TENSILE PROPERTIES OF LOW ACTIVATION FERRITIC STEELS FOLLOWING IRRADIATION IN ORR - M. L. Hamilton, and D. S. Gelles (Pacific Northwest National Laboratory)

OBJECTIVE

The objective of this effort is to determine irradiation hardening response in low activation ferritic steels following irradiation at temperatures below 400°C in order to better understanding behavior in this alloy class at low irradiation temperatures.

SUMMARY

Post-irradiation tensile test results are reported for a series of low activation steels containing Mn following irradiation in the Oak Ridge Reactor at 60, 200, 330 and 400°C to 10 dpa. Alloy compositions included 2Cr, 9Cr and 12Cr steels with V to 1.5% and W to 1.0%.

Strength increases were higher in all alloys for irradiation conditions below 400°C, with peak hardening occurring following irradiation at 200°C, corresponding to a minimum of 4% total elongation. The 9Cr alloy class exhibited the smallest increases in hardening. Test results are provided and compared with behavior following irradiation in FFTF.

PROGRESS AND STATUS

Introduction

Post-irradiation tensile test response has been reported for a series of alloys containing manganese following irradiation in FFTF at 420 and 585°C to 15 and 45 dpa.[1] That work investigated the response of a series of alloys including 2% Cr alloys with V additions, and 9% and 12% Cr alloys containing Mn with V and W additions. It was found that irradiation at 420°C to 15 dpa produced significant hardening in the 2Cr alloys whereas the other alloys where unaffected, and irradiation at 585°C produced softening for all alloys. Further irradiation to 45 dpa resulted either in little change or in softening. Similar specimens irradiated in ORR at 60, 200, 330 and 400°C to 10 dpa were recently retrieved; the tensile data obtained from these specimens are documented in this report.

Experimental Procedure

Compositions and identification codes for specimens irradiated in the ORR-MFE 6J and 7J tests are provided in Table 1. Specimens were of SS-3 flat tensile geometry, with nominal gauge dimensions of 0.3" x 0.030" x 0.060" (7.62 mm x 0.76 mm x 1.5 mm). Tests were performed at both room temperature and the nominal irradiation temperatures. The initial strain rate was 4×10^{-4} /sec. The 6J test accumulated a midplane fluence of 2.4×10^{22} n/cm^2 (total) or 8.8×10^{21} n/cm^2 (E>0.1 MeV) and the 7J test accumulated a fluence of 2.7×10^{22} n/cm^2 (total) or 9.5×10^{21} n/cm^2 (E>0.1 MeV).[2,3] This corresponds to damage levels of 6.6 - 6.8 and 7.1 - 7.3 dpa respectively, variations corresponding to lower or higher chromium levels. Predicted helium levels are 2.1 to 2.3 for both tests, with variations due to higher or lower chromium levels, respectively.

Table 1. Compositions and identification codes for specimens irradiated in the ORR-MFE 6J and 7J tests.[1]

ID code	Heat # or alloy name	Composition (w/o)								
		Cr	V	W	Ta	Mo	C	Mn	Nb	Ni
TE	V02262	2.25	0.5				0.1			
TZ	UC-19	2.25	1.5			0.2	0.1	0.3		
TH	V02263	2.25	1.0				0.1			
	2.25Cr1Mo	2.25	0.03			1.0	0.1	0.5		
TR	V02268	9	0.3	1.0			0.1	2.5		
TM	V02264	9	0.5				0.1			
TP	V02266	9	0.5				0.1	2.0		
TN	V02265	9	1.3				0.2	1.0		
	9Cr1Mo	8.75	0.2			0.9	0.1	0.5	0.08	
TT	V02702	12	0.2	0.8			0.1	6.5		
TU	V02269	12	0.3	1.0			0.1	6.5		
TW	V02754	12	0.3	1.0	0.2		0.1	6.5		
TL	V02267	12	1.0				0.1	6.5		
TF	V02700	12	1.0				0.1	6.5		
TX	V02755	12	1.0	0.2	0.2		0.1	8.0		
	HT9	12	0.3	0.5		1.0	0.2	0.6		0.5

Results

The tensile results are given in Table 2 and plotted in Figures 1 - 8. Significant hardening and loss of ductility were observed at room temperature in all three alloy classes for irradiation at 330°C and below. Similar trends were observed in tests conducted at the irradiation temperature, although the results are less well-defined because of the paucity of data on unirradiated material.

Discussion

Tensile data obtained on FFTF-irradiated specimens were comparable to the data obtained for specimens irradiated in ORR under similar conditions. These results were obtained for all materials where such a comparison was possible, for specimens irradiated at about 400°C to 10 dpa and tested at room temperature. Such a comparison was not possible for all of the alloys. Yield and ultimate strengths, and uniform and total elongations, were essentially the same as the comparable data provided in reference 1 for two of the 2Cr alloys (TE [V02262] and TZ[UC-19]), four of the 9Cr alloys (TN[V02265], TR[V02268], TP[V02266] and TM[V02264]), and a single 12Cr alloy (TU[V02269]).[1] The 9Cr alloys exhibit the most stable properties, and significant hardening can occur following irradiation at low temperatures. The ORR database indicates that property degradation is worst following irradiation at 200°C, but irradiation at 60°C produces similar behavior for the 12Cr alloys. However, it can be anticipated that irradiation to higher dose at 60°C can be expected to

degrade properties further,[4] and therefore it appears worthwhile to continue this work by testing identical specimens from ORR that were further irradiated in HFIR.

Table 2. Tensile results on low activation steel specimens following irradiation in ORR.

