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EUROPEAN DEVELOPMENT OF FERRITIC-MARTENSITIC STEELS FOR FAST REACTOR WRAPPER APPLICATIONS

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European Development of Ferritic-Martensitic Steels for Fast Reactor Wrapper Applications

by

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Abstract

9-12%Cr ferritic-martensitic stainless steels are under development in Europe for fast reactor sub-assembly wrapper applications. Within this class of alloys, attention is focussed on three key specifications, viz. FV448 and DIN 1.4914 (both 10-12%CrMoVNb steels) and EM10 (an 8-10%Cr-0.15%C steel), which can be optimized to give acceptably low ductile-brittle transition characteristics. The results of studies on these steels, and earlier choices, covering heat treatment and compositional optimization, evolution of wrapper fabrication routes, pre and post-irradiation mechanical property and fracture toughness behaviour, microstructural stability, void swelling and in-reactor creep characteristics are reviewed. The retention of high void swelling to displacement doses in excess of 100 dpa in reactor irradiations reaffirms the selection of 9-12%Cr steels for on-going wrapper development. Moreover, irradiation-induced changes in mechanical properties (e.g. in-reactor creep and impact behaviour), measured to intermediate doses, do not give cause for concern; however, additional data to higher doses and at the lower irradiation temperatures of 370°-400°C are needed in order to fully endorse these alloys for high burnup applications in advanced reactor systems.

INTRODUCTION

1. The 9-12%Cr martensitic or ferritic-martensitic stainless steels are now well established as leading candidate materials for fast reactor core components. Their selection is based primarily on high void swelling resistance under irradiation, but other features (viz. in-reactor creep behaviour, mechanical properties, sodium compatibility, etc.) also appear attractive. The principal disadvantage compared with austenitic steels is that these materials possess a ductile-brittle transition temperature (DBTT) which increases with irradiation. Furthermore, their limited creep strength above 550°C implies - at least at the present stage of development - that these alloys may be suitable only for wrapper applications.

2. Although significant irradiation data now exists, further information is required, particularly at high displacement doses, before the 9-12%Cr steels can be fully endorsed for high burn-up applications in future commercial fast reactor designs. Thus, the significance of the irradiation-induced DBTT shift and associated fracture toughness changes on wrapper integrity, and the extent to which such changes can be minimized by compositional and/or heat treatment modifications all need to be critically evaluated. Further high dose data on swelling, in-reactor creep and phase stability, and the effects of temperature excursions on these properties are also desirable in order that the irradiation characteristics of the martensitic steels are fully understood.

3. Within Europe, the development of the 9-12%Cr steels is now carried out on a collaborative basis between the UK, France, Germany, Belgium and Italy. This takes the form of joint research programmes, data exchange and rationalization towards common objectives. Cooperative European research programmes in other areas of fast reactor technology are also in operation, as described elsewhere (refs. 1,2).

4. The present paper reviews the current status of European research and development of ferritic-martensitic steels for fast reactor wrappers and covers the following areas: (i) materials selection and specification; (ii) pre-irradiation microstructural and mechanical property optimization and associated wrapper fabrication aspects; (iii) post-irradiation

mechanical property behaviour, including fracture toughness and DBTT shifts; and (iv) phase stability, void swelling and in-reactor creep characteristics.

ALLOY SELECTION AND COMPOSITIONS

5. Designations and typical chemical analyses of alloys previously investigated or currently considered for wrapper applications in the UK, France and Germany are given in Table 1; also listed are other alloys which feature in data comparisons in later sections.

United Kingdom

6. Four 12%Cr grades were initially examined (refs. 3-5), viz. FI (plain 12%Cr); FV607 and CRM-12 (both 12%CrMoV) and FV448 (12%CrMoVNb). Detailed evaluations led to selection of FV448 as the principal choice for fabrication of wrappers. Studies of the role of δ-ferrite highlighted the importance of eliminating this phase and ensuring a fully martensitic structure for control of impact properties of 12%Cr steels (refs. 3, 4). This is achieved by close specification of Ni and Cr equivalents (viz. the "effective" levels of austenite-forming elements - C,N,Ni,Mn - and ferrite-formers - Cr,Si,Mo,V,Al,Nb - respectively) in relation to the Schaeffler diagram (ref. 6). The result is that the composition of FV448 is closer to ~10.5%Cr, with Mo in the range ~0.5-0.6%, plus an addition of Ni of ~0.5-0.6% in order that the C level can be held at ~0.1%.

France

7. A broad range of materials has been characterized, including F17 (a fully ferritic non-transformable 17%Cr alloy), EM12 (a 9%Cr2MoVNb duplex ferritic-martensitic steel) and two fully martensitic 9%Cr grades, viz. EM10 (unstabilized) and T91 (stabilized with V and Nb). The latter two alloys may eventually be favoured for wrapper applications, in preference to the earlier choice of EM12. It is recognised, however, that F17 cannot meet DBTT requirements in the irradiated condition.

Germany

8. Although some earlier studies have been carried out on 1.4923 steel (a

12%CrMoV alloy), investigations have focussed principally on 1.4914 steel - a fully martensitic 12%CrMoVNb grade similar to FV448. The composition has now been optimized; low nitrogen casts (<100ppm, and typically ~30ppm) are now specified for wrappers, in order to achieve the requisite balance of mechanical properties (ref. 7).

OPTIMIZATION OF UNIRRADIATED MECHANICAL PROPERTIES

9. A comparison of the yield strength as a function of temperature for the three materials categories used for fast reactor core components, viz. ferritic-martensitic steels, austenitic steels and nickel-base alloys, is illustrated schematically in Fig. 1; elevated temperature creep rupture strengths essentially follow the same ranking order. It is generally accepted that the significantly lower strength characteristics evident for the ferritic alloys, particularly above ~550°C, compared to the austenitics and nickel-base alloys renders them inappropriate for fuel pin cladding. This shortcoming may however be circumvented by the use of oxide-dispersion strengthened (ODS) ferritic alloys, when fabrication routes are fully established (ref. 8). At present therefore, ferritics are considered only for wrapper applications.

