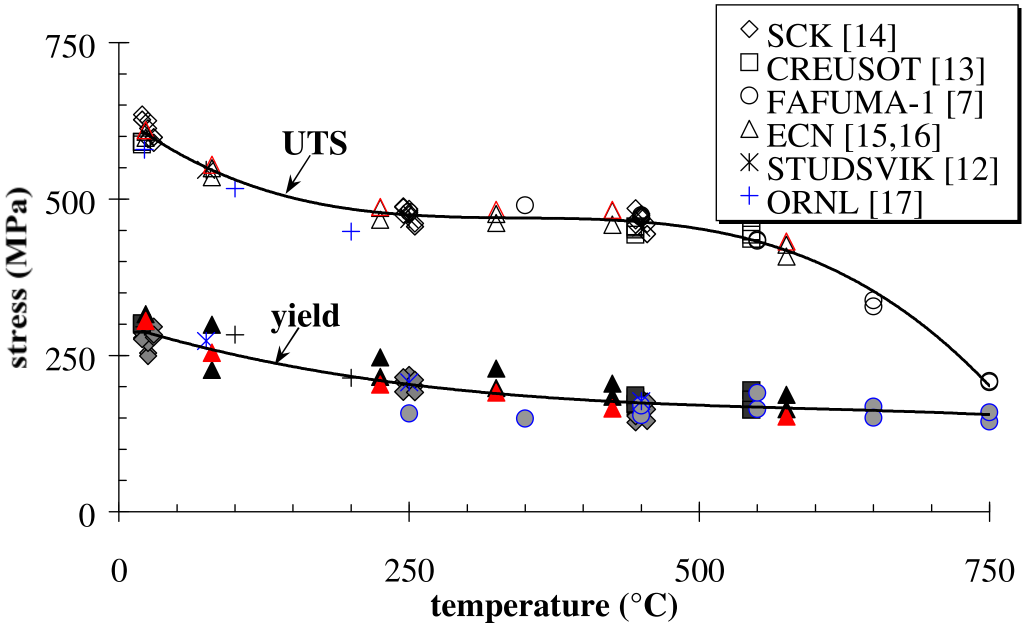

Fig. 6. Comparison of tensile strength properties of the AISI 316L plate material in the baseline condition.

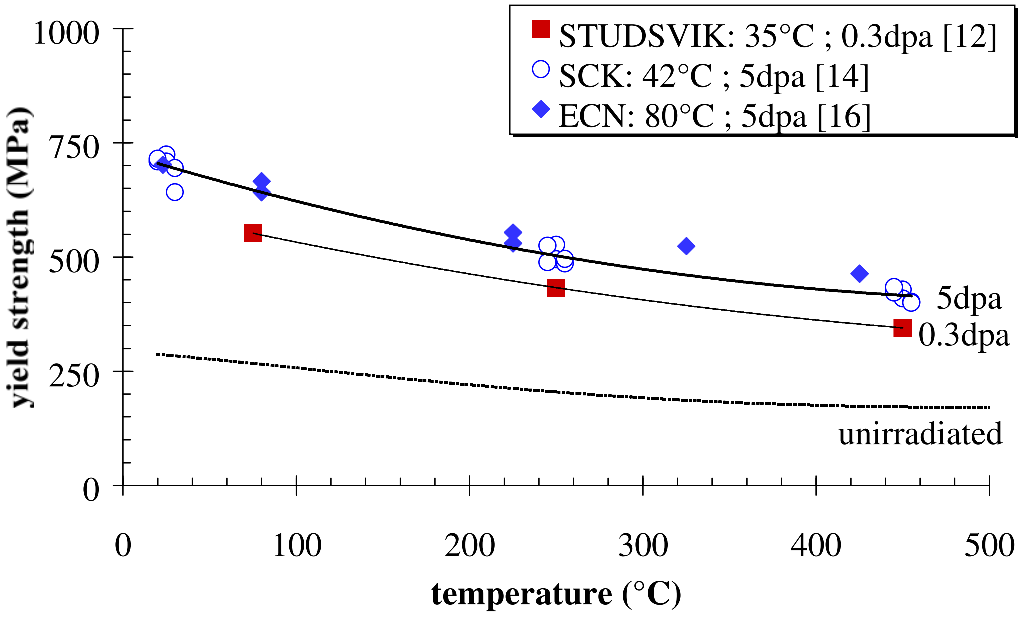

Fig. 7. Yield strength of AISI 316L plate material irradiated at T<100°C.

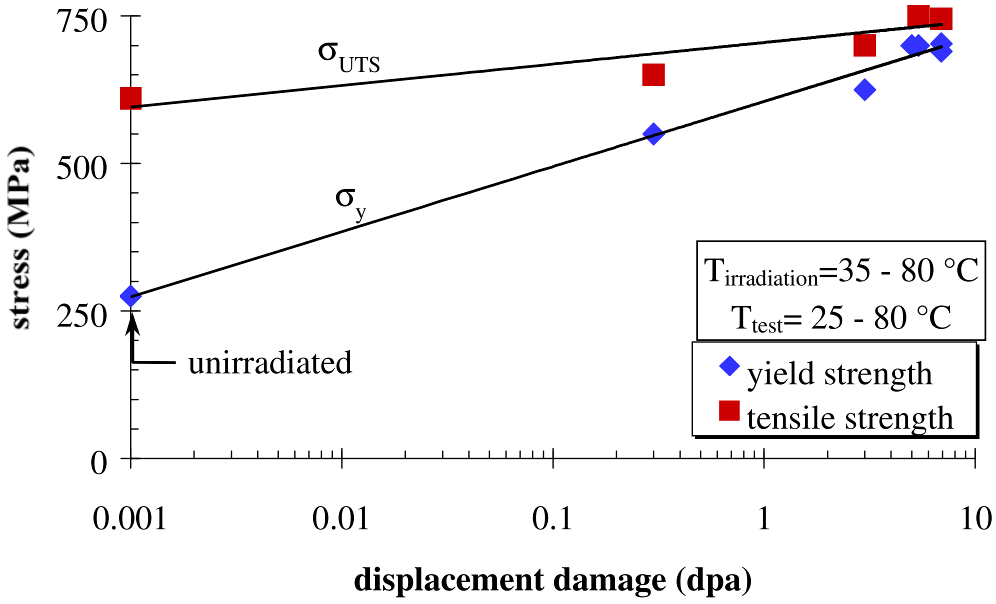

Fig. 8. Hardening saturation. Some of the data are taken from literature [12,17,20].