ID	Dose (dpa)	Thick-ness (mils)	Width (mils)	Irr Temp (C)	Test Temp (C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Comments*
TE22	0	28.74	51.65	0	22	791	886	4.6	13	
TE23	0	29.49	53.33	0	22	769	870	3.4	11.5	Rusty
TE17	10	29.24	53.49	200	22	1315	1345	0.6	4	RP, some rust
TE11	10	29.97	49.99	330	22	1367	1412	0.8	5.8	RP, small P
TE13	10	29.26	51.80	400	22	1198	1230	0.8	6.9	RP?, rusty
TF11	10	28.47	53.66	330	22	954	997	1.4	8.1	Rusty
TF15	10	28.52	52.30	400	22	828	912	3.8	10.4	
TF12	10	27.66	53.81	330	330	787	832	1.2	6	Semi RP, rusty
TF16	10	28.49	55.67	400	400	665	728	1.6	6.7	Rusty
TH09	0	29.02	59.87	0	22	328	532	14.4	28.7	Large bow
TH10	0	29.29	59.16	0	22	345	538	11.9	24.2	Slight bow
TL25	0	29.32	58.70	0	22	761	911	3.2	11.1	P
TL16	10	29.26	57.29	60	22	1073	1114	0.7	5.4	RP, some rust
TL19	10	29.07	56.54	200	22	1203	1255	1	6.8	RP, some rust
TL11	10	29.52	59.47	330	22	970	1004	3	10.8	P
TL13	10	29.34	59.79	400	22	719	846	7.1	15.3	Small P, rusty
TL17	10	29.99	59.61	60	60	1012	1053	0.8	6.5	RP, some rust
TL20	10	28.87	59.47	200	200	1072	1141	1	6.1	RP, some rust
TM25	0	28.89	55.67	0	22	565	646	4.3	15.4	P
TM19	10.4	28.99	61.31	200	22	918	920	0.2	9	RP, some rust
TM11	10.4	29.37	61.88	330	22	879	883	0.3	9.6	RP
TM13	10.4	29.22	62.53	400	22	584	640	3.5	15.4	Rusty
TM26	0	28.89	55.40	0	200	512	566	1.9	12.4	RP
TM22	10	28.79	55.09	200	200	845	851	0.2	9.2	RP, rusty
TN09	0	29.54	60.49	0	22	538	665	7.2	18.7	P
TN10	0	29.02	60.31	0	22	559	688	6.8	17.4	P
TN19	10.2	28.96	59.16	200	22	998	1005	0.4	7.8	RP, rusty
TN11	10.2	29.41	59.11	330	22	917	933	0.6	8.9	RP, rusty
TN13	10.2	29.76	62.22	400	22	504	618	7.4	20.1	P, rusty

ID	Dose (dpa)	Thick-ness (mils)	Width (mils)	Irr Temp (C)	Test Temp (C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Comments*
TP16	10	28.21	62.62	60	22	899	901	0.3	5.5	RP, rusty
TP19	10	29.44	63.03	200	22	1021	1030	0.4	7.5	RP, rusty
TP11	10	29.37	63.00	330	22	960	971	0.5	8.1	RP, some rust
TP13	10	29.29	62.88	400	22	565	643	5.1	17.8	P, rusty
TP17	10	29.39	62.88	60	60	770	773	0.3	5.1	RP, rusty, odd test
TP25	0	31.60	57.88	0	200	500	580	3.8	15.8	Small P
TP20	10	29.31	58.46	200	200	862	902	0.6	9.3	RP, rusty
TR10	9.8	28.82	59.84	200	22	1012	1030	0.5	8.7	RP
TR11	9.8	29.57	52.13	330	22	885	893	0.4	8.4	RP, some rust
TR15	9.8	29.76	54.98	400	22	576	673	6.2	16.6	P
TR22	10	29.07	58.03	200	200	909	918	0.4	9.2	RP
TR12	10	29.29	54.78	330	330	731	736	0.3	8.3	RP, rusty
TR08	0	29.79	59.94	0	400	443	518	2.6	12.8	Small P
TR16	10	29.52	53.91	400	400	468	520	2.1	11	RP, some rust
TT11	10	29.02	57.09	330	22	1016	1073	2.7	10.8	P, some rust
TT15	10	28.76	59.41	400	22	833	938	4.1	10.8	Rusty
TT12	10	28.56	58.14	330	330	828	890	1.3	6.3	Some rust
TT16	10	28.91	59.20	400	400	760	817	1.5	7.7	RP, some rust
TU07	10	28.47	60.22	60	22	1132	1174	0.7	7	RP, rusty
TU10	10	28.96	60.29	200	22	1189	1263	0.8	6.7	RP, some rust
TU11	10	30.02	59.57	330	22	1009	1066	1.4	7.8	Small P, rusty
TU15	10	29.77	59.15	400	22	755	888	5	10.2	Some rust
TU19	10	30.02	60.01	60	60	1010	1067	0.7	7	RP, rusty
TU22	10	28.91	53.84	200	200	1123	1204	1.1	4.2	Small P, some rust
TU12	10	30.09	55.35	330	330	846	912	1.7	6.5	Small P?, rusty
TU16	10	30.22	60.96	400	400	597	678	3	9.6	Small P, some rust
TW11	10	29.62	61.19	60	22	1100	1161	0.8	7.6	RP, rusty
TW14	10	29.05	61.12	200	22	1265	1304	0.8	7.3	RP, some rust
TW13	10	29.07	60.32	60	60	1099	1158	0.8	9.6	RP, rusty
TW15	10	28.79	60.54	200	200	1105	1170	1	6.5	RP, some rust

ID	Dose (dpa)	Thick-ness (mils)	Width (mils)	Irr Temp (C)	Test Temp (C)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)	Comments*
TX12	10	31.30	58.78	60	22	1108	1138	0.5	4.9	RP, some rust
TX14	10	28.72	61.62	60	22	1235	1280	0.6	8.1	RP, rusty
TX15	10	29.15	58.20	200	22	1311	1377	0.9	7.7	RP, some rust
TX13	10	29.39	60.39	60	60	1139	1218	0.8	5.9	RP, rusty
TZ22	10	28.92	56.70	200	22	826	826	0	0	Failed without yielding; yield given as maximum/failure strength
TZ11	10	29.49	56.62	340	22	1014	1014	0	0	Failed without yielding; yield given as maximum/failure strength
TZ15	10	25.39	57.02	400	22	661	700	1.4	8.6	RP, rusty
TZ10	0	28.69	61.07	0	330	240	370	9.2	17.4	P
TZ12	10	26.36	56.29	330	330	872	875	0.4	5.1	RP
TZ25	0	28.27	56.79	0	400	334	437	4.5	13.6	
TZ16	10	28.67	56.87	400	400	598	612	0.4	6.3	RP

*The comment RP indicates that the specimen reached a peak load quite rapidly, with little work hardening. The comment P indicates that the load trace exhibited a load plateau at maximum load.