10. Up to 550°C in conventional engineering practice, the 9-12%Cr steels are specified with heat treatments designed to optimize their proof and creep strengths. This differs from the requirements for wrappers, which are not highly stressed in normal service. Instead, good elevated temperature ductility, low initial DBTT and enhanced fracture toughness are more relevant, in order to accommodate irradiation-induced degradation of these properties and thereby maintain component integrity to end-of-life. Adequate formability and weldability are also essential to permit defect-free fabrication of wrappers to high tolerances. These requirements can be met with modified heat treatments based on detailed appraisals of the effects of austenitizing and tempering variables on microstructures and mechanical properties.

11. UK optimization studies have identified prior austenite grain size and tempered strength as essentially controlling impact and toughness properties (refs. 3, 4). Of the three 12%Cr steels examined, FV448 exhibited highest resistance to strength loss by tempering (Fig. 2),

together with lowest achievable prior austenite grain size as a function of solution treatment temperature (Fig. 3). The behaviour could be explained in terms of (i) the grain-refining action of NbC precipitates; and (ii) the role of V and Nb in enhancing the stability of M_2X and $M_{23}C_6$ phases, leading to retention of higher pinned dislocation densities during tempering.

12. Parallel studies have been undertaken in other European programmes. For example, the effects of tempering on the DBTT of EM10 steel are shown in Fig. 4; anneals in the range 740°-780°C are favoured and produce significant enhancement in upper shelf energy after saturation of the DBTT. In contrast, German studies of 1.4914 steel emphasise the importance of nitrogen content in influencing DBTT, and thus low N casts (<100ppm) are preferred, to achieve low DBTT values (ref. 7).

13. The above programmes have resulted in recommendations for optimized "high toughness" heat treatments for wrapper tubes, which combine low DBTT, high upper shelf toughness and good ductility, but at the expense of some loss of creep strength. Current heat treatment schedules for key alloy choices, together with resultant DBTT and creep strength values, are listed in Table 2. Differences in creep strength between high toughness and standard heat treatments are exemplified by the earlier UK studies illustrated in Fig. 5, which compare 550°C stress-rupture properties (ref. 5).

14. Recent studies have provided further insight into the importance of heat treatment control of 12%Cr steels. Severe loss of creep strength can be induced by austenitization below 950°C, associated with formation of heavily spheroidized structures (ref. 9). Strong segregation of alloying elements (specifically silicon) to lath boundaries occurs for intermediate cooling rates (e.g. oil quenching) following austenitization, and associated with beneficial improvements in impact properties (ref. 10). This is a non-equilibrium segregation phenomenon induced by solute interaction with transient vacancy fluxes.

WRAPPER FABRICATION

15. Two fabrication routes for wrappers have been developed: (i) extrusion

and pilger rolling of a seamless tube, with intermediate anneals, followed by drawing to hexagonal cross-section; and (ii) longitudinal seam welding of half-hexagons, formed by bending of sheet stock, followed by appropriate post-weld heat treatment (PWHT). The seamless route is currently favoured since it provides a completely homogeneous product; however, the welding route has merits in terms of reduced costs and production time.

16. Seamless production requires close specification of intermediate tempering anneals between extrusion/drawing passes to prevent cracking due to ductility exhaustion. In this respect, the martensitic grades are less tolerant of heat treatment variations than their austenitic counterparts. UK fabrication studies (ref. 11) have identified the tensile work-hardening exponent, n (i.e. in the yield stress vs. strain relation: $\sigma = k\varepsilon^n$) as the best guide to drawability, with higher n values corresponding to improved properties. The variation in n with tempering time (t) and temperature (T°K) (plotted as the combined parameter: H = T (20 + log t)) and based on tensile specimens cut from FV448 wrappers, is given in Fig. 6. Sharp decreases in n occur for H < 21×10^3, and a window of n values giving adequate drawability without cracking can be defined.

17. A welding route has also been validated in UK and German studies, and wrappers fabricated in FV448 and 1.4914 steels, respectively (refs. 7, 12). Detailed TIG welding trials of 3mm thick FV607 and FV448 plate, with and without filler additions have further demonstrated: (a) high quality welds, free from cracking or porosity, can be routinely produced; (b) PWHT is essential to soften the martensite in the weld metal, but mechanical properties close to that of parent plate can be achieved; (c) weld metals generally contain small levels of δ-ferrite, but which does not appear deleterious to mechanical properties; however, this phase can be virtually eliminated by control of weld pool chemistry; and (d) the upper shelf toughness of the weld metal is superior to that of the parent plate, as a consequence of spheroidization of initially lenticular MnS inclusions during the fusion process (ref. 12).

VOID SWELLING

18. The overall swelling behaviour of ferritic-type alloys under neutron, electron and charged particle irradiations have been detailed in recent

reviews (refs. 13-16). Early trends of high resistance to void swelling in the 9-12%Cr commercial grades - on which the selection of this alloy class for wrapper applications was based - have been essentially reaffirmed with new high dose fast reactor data extending above 100 dpa (NRT).

19. Studies on FV448 based on irradiation experiments in the EBR-II reactor, to complement PFR data from wrappers, confirm virtually negligible swelling in this alloy following irradiations to ~70 dpa at temperatures in the range 400°-650°C (ref. 17).

20. Recent French data covering irradiations of F17 (fully ferritic) and EM12 (duplex ferritic-martensitic) steels in Phénix in the lower temperature ranges (400°-460°C) and to displacement doses >100 dpa are illustrated in Fig. 7. It appears that these materials do exhibit limited swelling, which occurs principally at the lower irradiation temperatures (viz. 400°C); furthermore, there are indications of differences in swelling response between the two alloys. Confirmation of trends for EM12 are available from EBR-II irradiations for which density measured swellings of ~0.6% are observed for 400°C/77 dpa and 425°C/99 dpa irradiation conditions, and which correlate with the observation of void populations (refs. 18, 19).