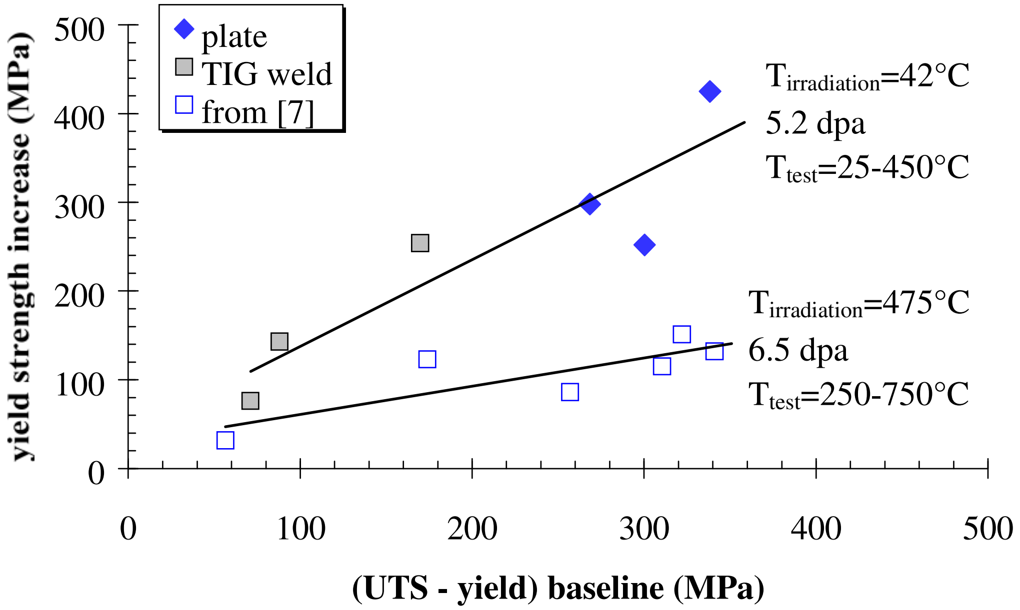

Fig. 9. Yield strength increase correlates well with the initial strain hardening capacity.

3.2 Low cycle fatigue tests

Tensile properties have not shown any major influence of specimen orientation. Therefore, only the T orientation was selected for the plate material. For the TIG weld, specimens available in two orientations are tested, L and T, respectively.

The fatigue test specimen is cylindrical with a cross section of 3 mm diameter and 7.5 mm gauge length. Most of the tests on unirradiated materials were performed at the VITO using a closed loop servo hydraulic INSTRON test frame type 1340. The same type of machine was used to test some the irradiated specimens in hot-cell at SCK•CEN.

Testing was conducted in total axial strain control by a means of an axial extensometer. Specimens were alternatively loaded in tension and compression using a rigid load line. A sine strain versus time waveform was applied, starting in tension. The tension/compression loading line was carefully aligned to avoid any excessive bending. Before testing, each specimen was loaded/unloaded twice in the elastic domain in order to check the strain measurements.

The following testing procedure was used:

- For the unirradiated samples, a constant frequency of 0.5 Hz was applied for N<40000 and 2.5 Hz above.
- For the irradiated samples, the frequency was successively increased with the number of cycles: 1.5 Hz up to 1000 cycles, 2.5 Hz up to 10^4 cycles, 5 Hz up to 10^5 cycles and 10 Hz above.

The stress versus total strain hysteresis loops were recorded in logarithmic increments of fatigue life, i.e., 1 to 10, 100, 1000, 10000 and 100000th cycle. The minimum and maximum loads reached during cycling as a function of time were continuously recorded. Throughout the tests, the R-ratio ($\sigma_{min}/\sigma_{max}$) was taken equal to –1 (mean strain=0). The tests were conducted as much as possible until failure occurs.

3.2.1 Plate material

The LCF test results on unirradiated and irradiated plate material are depicted in Table 4. Three diagrams are extracted of the LCF tests: the strain range versus number of cycles to rupture (ε-N_f) diagram, the stress range versus number of cycles (σ-N) for different strain ranges and the stress range versus strain range (σ-ε) at two different stages of fatigue life (N=1 and N=1000).

Figure 10 shows the LCF curve ($\Delta\varepsilon$-N_f) of the unirradiated and irradiated samples. At 1% strain range, a decrease of the fatigue life is observed (by a factor of 2 to 3) but the reverse occurs for lower strain ranges. However, within the experimental and statistical uncertainties, there is no or little effect of irradiation on the low cycle fatigue life.

Table 4. Low cycle fatigue results. EC316L plate material. All tests are performed at 25°C.