It has been noted that the alloy series being studied in this effort contains manganese additions for austenite stabilization, and that manganese additions are now understood to cause chi phase formation during irradiation in the vicinity of 400°C,[5] leading to embrittlement as evidenced by an increase in the DBTT.[6] It was therefore expected that the hardening observed in the 9 and 12Cr alloys at 330°C and below would also be due to precipitation of chi phase. Further evaluation of the results in Table 2 (see Figure 9), however, shows that no direct correlation exists between irradiation hardening and Mn content and the hardening observed at 330°C and below must be due to something other than chi phase formation. It must also be concluded that the correlation of DBTT with Mn content is due to the effect of chi phase on toughness per se rather than hardening.

CONCLUSIONS

ORR and FFTF irradiation under comparable conditions (400°C, to ~10 dpa) appear to produce similar changes in tensile behavior for a series of low activation alloys containing Mn additions. Significant hardening and loss of ductility resulted from irradiation at

temperatures ranging from 60 to 330°C. The hardening cannot be attributed directly to Mn additions, indicating that chi phase does not cause the hardening. The cause of the observed hardening is not yet understood.

FUTURE WORK

Companion TEM specimens will be shear punch tested and examined by TEM using 1 mm specimen preparation techniques. Effort is then expected to shift to acquisition and testing of the ORR specimens further irradiated in HFIR.

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4. W. L. Hu and D. S. Gelles, Influence of Radiation on Material Properties: 13th International Symposium, ASTM STP-956 (1987) 83.

