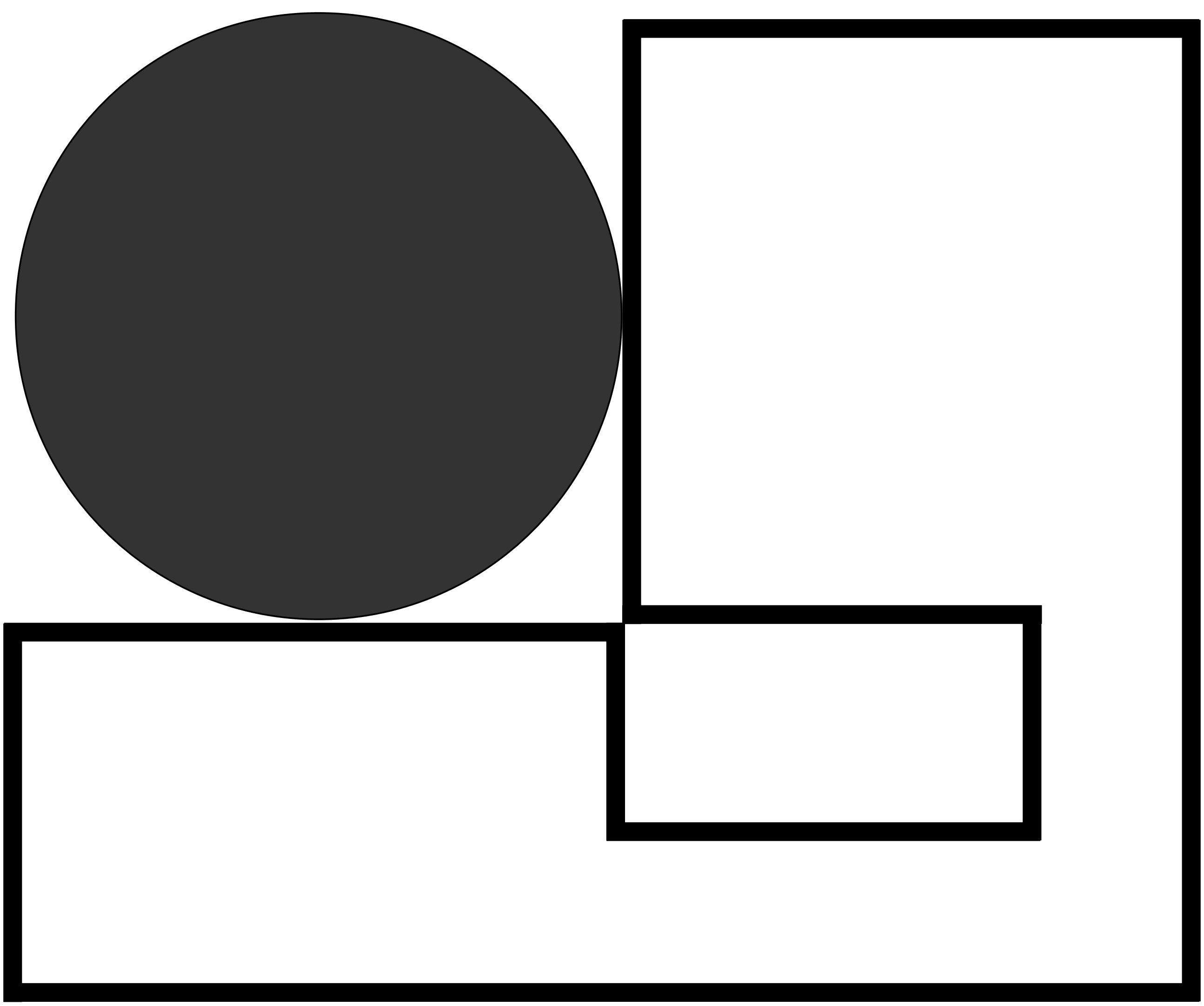
IN-519 cast chromium-nickel-niobium heat-resisting steel

Engineering properties



INCO

INCO databooks

Inco, the leading producer and marketer of nickel, conducts research and development programmes on nickel alloys, products and processes, establishing engineering and performance data. This knowledge is collated in a library of INCO databooks, which are freely available.