21. In summary, current data trends now high light minor variations in low level swelling between alloy variants at the higher doses, indicating potential compositional and/or microstructural dependency. However, the magnitudes of the swelling are all cases ≤1% at >100 dpa, which is regarded as acceptable for wrapper applications.

PHASE STABILITY

22. Studies of microstructural evolution under fast reactor irradiation can provide a basis for understanding , and possibly modifying, irradiation-induced mechanical property changes. Detailed evaluation of the phases induced by irradiation to ~23 dpa at temperatures in the range 380°-615°C in FI, CRM-12 and FV448 12%Cr steels have been carried out to provide data trends (refs. 20, 21).

23. In FV448 the NbC distribution remains essentially unaffected by irradiation, whilst the normally thermally-induced Laves phase formation at

615°C is suppressed. Furthermore, irradiation-induced formation of M_6X, chi and sigma phases, rich in Si, Ni and P, is observed in all three steels and attributable to non-equilibrium segregation brought about by solute-point defect interactions. Unusual phosphide phases are also detected (ref. 21). Irradiation also induces α' phase (Cr-rich ferrite), which when produced by thermal ageing in high-Cr fully ferritic alloys, is responsible for degradation of impact properties. This phase is widely distributed in the FI steel but appears in only small quantities in the CRM-12 and FV448 alloys.

24. Overall the Nb-bearing FV448 steel possesses superior phase stability compared to the alternative FI and CRM-12 grades, and the data thus reaffirms the selection of this alloy as the preferred choice for UK wrapper development. The studies, however, also imply that lower Cr variants may possess better resistance to irradiation-induced α' formation, and further that compositional tailoring (e.g. of Si, Ni and P levels) may provide the prospect of suppressing undesirable irradiation-induced phases.

EFFECTS OF IRRADIATION ON MECHANICAL PROPERTIES

Strength Changes

25. Fast reactor irradiation of 12%Cr steels can result in either increases or decreases in strength, depending on the irradiation temperature, T_{irr} (ref. 20). Irradiations of FV448 and other 12%Cr steels to ~23 dpa over the temperature range 380°-615°C demonstrated: (i) irradiation hardening occurs for T_{irr} < 420°C, and increases with decreasing irradiation temperature; and (ii) irradiation softening occurs for T_{irr} > 460°C. These trends are illustrated in Fig. 8. The results are consistent with microstructural observations which reveal irradiation-induced loop or precipitate strengthening at low irradiation temperatures and recovery of the dislocation substructure, giving net softening, at higher irradiation temperatures.

26. Broadly similar conclusions based on tensile test behaviour emerge for the 12%Cr martensitic alloys 1.4923 and 1.4914, based on BR2 reactor irradiations (ref. 22). There is also now extensive confirmatory tensile

data showing softening effects from US irradiation programmes (refs. 23-25).

DBTT and Fracture Toughness

27. Irradiation-induced degradation of Charpy V-notch impact properties, in terms of both rise in DBTT and fall in upper shelf toughness, could impose limitations on the exploitation of 9-12%Cr steels for wrapper applications because of increased propensity for brittle-type failure. Since the shift in DBTT is primarily controlled by the level of radiation hardening, the peak shift in DBTT is likely to occur at the low temperature end of the wrapper since, as described above, irradiation strengthening increases rapidly with decreasing irradiation temperature over the range <380°-420°C. Thus the problem is likely to be most crucial for future European reactor designs with proposed coolant inlet temperatures of ~370°C.

28. In terms of wrapper integrity, the desired goal would be to ensure that the DBTT after irradiation does not rise above the stand-by or wrapper-unload temperature of ~230°C. A materials data base is therefore being established in order to gauge sensitivity of DBTT shift to irradiation temperature and displacement dose, and its dependence on alloy composition, etc., and with particular reference to irradiation temperatures in the 370°-420°C range.

29. Relatively high dose DBTT data are now available for the EM10 (fully martensitic) and F17 (fully ferritic) grades from French irradiation programmes in Phénix. Irradiation temperatures and doses cover the ranges 410°-558°C/7-36 dpa and 394°-537°C/4-60 dpa for EM10 and F17, respectively, using Charpy V-notch specimens typically of 3.5mm thickness. Figs. 9 and 10 illustrate the data trends. It is clear that F17 is prone to marked embrittlement, with severe DBTT shifts and associated loss of upper shelf energy at the lowest irradiation temperatures (394°-436°C); thus, 394°C-irradiation results in a DBTT of ~275°C. The 17%Cr steels are noted for susceptibility to 475°C-embrittlement caused by precipitation of α' during thermal ageing, and it seems likely that irradiation-induced α' formation could be responsible for the observed DBTT shifts. In contrast, data for EM10 indicate a highly satisfactory irradiation response with relatively low DBTT shifts and absolute DBTT values <0°C after

irradiation.

30. Parallel studies in German programmes on 1.4914 steel have been carried out in both BR2 and Phénix reactors, with doses now extending to 55 dpa. A compilation of DBTT shift data (including both standard and subsize Charpy V-notch samples) as a function of irradiation temperature is given in Fig. 11 in order to compare current trends for 1.4914 steel with UK thermal reactor data for FI, FV607 and FV448 steels (ref. 5), US data on HT9 and T91 (9%Cr1Mo-modified) (refs. 26, 27) and early Canadian thermal reactor data on AISI 403 steel (refs. 28, 29). Data points for 1.4914 steel at 55 dpa and irradiation temperatures of ~400°C indicate DBTT shifts of ~70°C. The overall trends further demonstrate that at and above irradiation temperatures of 450°C, fully martensitic δ-ferrite-free grades (e.g. 1.4914) exhibit virtually zero DBTT shift, but below 450°C DBTT increases strongly with decreasing irradiation temperature. This behaviour is consistent with the observed irradiation softening of 12%Cr steels which sets in above ~420°-460°C (ref. 20).