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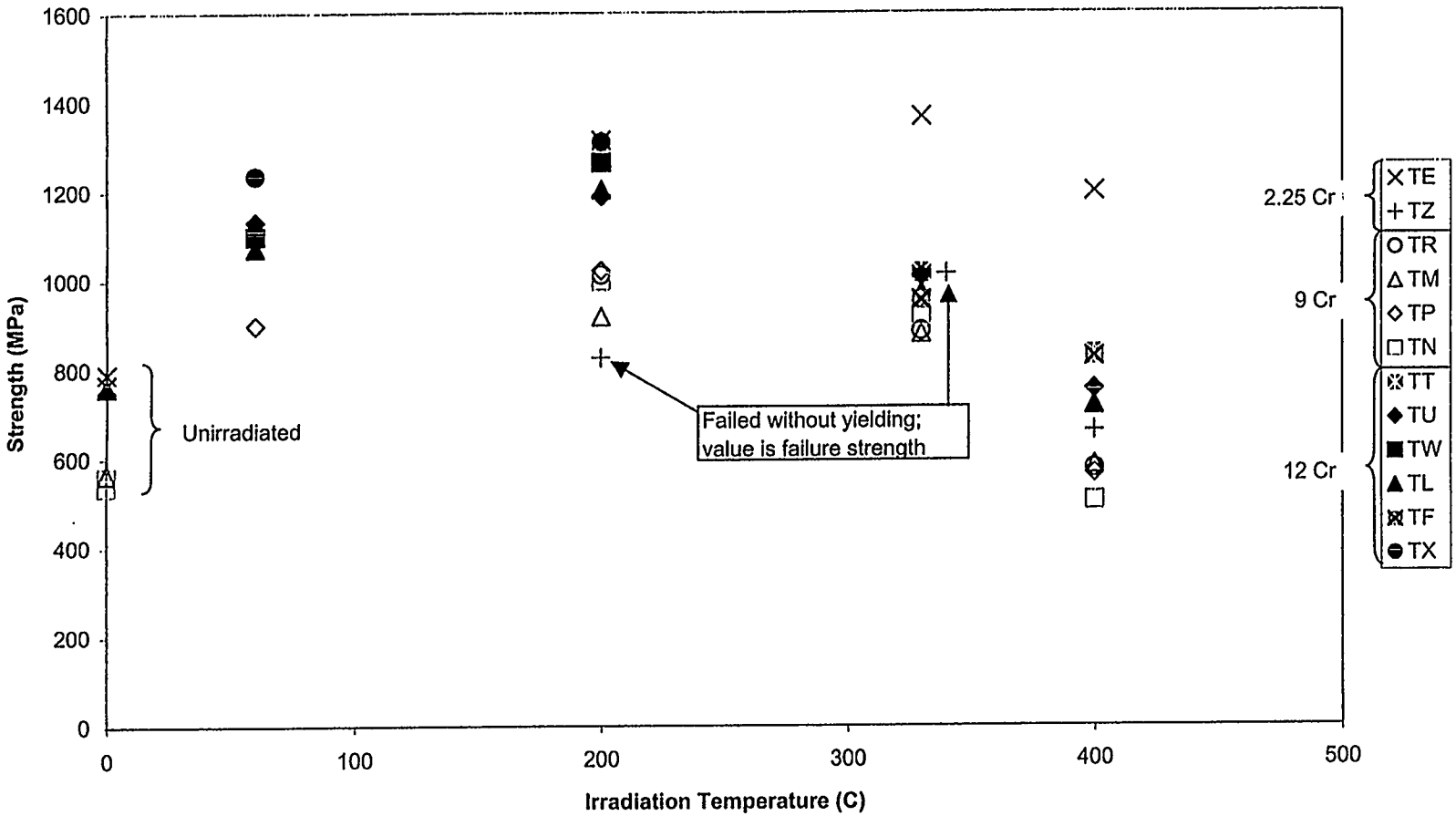
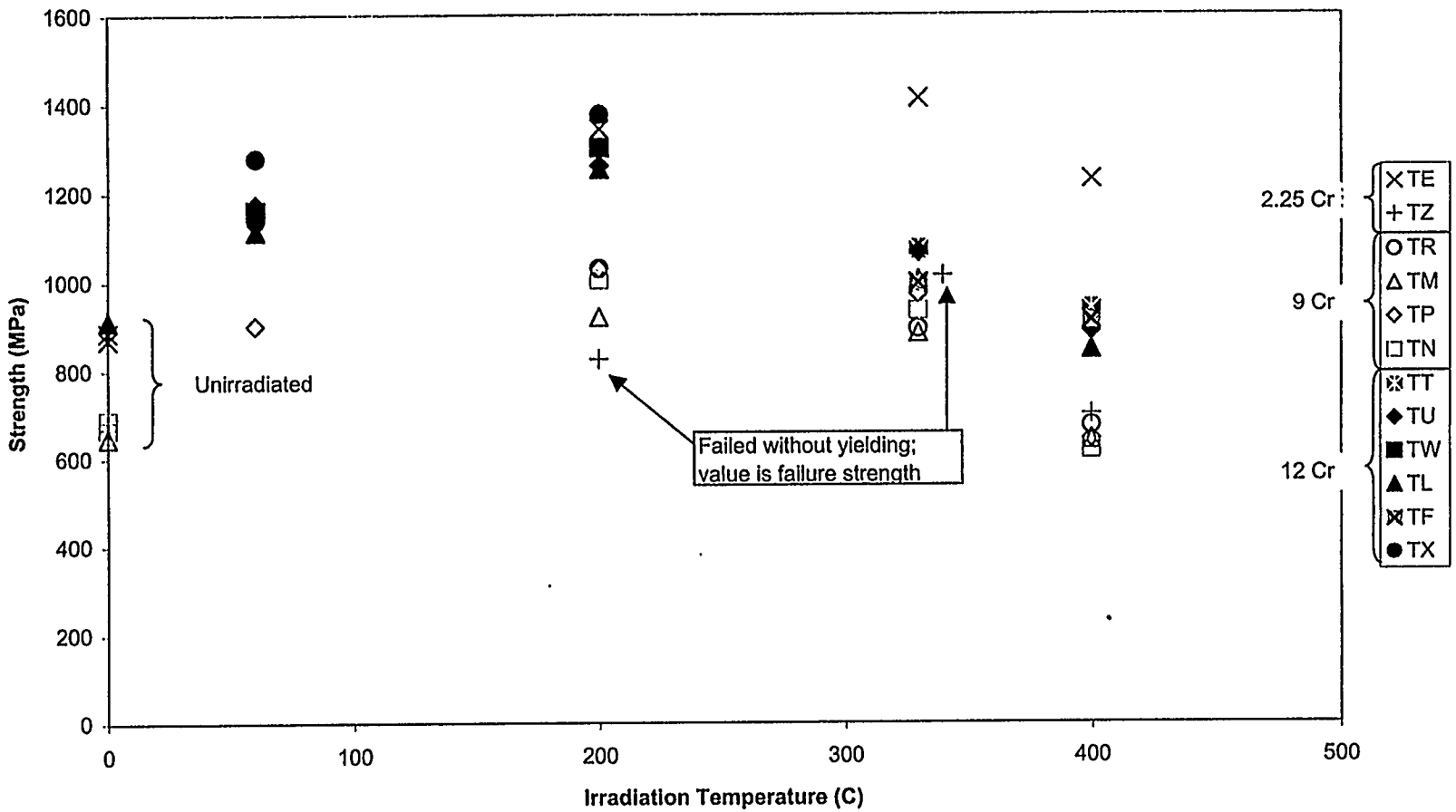
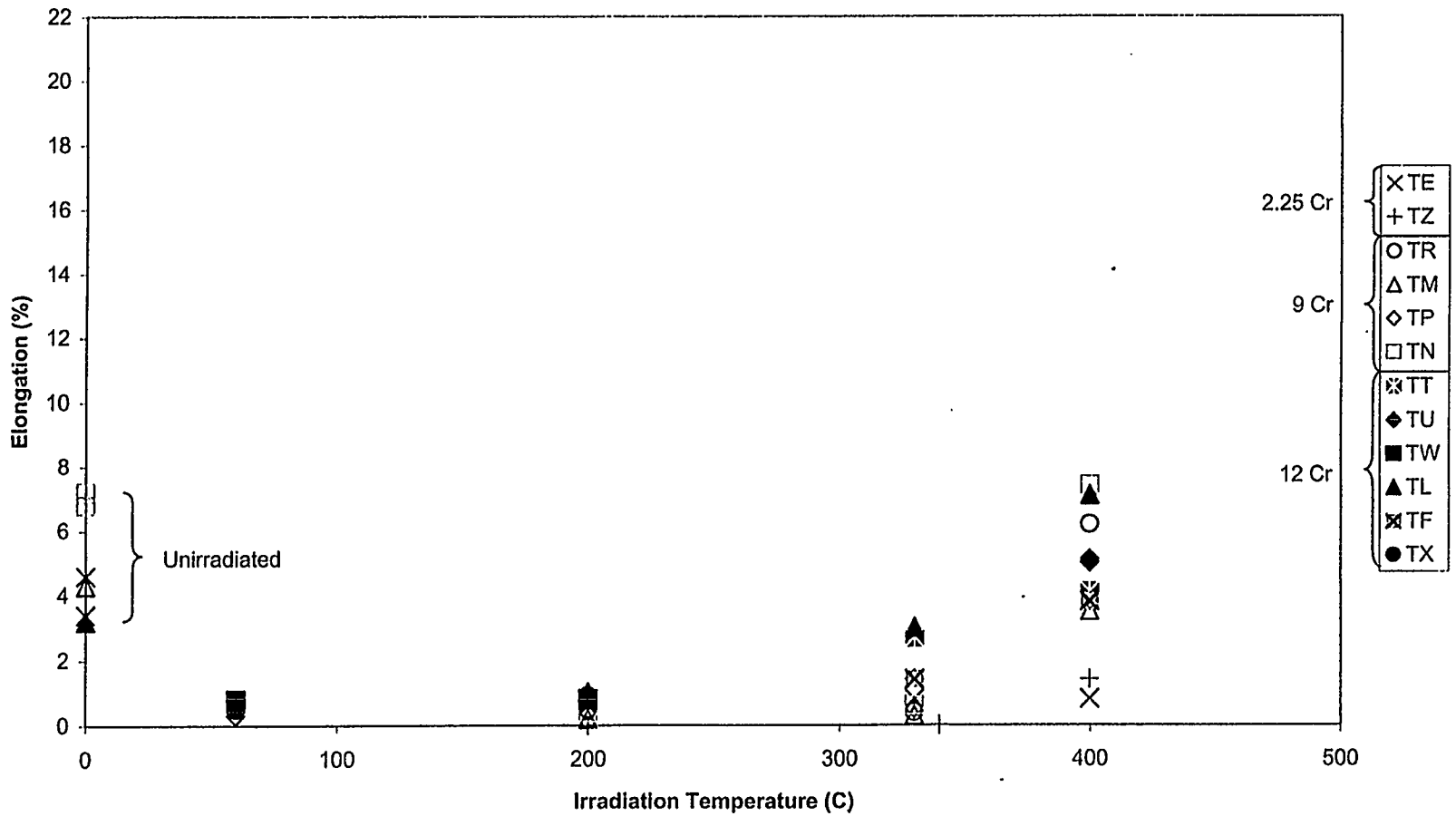