Id.	dose (dpa)	$\sigma_{1/4cycle}$ (MPa)	$\Delta\sigma_1$ (MPa)	$\Delta\sigma_{10}$ (MPa)	$\Delta\sigma_{100}$ (MPa)	$\Delta\sigma_{1000}$ (MPa)	$\Delta\sigma_{10^4}$ (MPa)	$\Delta\sigma_{10^5}$ (MPa)	$\Delta\varepsilon$ (%)	N_f
F2-1	0	345	690	764	733	693	--	--	1	9250
F2-22		330	677	751	721	689	--	--	1	7810
F2-50		322	676	749	722	689	--	--	1	7737
F2-10		296	632	671	639	597	567	--	0.6	64350
F2-56		300	628	671	639	594	566	--	0.6	49898
F2-13		297	592	606	575	547	524	--	0.4	1869260
F2-53		268	578	631	603	567	549	532	0.4	245483
F2-19		275	596	651	626	594	560	548	0.4	175200
F2-31		245	519	564	554	532	512	499	0.35	478244
F2-41		292	598	598	579	553	526	529	0.35	214246
F2-20		270	560	574	546	524	506	--	0.35	>2029790
F2-2		268	555	570	541	520	501	--	0.35	627940
F-II-3-24	5.4	721	1433	1184	1020	880	--	--	1	2750
F-II-4-27	5.4	727	1444	1179	1017	882	--	--	1	3176
F-III-5-51	5.1	680	1392	1193	1036	878	--	--	1	4119
F-II-1-18	5.4	589	1175	1131	1051	883	756	--	0.6	81397
F-II-2-21	5.4	622	1242	1165	1054	881	768	--	0.6	89103
F-II-5-30	5.4	462	986	967	973	928	813	691	0.45	637144†
F-III-1-33	5.1	431	860	857	857	846	767	--	0.45	>17000‡
F-III-2-36	5.1	470	941	938	927	874	754	652	0.45	591191
F-III-3-45	5.1	480	945	943	941	908	800	700	0.45	>304705
F-III-4-48	5.1	445	907	906	902	867	769	691	0.45	415795

† fracture in the specimen head

‡ test interrupted

Legend: $\Delta\varepsilon$ is the total strain range

N_f is the number of cycles to failure or the number of cycles before test interruption

$\sigma_{1/4cycle}$ is the stress at the first ¼ cycle and $\Delta\sigma_1$, $\Delta\sigma_{10}$, $\Delta\sigma_{100}$, $\Delta\sigma_{1000}$, $\Delta\sigma_{10^4}$ and $\Delta\sigma_{10^5}$ are the total stress ranges after 1, 10, 100, 1000, 10^4 and 10^5 cycles, respectively.

3.2.2 TIG weld

The fatigue test results on the unirradiated and irradiated TIG-weld materials are given in Tables 5 and 6 for both orientations, T and L, respectively. Similarly to the plate, Figure 11 shows that no statistically significant effect of irradiation can be depicted. The scatter, indicated with dashed lines, seems slightly larger than the plate material. Consistent with the tensile data, no orientation effect could be detected.

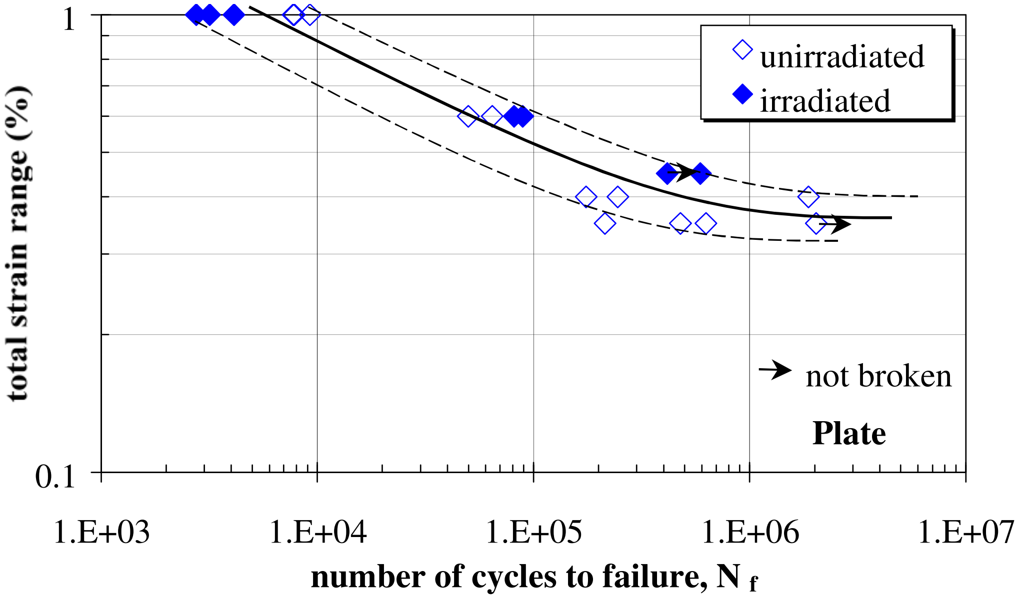

Fig. 10. Low cycle fatigue behavior of the 316L plate material.

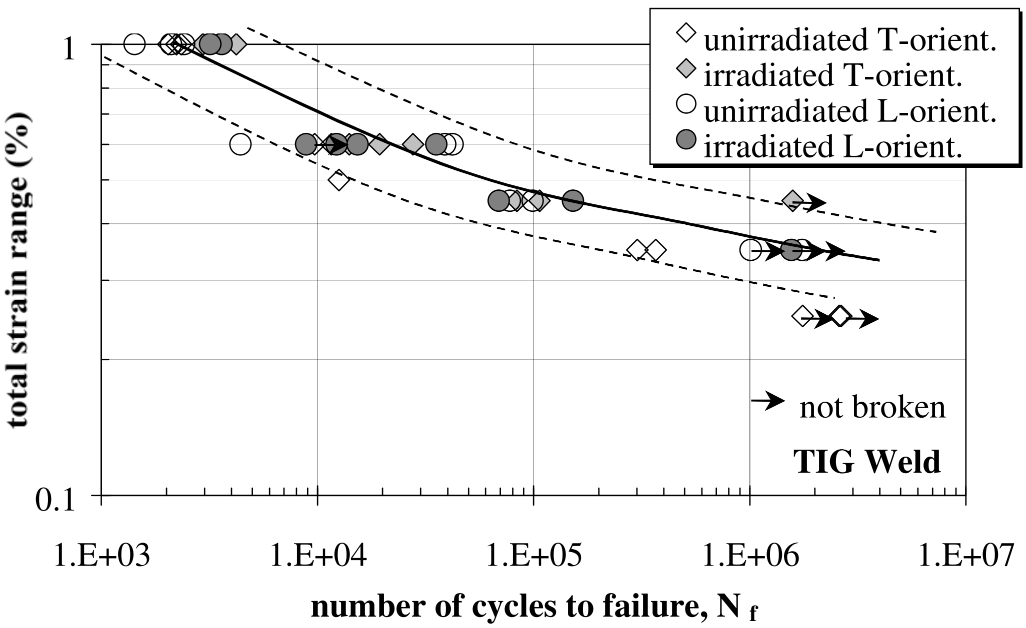

Fig. 11. Low cycle fatigue behavior of the TIG metal deposit.