31. Since absolute magnitudes of irradiated DBTT, rather than shifts, are of more direct relevance for wrapper operation, such values from the above data base are plotted as a function of irradiation temperature in Fig. 12. It is clear that for irradiations >400°C the irradiated DBTT is always <50°C, and hence regarded as satisfactory for reactor operation. Higher dose data is required to confirm that DBTT values still remain acceptable towards end-of-life. In this respect, recent US data indicating saturation in DBTT changes in HT9 with increasing dose is encouraging (ref. 30).

32. Whilst Charpy impact results provide a useful empirical measure of materials performance, fracture toughness values in terms of K_{IC} or J_{IC} are required for design purposes, for example, in order to evaluate critical crack sizes for fast fracture under steady state or off-normal wrapper stressing (ref. 31). On-going European programmes include irradiation of samples suitable for determination of dynamic and static J_{IC} from instrumented impact and slow three-point bend R-curve tests, respectively, to meet these objectives.

In-Reactor Creep

33. In-reactor creep deformation has two important consequences for

wrapper performance: (i) some deformation may be beneficial for relief of local stress concentrations, e.g. at wear pad locations; however, (ii) wrapper bulging under the action of sodium pressure, particularly in the lower, cooler region of the core can lead to problems for wrapper unloading. Characterization of the in-reactor creep properties of candidate 9-12%Cr steels is therefore an important aspect of the European alloy development programmes.

34. UK studies are in progress in PFR covering irradiations at 420°-600°C on a variety of cladding and structural alloys, including FI, FV607 and FV448 martensitic steels. Two specimen geometries, viz. pressurized tubes and helical springs, are under test; details of the helical spring technique have been described previously (ref. 32). Recent spring data at 420°C are presented in Fig. 13 as plots of normalized creep strain (strain per unit stress, γ/τ) versus displacement dose, assuming creep strain linearly dependent on stress (ref. 33). The behaviour of FV448 is compared with a high-carbon Type 316 austenitic steel. The data illustrate that the steady state creep rate for FV448 is significantly lower than for the austenitic steel, and this conclusion is further confirmed from data comparisons with other austenitic alloys in the programme (ref. 33). The assumption of a linear stress dependence has been re-examined where data are available for at least two stress levels. For most materials the stress exponents are fractionally greater than unity; e.g. for FV448 at 420°C an exponent of 1.26 is derived.

35. German studies have generated in-reactor creep data on 1.4914 steel from irradiations in both BR-2 and PFR, as part of a programme aimed at understanding the underlying deformation processes. BR-2 irradiations (the MOL 5B programme) utilize uniaxial creep tests between 450°-600°C, and creep rate versus stress plots are presented in Fig. 14 (refs. 34, 35). The results are interpreted in terms of an irradiation-enhanced thermal creep mechanism with a stress exponent of 5 and an activation energy of ~3eV, close to that for self-diffusion.

36. Data is now available for in-reactor creep of 1.4914 steel from pressurized tube experiments in PFR, and creep rates at 500°C have been compared with the BR-2 data and with published US data on HT9 (refs. 36, 37) as shown in Fig. 15. The PFR data (PFR-M2 experiment) indicate

behaviour similar to HT9 insofar as a near linear stress dependence and weak temperature effect are observed. The differences between the two data sets (viz. σ^1 and σ^5 dependences) are explained in terms of the effects of intermediate load changes and recovery stages which are present in the BR-2 tests (ref. 38). These appear to initiate a different creep mechanism. Such effects, however, would not occur in fast reactor applications since wrapper loading is continuously applied.

CONCLUSIONS

37. The position of 9-2%Cr martensitic steels as fast reactor wrapper materials continues to look promising, and these alloys provide quite clear advantages over austenitic alloys, particularly for high burn-up applications. Fabrication experience has not highlighted any major obstacles whilst new irradiation data reaffirms trends deduced from lower dose experiments. Void swelling data has now been generated to displacement doses >120 dpa, but corresponding information for DBTT shifts, fracture toughness and in-reactor creep behaviour is still at significantly lower doses. The trends in these properties to much higher doses will need to be established before the ferritic-martensitic steels can be fully endorsed for advanced fast reactor systems.

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Table 1. Typical Compositions or Optimized Specifications of Ferritic-Martensitic Steels for Wrapper Applications (wt.%)

Designation	C	Cr	Ni	Mo	V	Nb	Si	Mn	N	B (ppm)	Others
(a) United Kingdom											
FI	0.15	13.0	0.47	-	-	-	0.30	0.45			
FV607	0.13	11.1	0.59	0.93	0.27	-	0.53	0.80			
CRM-12	0.19	11.8	0.42	0.96	0.30	-	0.45	0.54			
FV448	0.10	10.7	0.64	0.64	0.16	0.30	0.38	0.86			
(b) France											
F17‡	0.10	17.0	0.20	-	-	-	0.30	0.80			
EM10	0.10	9.0	-	1.0	-	-	0.30	0.50			
EM12	0.10	9.0	0.30	2.0	0.30	0.40	0.40	1.00			
T91	0.10	9.0	<0.40	0.95	0.22	0.08	0.35	0.45	0.050		
(c) Germany											
1.4923	0.21	11.2	0.42	0.83	0.21	-	0.37	0.50			
1.4914	0.14	11.3	0.70	0.50	0.30	0.25	0.45	0.35	0.029	70	
1.4914*	0.16-0.18	10.2-10.7	0.75-0.95	0.45-0.65	0.20-0.30	0.10-0.25	0.25-0.35	0.60-0.80	0.010 max.	15 max.	
(d) Others											
HT9	0.20	11.9	0.62	0.91	0.30	-	0.38	0.59			0.52W
AISI 403	0.12	12.0	0.15	-	-	-	0.35	0.48			