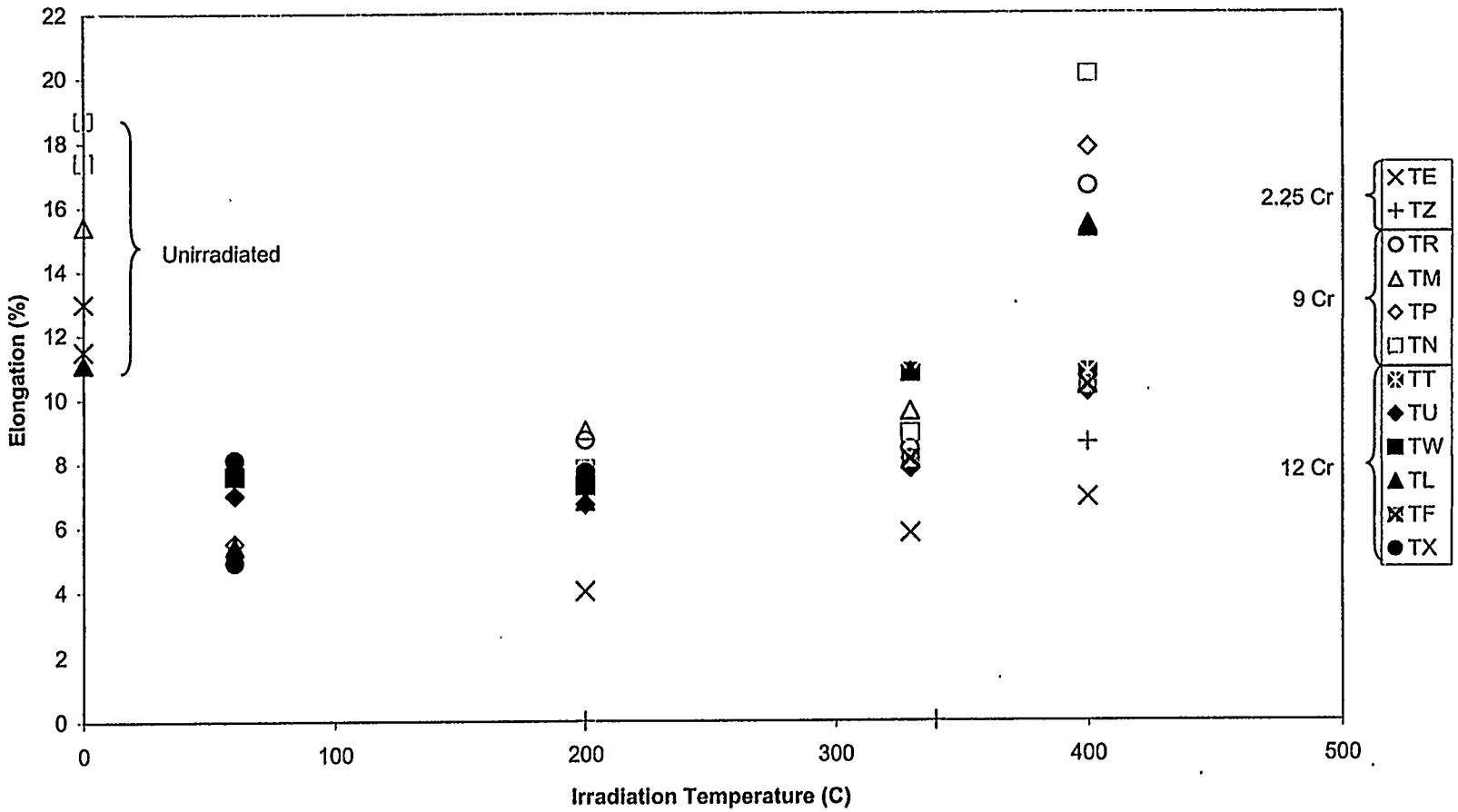
1. Yield strength of low activation alloys at room temperature after irradiation in ORR.