3.3 Discussion

Other investigators reported the little or no effect of irradiation on LCF properties. However, the number of specimens is usually very limited. Therefore, it is interesting to combine the experimental data presented here to those found in literature. First, in the unirradiated condition, a large number of experimental data on LCF of type 316L steel was found, but at various test temperatures, ranging from 75 to 550°C. These are shown in Figure 12 where one additional data set on type 316 steel tested at 625°C is added [22]. It is obvious that test temperature plays no or very little role on the LCF properties. However, one can distinguish two trend curves corresponding to temperature ranges of 25 to 430°C and 450 to 625°C. Another curve (Langer equation) proposed by Tavassoli [23] is also shown. The overall agreement between the various data is very good. Note however that, for strain ranges >1%, there might be a more significant temperature effect as reported by Chung et al. [11]. In Figure 13, the test data in the range 25 to 430°C do not show any test temperature effect on the LCF properties.

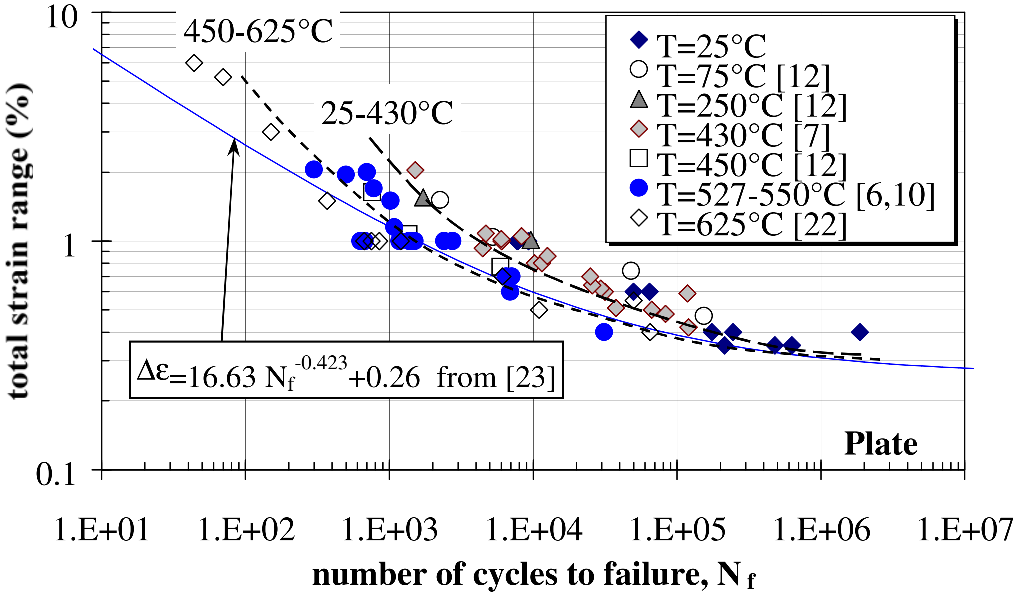

Fig. 12[‡]. Test temperature effects on the LCF behavior of the plate material.

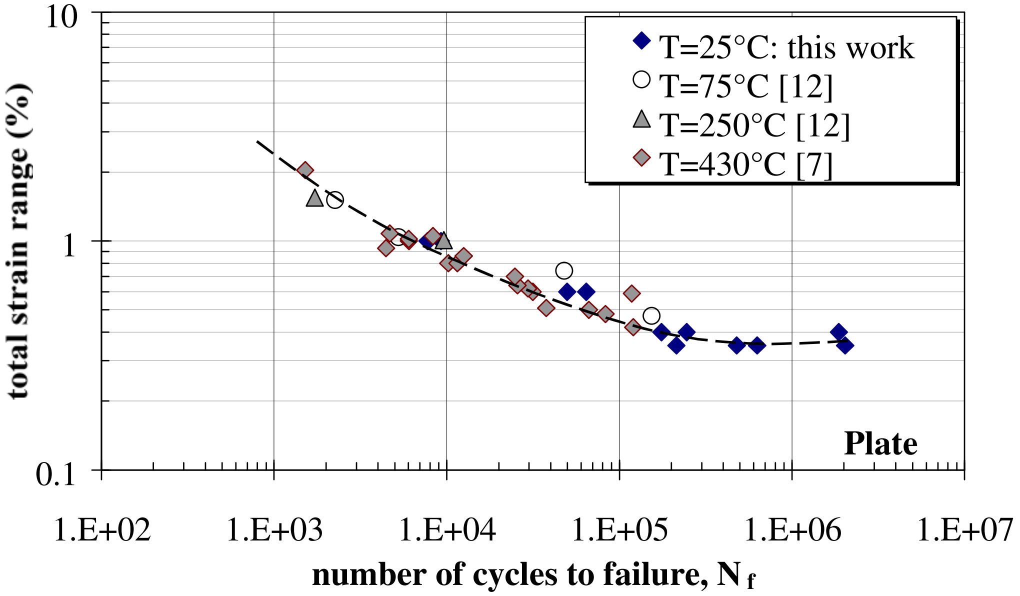

Fig. 13. Low cycle fatigue behavior of the 316L plate material. Very good agreement with literature over the temperature range [25 – 430°C].

[‡] Unbroken specimens are removed for clarity.