* Optimized wrapper composition

‡ F17 is a fully ferritic non-transformable alloy

Table 2. Optimized Wrapper Heat Treatments

Steel	Heat Treatment	DBTT	Creep Strength
FV448	1h/1100°C, AC + T 6h/750°C, AC	-50°C	250MPa for 550°/10^4h
1.4914	0.5h/1075°C, AC + T 2h/700°C, AC	-17°C	80MPa for 600°C/10^4h
EM10	1h/980°C, AC + T 740-780°C, AC	-70°C	-

AC = air cool; T = temper

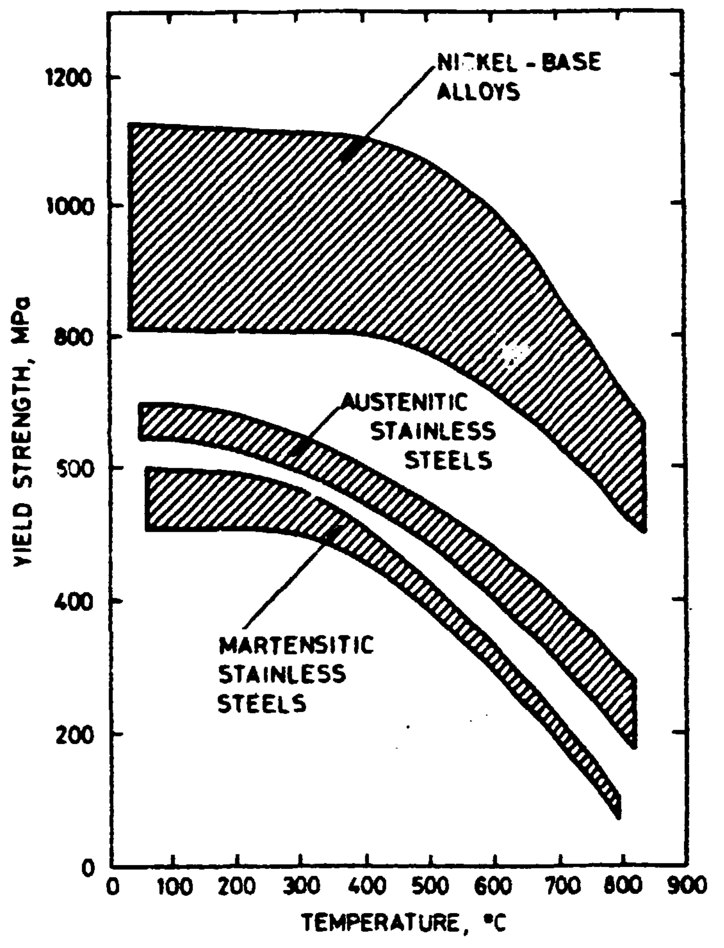


Fig. 1. Schematic of relative yield strengths of martensitic, austenitic and nickel-base alloys.

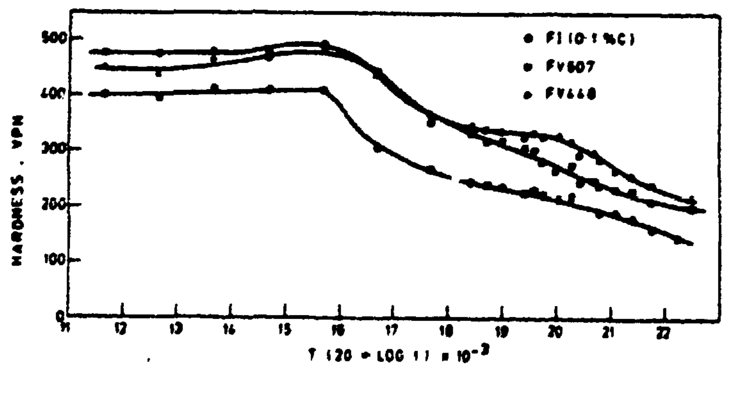


Fig. 2. Tempering characteristics of FI, FV607 and FV448 steels.

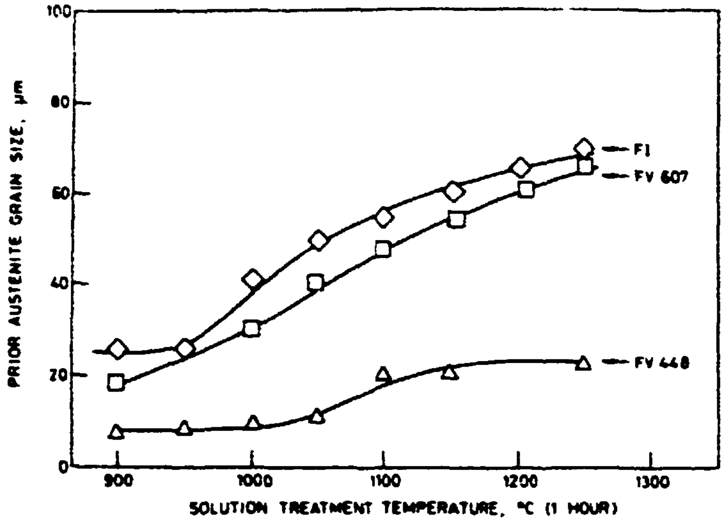


Fig. 3. Prior austenite grain growth characteristics of FI, FV607 and FV448 steels.

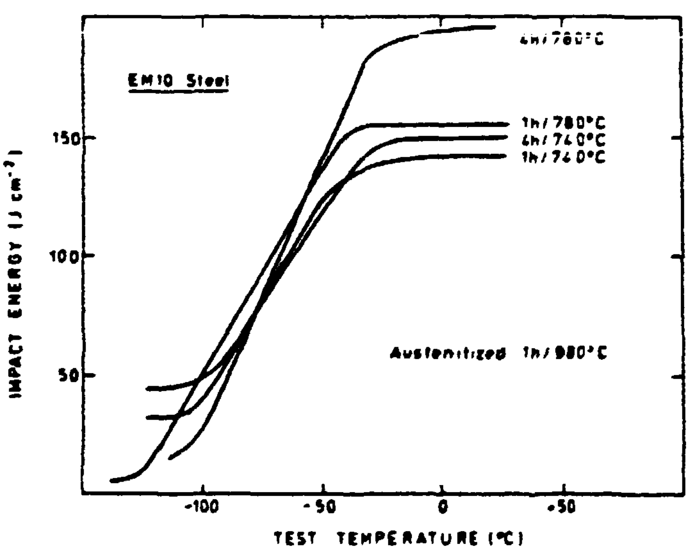


Fig. 4. Effect of tempering on DBTT of EM10 steel.