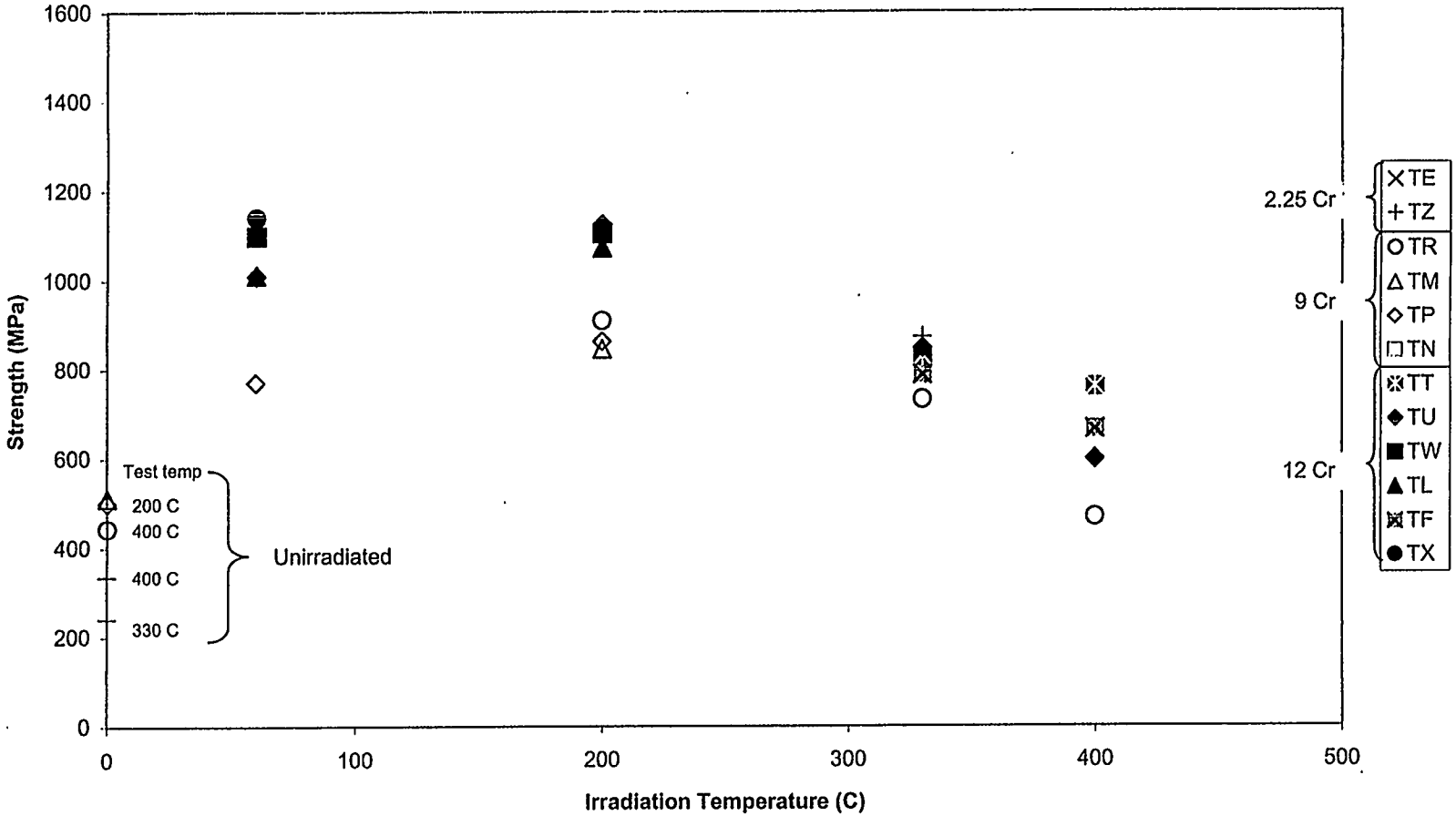
2. Maximum strength of low activation alloys at room temperature after irradiation in ORR.



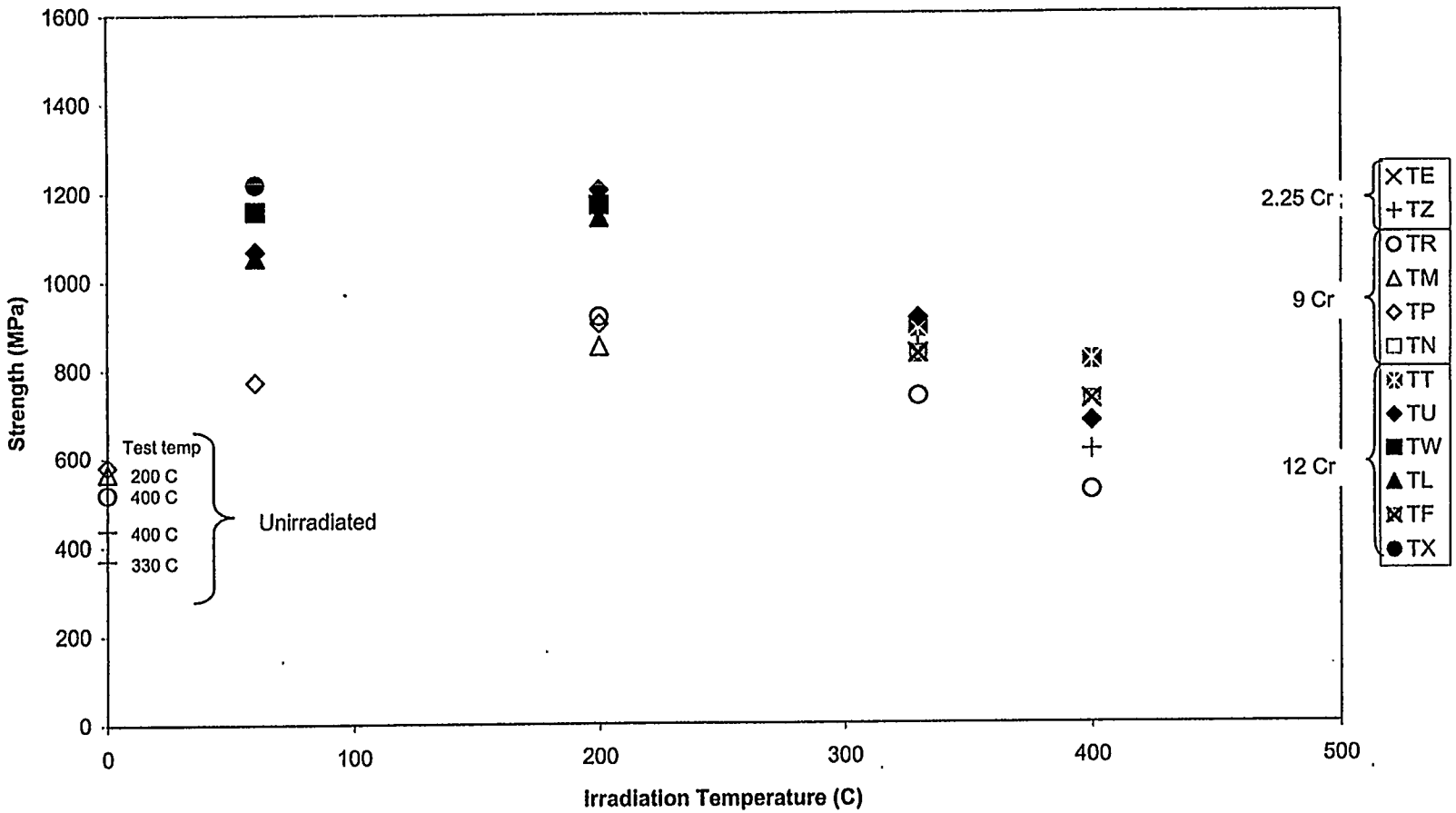
3. Uniform elongation of low activation alloys at room temperature after irradiation in ORR.