There are limited data on irradiated materials. This is complicated by the additional important parameters that should be taken into account, i.e., irradiation temperature, neutron flux and fluence. Therefore, in most cases, the available data for specific test temperature and irradiation conditions are not statistically representative. However, by gathering the available data in one single (ε-N)-diagram, it is very hard to clearly distinguish between the various data sets in terms of test temperature, irradiation temperature or neutron dose (Figure 14). Therefore, irradiation has little or no effect on the fatigue life of the 316L plate.

Table 5. Low cycle fatigue results. TIG weld material, T-orientation. All tests are performed at 25°C.

Id.	dose (dpa)	$\sigma_{1/4cycle}$ (MPa)	$\Delta\sigma_{1}$ (MPa)	$\Delta\sigma_{10}$ (MPa)	$\Delta\sigma_{100}$ (MPa)	$\Delta\sigma_{1000}$ (MPa)	$\Delta\sigma_{10^4}$ (MPa)	$\Delta\sigma_{10^5}$ (MPa)	$\Delta\varepsilon$ (%)	N_f
MD-1-1	0	419	900	887	817	769	--	--	1	2340
MD-1-37		441	926	923	842	800	--	--	1	2226
MD-1-43		441	949	949	867	818	--	--	1	2039
MD-1-25		379	866	855	820	761	690	--	0.6	11580
MD-1-45		396	861	849	810	746	--	--	0.6	>9700
MD-1-41		368	843	838	801	746	687	--	0.5	12553
MD-1-29		316	638	632	625	621	614	--	0.35	301970
MD-1-31		303	668	651	641	638	631	--	0.35	366950
MD-1-47		212	452	441	441	439	438	--	0.25	>1754000
MD-1-15		243	475	473	471	471	470	--	0.25	>2595000
MD-1-5		--	452	447	455	447	445	--	0.25	>2650000
A-II-1-12	4.8	543	1169	1166	1088	992	--	--	1	4206
A-II-2-14	4.8	594	1251	1222	1128	1016	--	--	1	2953
A-II-4-18	4.8	464	948	972	938	905	838	--	0.6	14035
A-III-1-22	5.4	509	1045	1029	992	940	876	--	0.6	27688
A-III-2-24	5.4	527	1053	1024	998	934	846	--	0.6	19381
A-III-3-26	5.4	317	706	741	742	731	726	--	0.45	83800
A-III-4-28	5.4	363	779	818	821	798	771	--	0.45	106631
A-III-5-30	5.4	311	628	613	615	627	625	622	0.45	>1580004

The test results obtained here are contrasting with the effects of irradiation on the tensile properties. Indeed, the flow properties of the materials were drastically affected by irradiation. As a consequence, it was expected that this would be reflected on the low cycle fatigue properties as well. However, throughout a literature review, it was found that low cycle fatigue properties are little if any affected by irradiation. The only published data showing some effect are those of Grossbeck and Liu [3], Tanaka et al [5] and Vandermeulen et al. [4] to a less extend. In all these cases, the irradiation and testing temperature is 430°C. On the other hand, no effect was found at 550°C for dose levels of 0 to 15 dpa [2,9,10,22,24]. However, the effect on the LCF life reported by [2] and [5] remains small. Note that the range of dose levels that was covered by the comparisons performed here is quite large, 0.3 to 35 dpa. As irradiation does not significantly affect the LCF behavior of 316L material, it is not surprising that test temperature would also not play a role. It should be mentioned, however, that the environmental conditions of testing could affect the LCF behavior. Indeed, as shown by Wood [22], testing in air reduces by a factor of about 5 the LCF life of 316 steel in comparison to inert gas environment.

Table 6. Low cycle fatigue results. TIG weld material, L-orientation. All tests are performed at 25°C.

Id	dose (dpa)	$\sigma_{1/4cycle}$ (MPa)	$\Delta\sigma_1$ (MPa)	$\Delta\sigma_{10}$ (MPa)	$\Delta\sigma_{100}$ (MPa)	$\Delta\sigma_{1000}$ (MPa)	$\Delta\sigma_{10^4}$ (MPa)	$\Delta\sigma_{10^5}$ (MPa)	$\Delta\varepsilon$ (%)	N_f
MD-2-11	0	412	853	842	808	796	--	--	1	1426
MD-2-27		421	870	830	767	725	--	--	1	2414
MD-2-29		488	1010	990	925	889	--	--	1	2100
MD-2-33		424	885	911	870	819	--	--	0.6	4400
MD-2-47		363	736	756	775	706	683	--	0.6	42082
MD-2-1		394	771	769	760	705	663	--	0.6	38980
MD-2-50		290	598	632	634	628	614	--	0.45	99167
MD-2-3		300	609	668	675	671	660	--	0.45	77727
MD-2-13		249	488	523	530	526	537	519	0.35	>1009995
MD-2-19		254	492	513	515	514	519	512	0.35	>1745042
C-III-1-28	5.4	644	1283	1185	1110	1004	--	--	1	3608
C-II-1-14	5.2	668	1322	1237	1148	1051	--	--	1	3194
C-II-5-26	5.2	508	1082	1076	1036	961	857	--	0.6	15302
C-III-5-12	5.4	544	1130	1116	1075	983	--	--	0.6	8865
C-II-3-18	5.2	459	1004	1034	998	876	640	--	0.6	12262
C-II-4-24	5.2	603	1222	1183	1141	1045	945	--	0.6	35435
C-III-2-32	5.4	400	821	821	820	806	781	756	0.45	152066
C-II-2-16	5.2	414	829	841	840	825	801	--	0.45	69063
C-III-4-36	5.4	259	534	534	533	532	533	532	0.45	>1560028