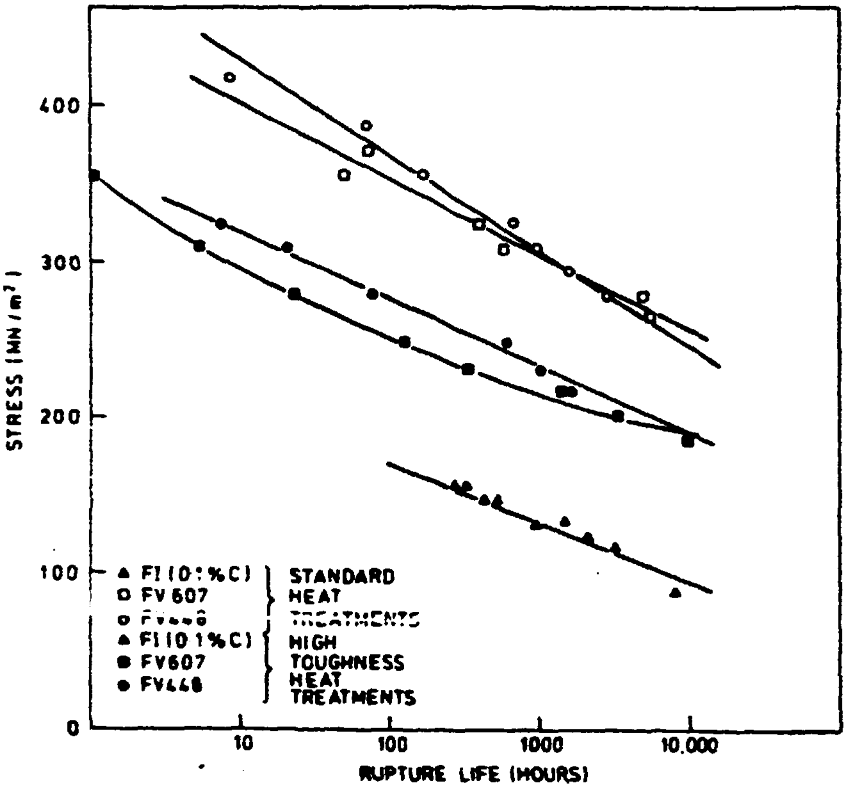
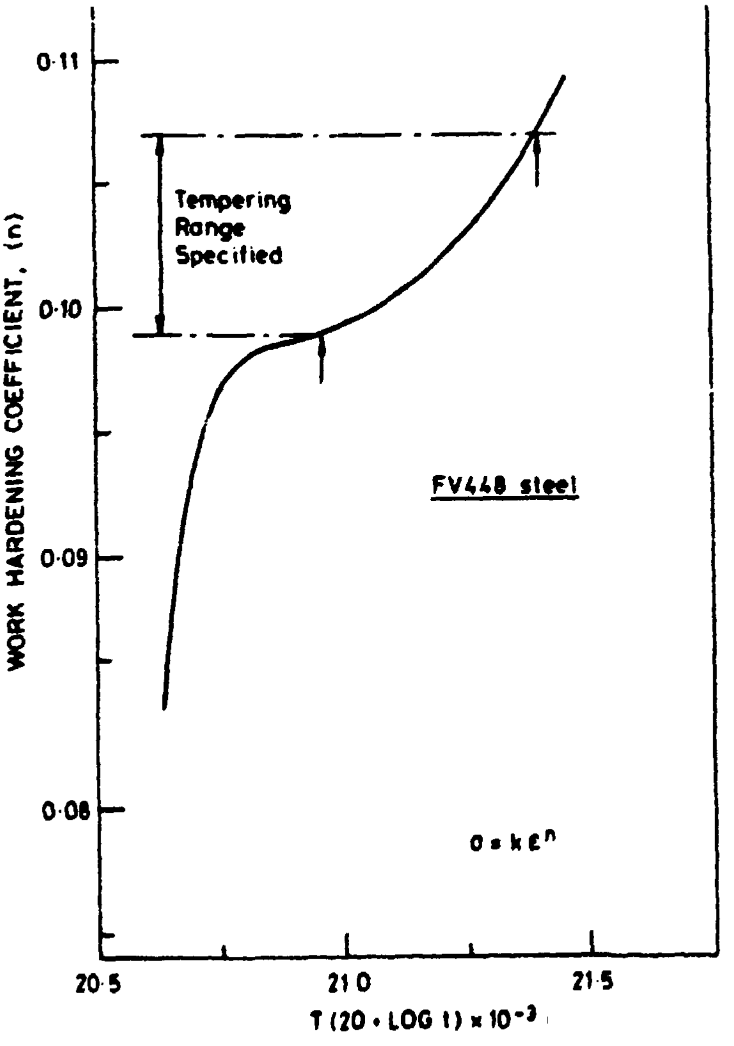


Fig. 5. Stress-rupture data at 550°C for FI, FV607 and FV448 steels as a function of heat treatment.

Fig. 6. Variation of work-hardening exponent with tempering condition for FV448 steel.