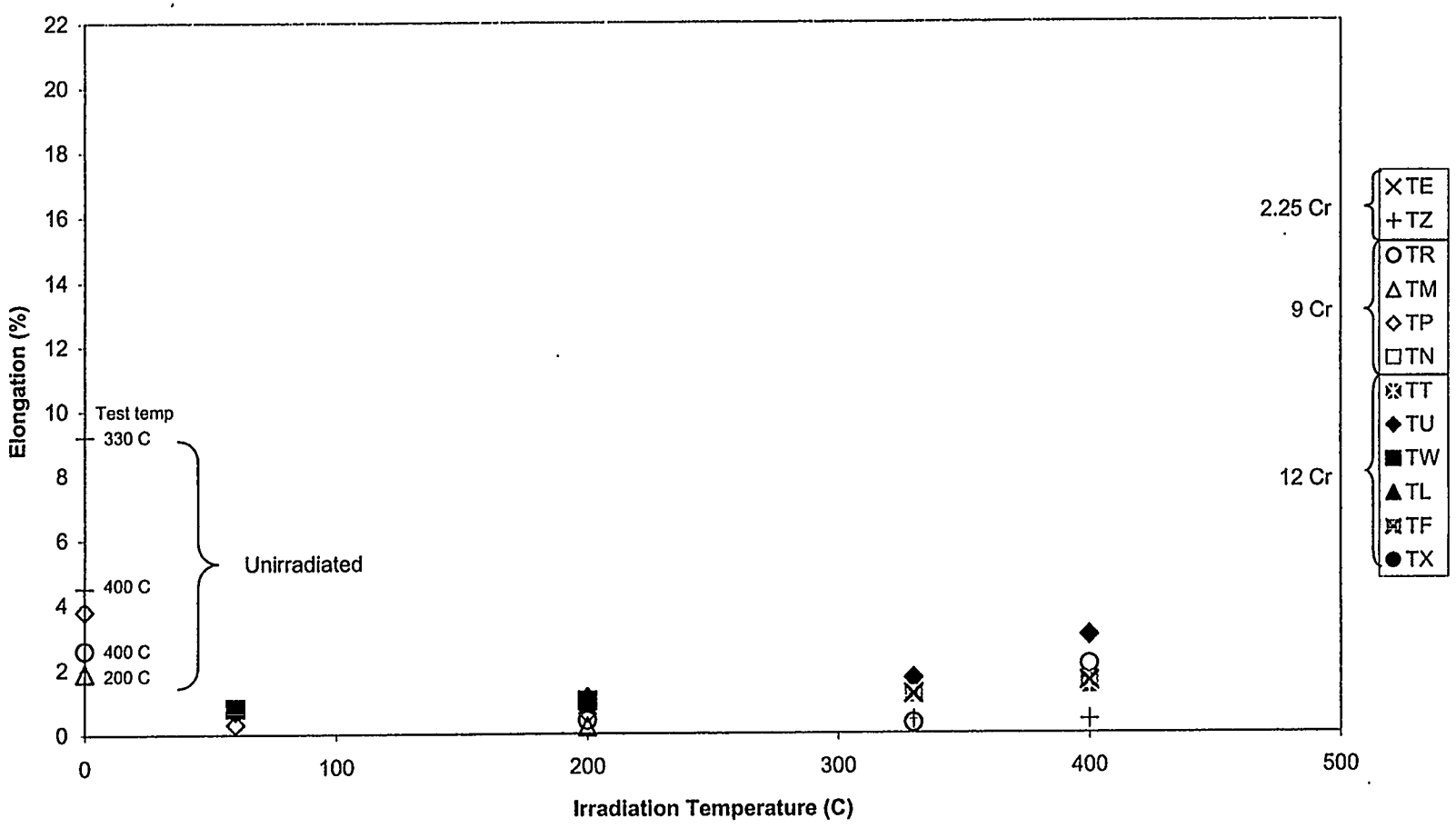
4. Total elongation of low activation alloys at room temperature after irradiation in ORR.