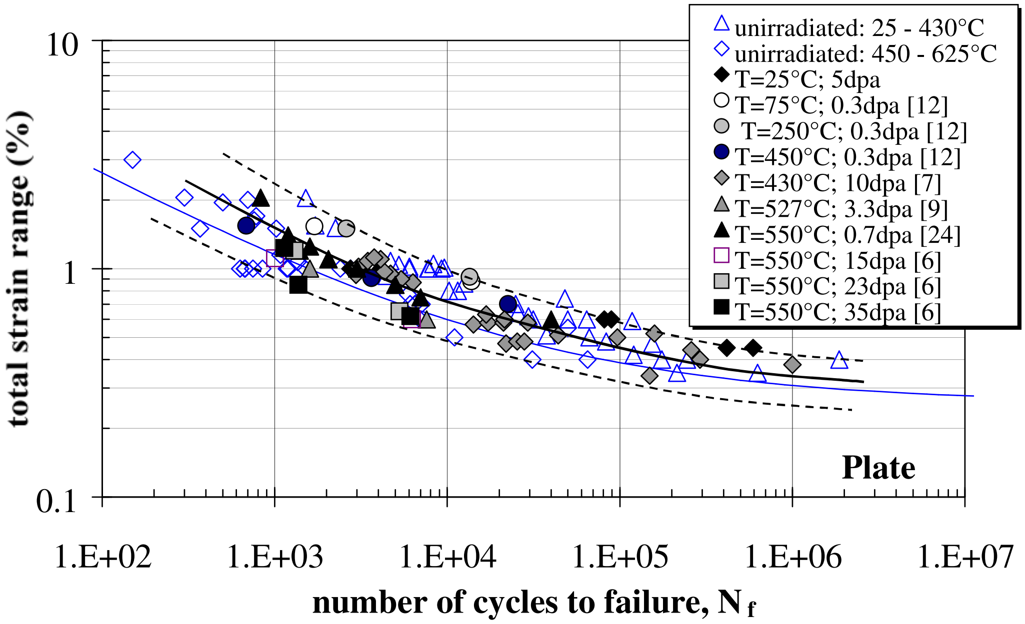

Fig. 14[‡]. Irradiation effects on the low cycle fatigue behavior of the 316L plate material.

[‡] Unbroken specimens are removed for clarity.

Comparison to data on 316L TIG weld material found in literature are reproduced in Figure 15 which clearly indicate a very good agreement despite the various irradiation and testing conditions. This is also consistent with the comparison made on the plate material. A very good agreement is found with the Langer equation curve proposed by Tavassoli [23] except at high strain ranges, where the experimental data are scarce.

At this stage, it is interesting to compare the unirradiated to the irradiated condition by considering the stress-strain behavior. In the unirradiated condition, the stress increases slowly during the first 20 to 30 cycles followed by a gradual decrease until fracture occurs. In the irradiated condition, up to a strain range of 0.45 %, the stress does not vary much. At higher strain ranges (>0.5%), the stress decreases continuously, the decrease rate increasing with the applied strain. The (σ-ε) diagram shows that, before irradiation, the evolution of the stress in the material is nearly the same at all strain ranges. On the other hand, in the irradiated condition, the fatigue process tends to recover the hardening induced by irradiation resulting in a softening of the material. Figure 16 shows the evolution of the hysteresis stress-strain loop of irradiated TIG weld sample under an applied strain of 1% with the number of cycles. In Figure 17, the (σ, ε) curve evolution is shown for two different stages of the fatigue life, N=1 and 1000 respectively. It can be seen that the higher the applied strain range, the larger the softening of the irradiated plate material. Similar behavior is found with the TIG weld material.

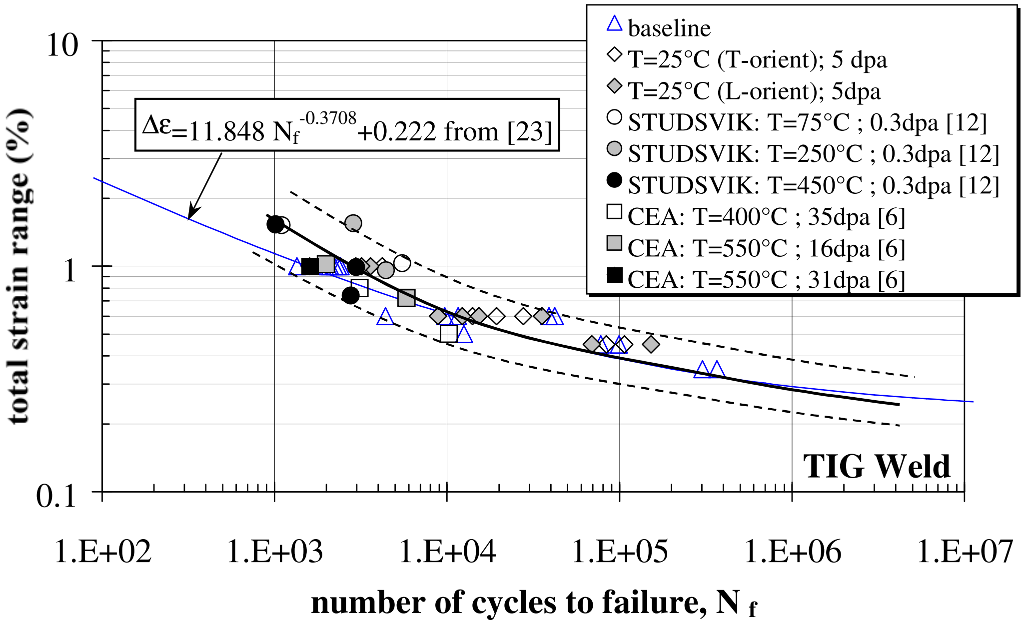

Fig. 15[‡]. Comparison of low cycle fatigue data of TIG metal deposit with literature. Good agreement is found despite the various irradiation and testing conditions.

[‡] Unbroken specimens are removed for clarity.