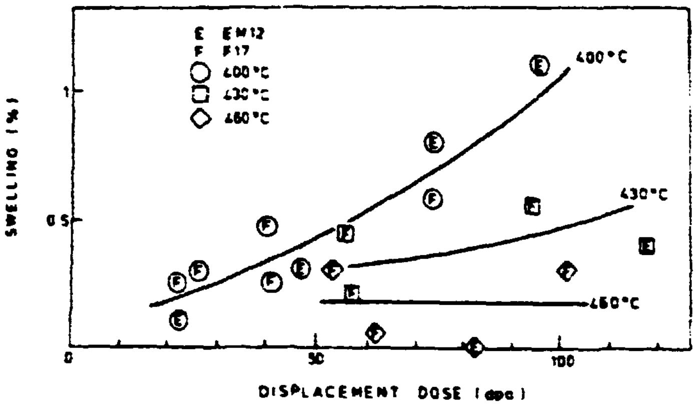


Fig. 7. Dose dependence of void swelling in reactor irradiated EM10 and F17 steels.

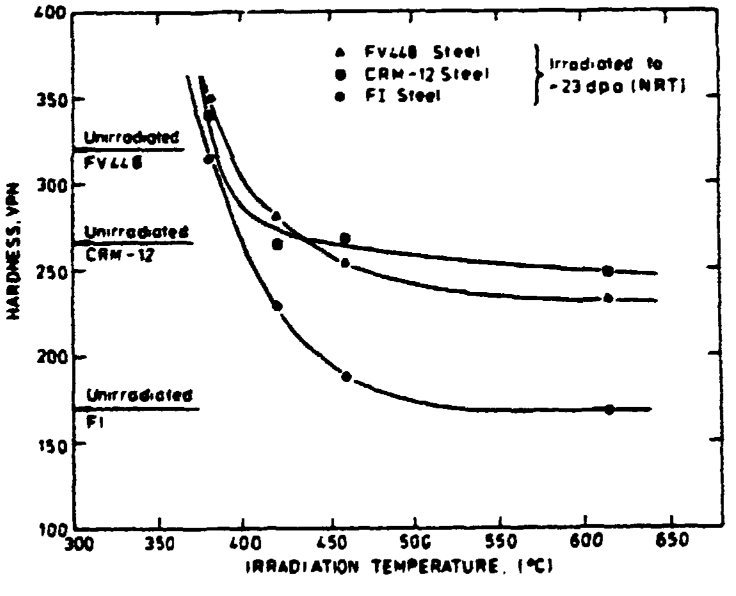


Fig. 8. Radiation-induced hardness changes in 12%Cr steels as a function of irradiation temperature.

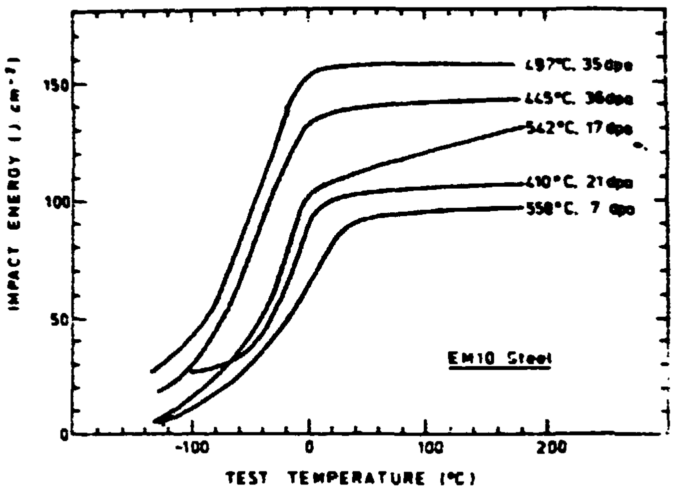


Fig. 9. DBTT data for irradiated EM10 steel.

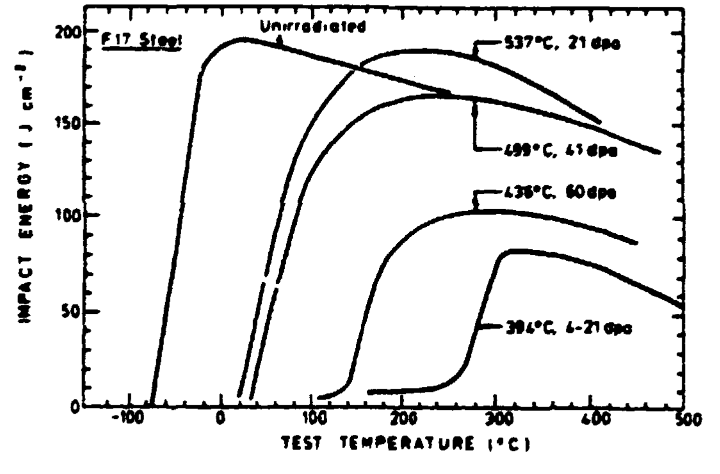


Fig. 10. DBTT data for irradiated F17 steel.

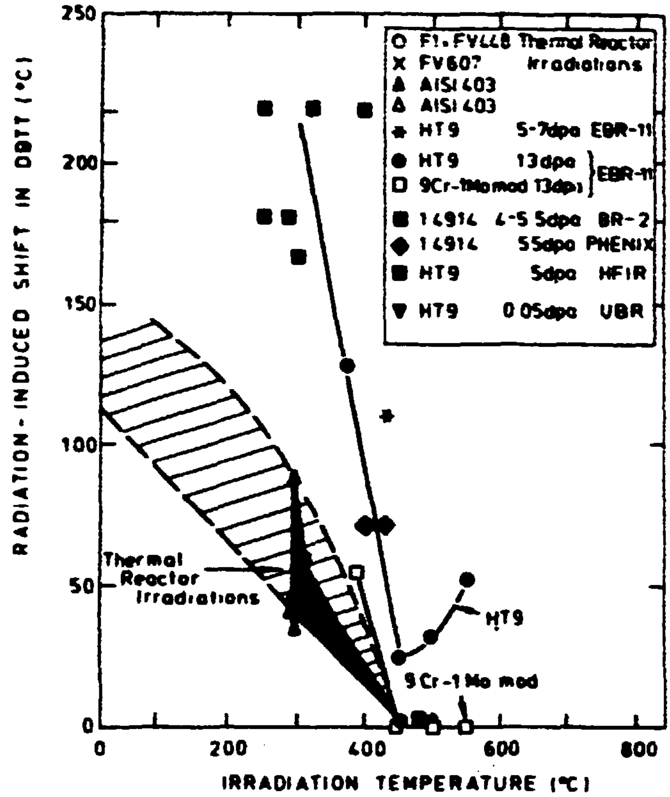


Fig. 11. DBTT shifts as a function of irradiation temperature for a range of 9-12%Cr alloys.