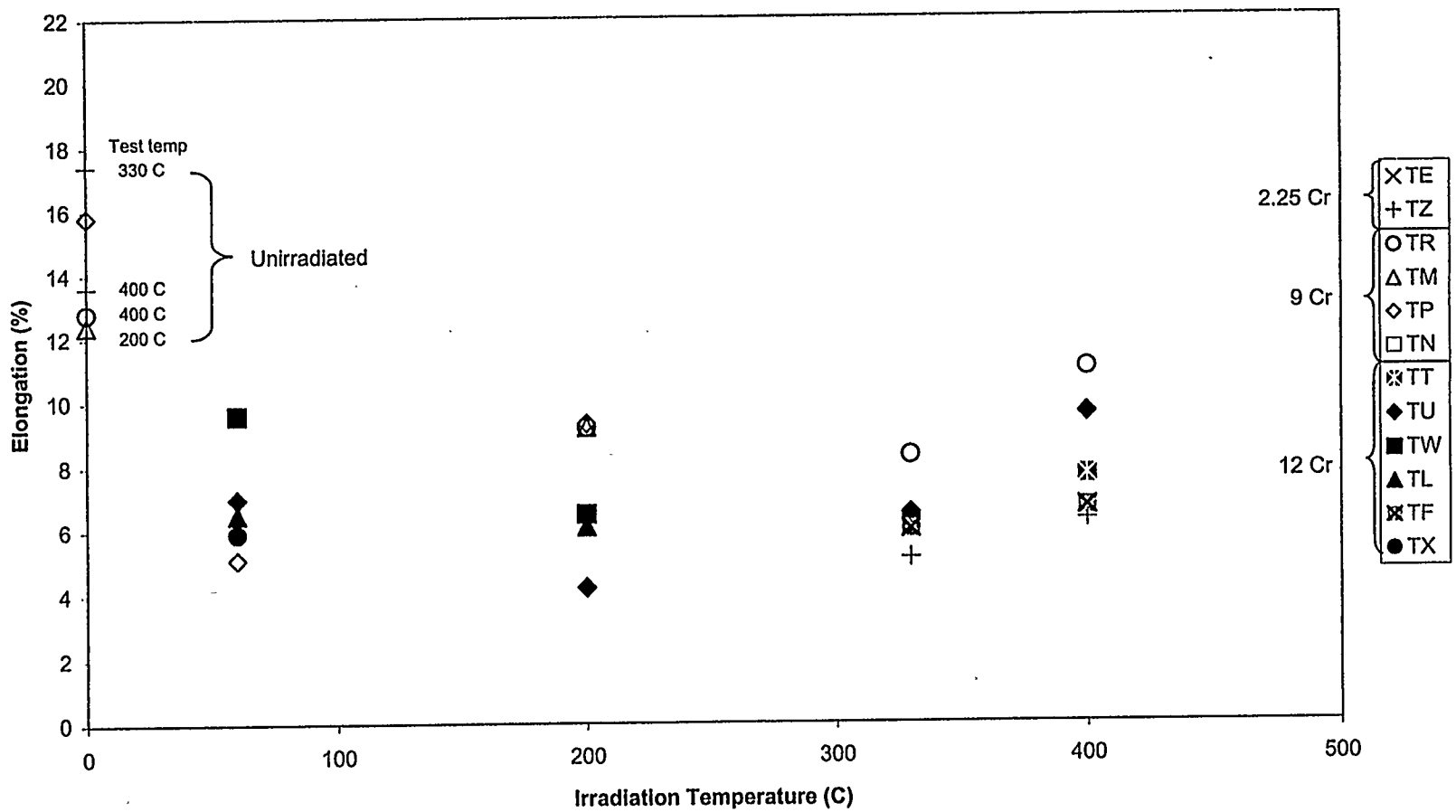
5. Yield strength of low activation alloys at the irradiation temperature after irradiation in ORR.



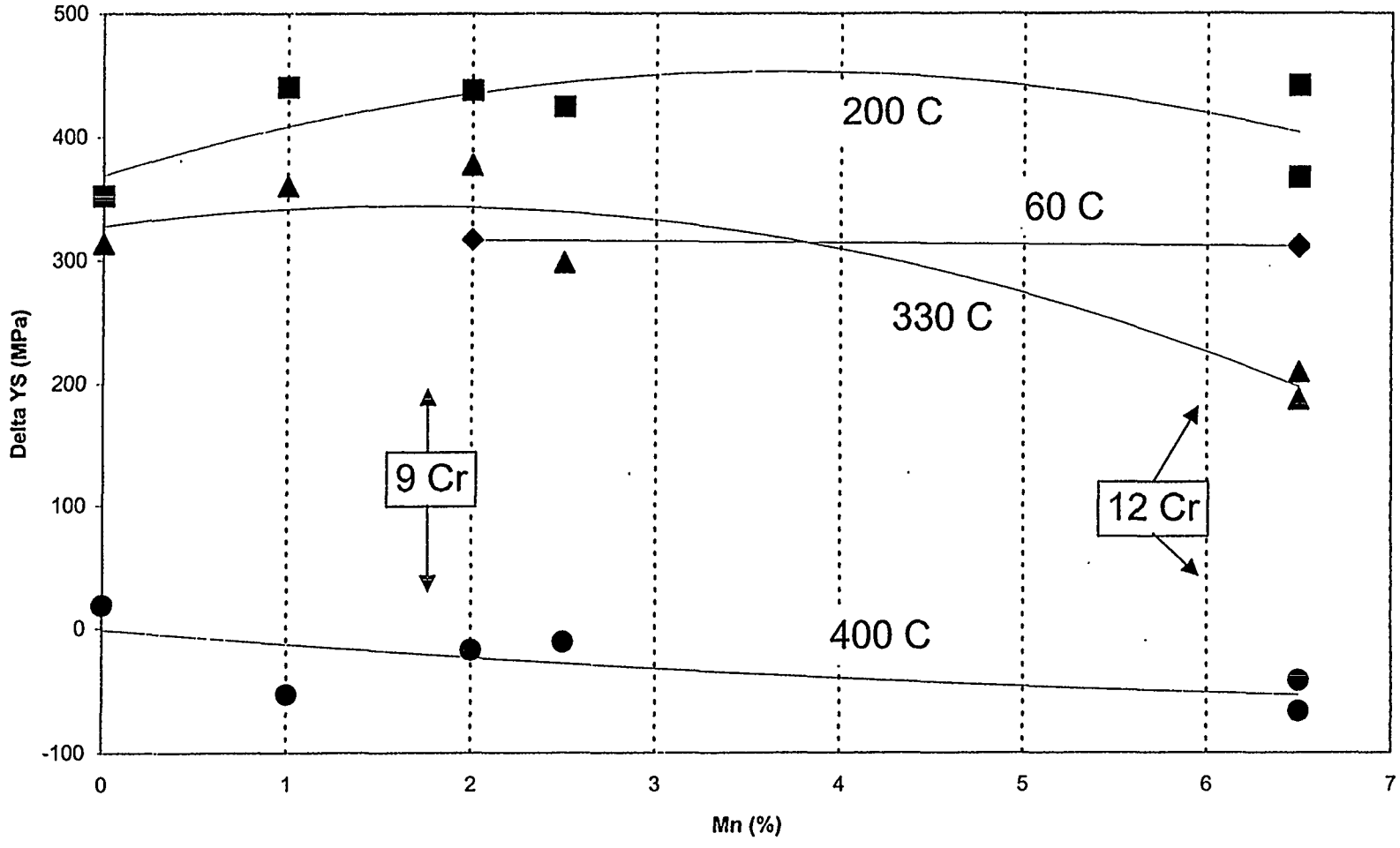
6. Maximum strength of low activation alloys at the irradiation temperature after irradiation in ORR.



7. Uniform elongation of low activation alloys at the irradiation temperature after irradiation in ORR.



8. Total elongation of low activation alloys at the irradiation temperature after irradiation in ORR.



9. Effect of Mn on hardening observed in low activation alloys at room temperature after irradiation in ORR.