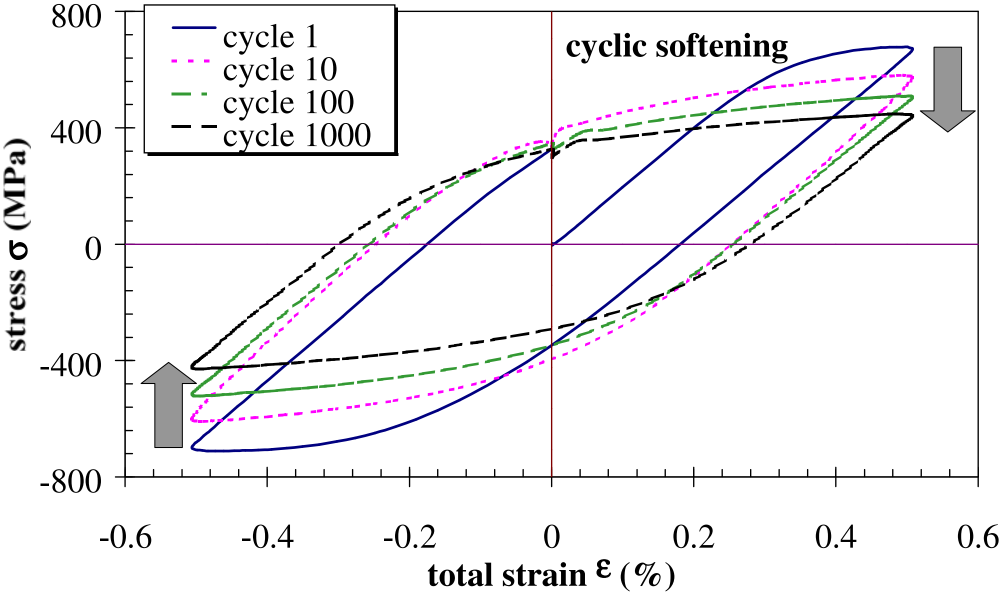

Fig. 16. Evolution of the hysteresis loop during the fatigue test under strain control. Irradiated specimen tested with a strain range of 1% exhibiting cyclic softening.

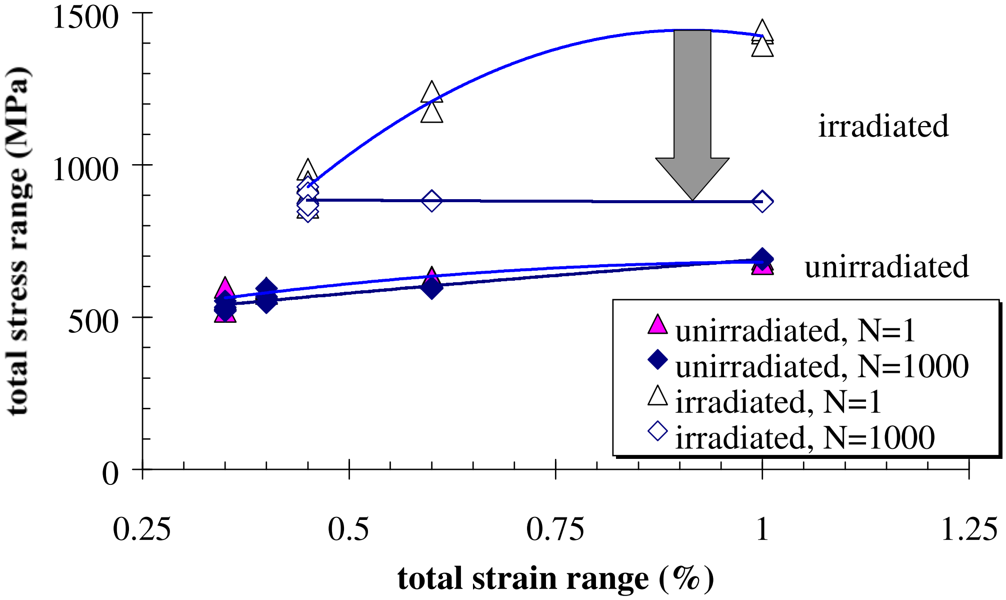

Fig. 17. Effect of irradiation on the total stress range Δσ (MPa) versus total strain range Δε (%) at N=1 and N=1000.

Finally, as the unirradiated and irradiated materials exhibit very different flow properties, it is interesting to examine how the applied total strain is distributed in terms of elastic versus plastic strain. Most of comparative illustrations on the irradiation effects on the LCF properties are based on the total applied strain. Figures 18 and 19 show the various strain components as a function of the number of cycles to rupture for the unirradiated and irradiated plate materials, respectively. Comparison of these figures indicates that part of the plastic strain component in the unirradiated condition is transformed into an elastic strain upon irradiation. Figure 20 shows the plastic component of the strain as a function of the number of cycles to rupture for both unirradiated and irradiated plate material. While all unirradiated samples were loaded in the plastic regime, only irradiated samples loaded to 1% total strain exhibit measurable plastic deformation. However, it is difficult to extract the irradiation effect alone from such an analysis as far as the effect of cyclic plastic strain on crack initiation and the effect of irradiation crack growth rate are unknown [7].

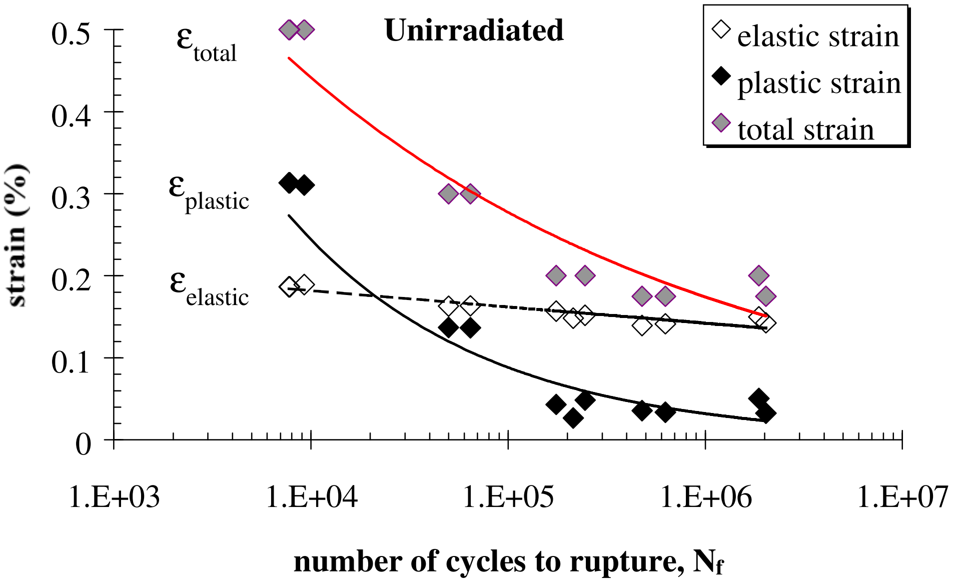

Fig. 18. Elastic versus plastic strain distribution in the unirradiated specimens.