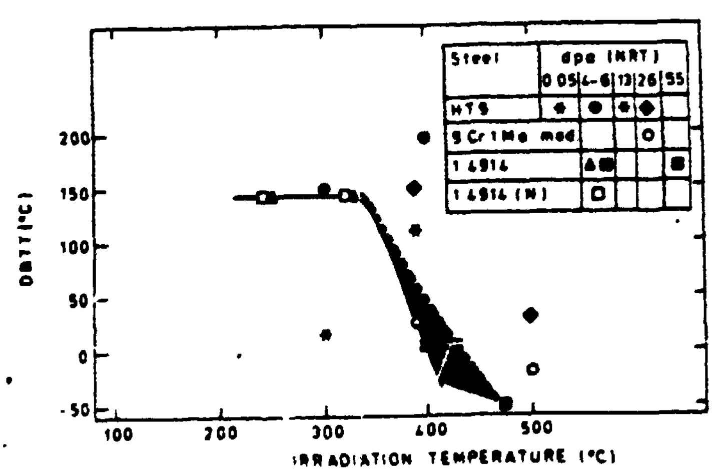


Fig. 12. DBTT data as a function of irradiation temperature.

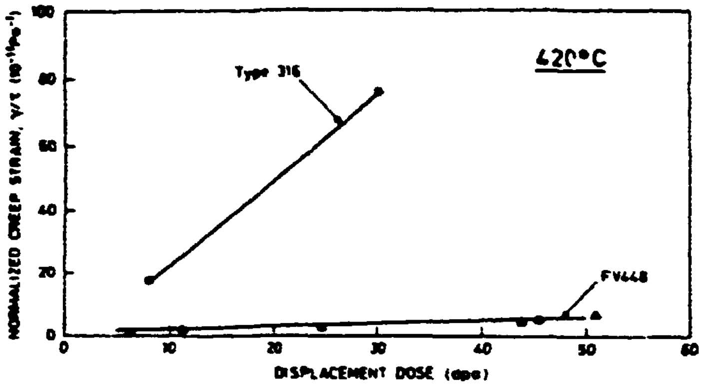


Fig. 13. In-reactor creep as a function of dose for FV448 and high-carbon 316 steel.

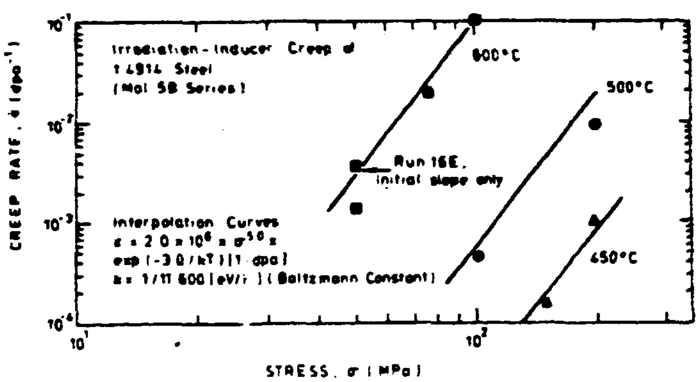


Fig. 14. Stress dependence of in-reactor creep of 1.4914 steel.

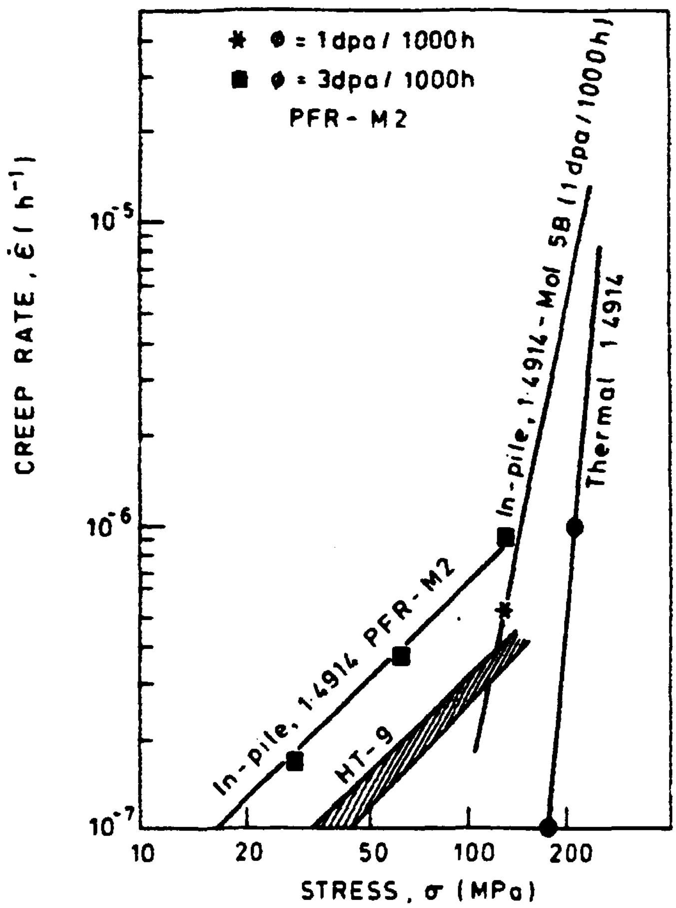


Fig. 15. Thermal and in-reactor creep at 500°C of 1.4914 and HT9 steels.