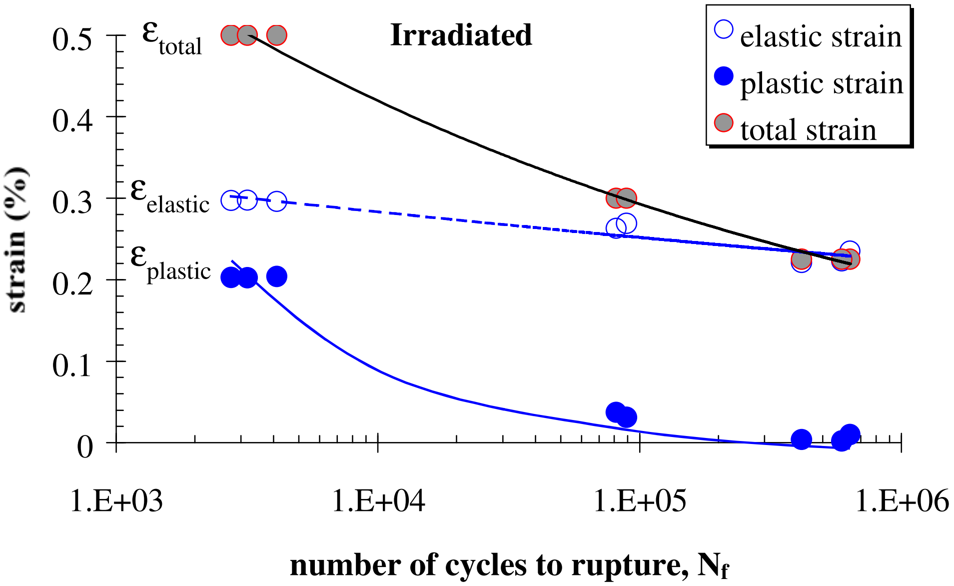

Fig. 19. Elastic versus plastic strain distribution in the irradiated specimens.

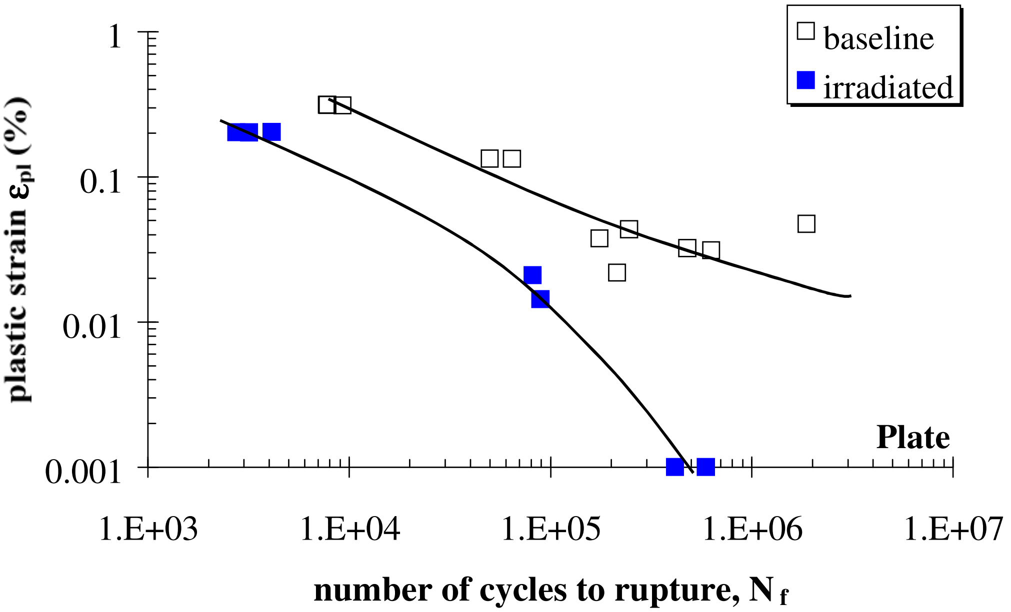

Fig. 20. Plastic strain versus number of cycles to rupture for the 316L plate material.

4 CONCLUSIONS

Tensile and low cycle fatigue properties of type 316L austenitic stainless steel (plate and TIG-metal deposit weld) were investigated in the baseline and irradiated condition (dose=5dpa, $T_{irradiation}$=42°C). The main results obtained are:

- No major difference was found on the flow properties in the three orientations, L, S and T.
- The tensile test data were found in very good agreement with literature on similar plate and weld materials.
- Neutron irradiation induces a substantial hardening and loss of ductility but without reduction of fatigue life of both plate and weld materials.
- Comparison to literature data on similar materials shows that the effect of test temperature on LCF is also very small up to about 430°C; above this temperature, oxidation effects may reduce (slightly) the fatigue life.
- For unirradiated materials, the stress range remains almost unchanged independent from the applied strain range.
- By contrast, in the irradiated condition, a cyclic softening is observed which increases with the applied strain. In other words, the stress component of the inelastic deformation tends to vanish.
- No major difference is found between plate and weld behavior except that the TIG weld exhibit larger initial stresses than the plate and the LCF properties are slightly better for the plate.
- An overall comparison of LCF data over a wide range of irradiation conditions (irradiation temperature and fluence) and test temperatures shows no or little effect on the LCF properties of 316L steel.

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