Conversion factors for stress and impact energy units

SI metric units have been adopted as the standard throughout this publication. To assist readers who may be more familiar with other units to which they have been accustomed, factors are given below for conversion of the more important of these to SI metric units and vice versa.

Stress units:
1 tonf/in^2 = 15.44 N/mm^2
1 kgf/mm^2 = 9.807 N/mm^2
10^3lbf/in^2 = 6.895 N/mm^2
1 N/mm^2 = 0.0647 tonf/in^2
or 0.102 kgf/mm^2
or 0.145 10^3lbf/in^2
or 0.1 hbar

Note that the newton per square millimetre (N/mm^2), meganewton per square metre (MN/m^2) and megapascal (MPa) SI units of stress are arithmetically identical.

Impact energy units
1 ft lbf = 1.356 J
1 kgf m = 9.807 J
1 J = 0.7375 ft lbf
or 0.102 kgf m
1 J (Charpy V impact) = 0.1275 kgf m/cm^2

The information and data in this publication are as complete and accurate as possible at the time of publication. The characteristics of a material can vary according to the precise method of production and treatment and therefore suppliers should always be consulted concerning the specific properties of their products.

IN-519 cast chromium-nickel-niobium heat-resisting steel

Engineering properties

Alloy IN-519 was developed by Inco primarily for centrifugally-cast catalyst tubes used for steam-hydrocarbon reforming furnaces. The work leading to the development of the new steel consisted essentially of optimising the composition of the established Alloy Castings Institute HK-40 steel (25Cr-20Ni) which is commonly used for this application, in order to provide a material with improved high-temperature stress-rupture strength and retention of good ductility after long-term service at elevated temperatures. The significantly improved stress-rupture strength, in spite of a lower carbon content, is the result of a 1½ per cent addition of niobium, while some improvement in ductility in stress-rupture tests, and in short-time tensile tests after service exposure, has been obtained by lowering the carbon content and modifying the 25–20 base composition to ensure good structural stability. The improvements are achieved whilst maintaining other essential pre-requisites of a reformer tube alloy, i.e. good weldability and resistance to oxidation, carburization and thermal fatigue.

Laboratory tests on trial commercial centri-cast tubes were made around 1965 and since that time the alloy has become firmly established as an attractive alternative to HK-40 as reformer tube material. It is currently produced by several major suppliers of heat-resisting castings throughout the world and is included as Material Number 1.4855 in a revised edition of the German Standard, Stahl Eisen Werkstoffblatt 595 that is to be issued. Other applications include various statically-cast components for heat treatment plant wherever the superior high-temperature strength and ductility of Alloy IN-519 in comparison with HK-40 steel is considered advantageous.

Chemical composition

Table 1 gives the nominal and recommended range of chemical composition of Alloy IN-519. Within the prescribed limits the balance achieved between the major alloying elements provides optimum stress-rupture strength and avoidance of embrittlement after long-term exposure at elevated temperatures.

Microstructure

As-cast IN-519 contains a proportion of inter-dendritic eutectic niobium carbide and chromium carbide as shown in Figure 1. During exposure at elevated temperatures precipitation of very fine secondary NbC occurs and these particles remain unchanged in size and distribution over long periods of exposure because of the high stability of this type of carbide (Figure 2). The secondary carbide strengthens the matrix and is primarily responsible for the improvement in stress-rupture strength compared with that of HK-40 steel. The mechanism of strength improvement becomes apparent when the morphology and distribution of carbides in Alloy IN-519 is compared with the size and frequency of occurrence of carbides in HK-40 steel. Eutectic chromium carbides in as-cast HK-40 are coarser and although a copious precipitation of fine secondary chromium carbides occurs on ageing at high temperatures, these agglomerate to give fewer and coarser particles as ageing continues. Hence strengthening of the matrix is less than that caused by the persistance of fine carbide particles as in Alloy IN-519. Kihara et al [1] have attributed the superior creep and stress-rupture properties of alloys of the IN-519 type to the effect of fine niobium carbides in restraining grain boundary sliding and in reducing the agglomeration of voids which are nucleated at the boundaries between the matrix and coarser chromium carbides that are also present.

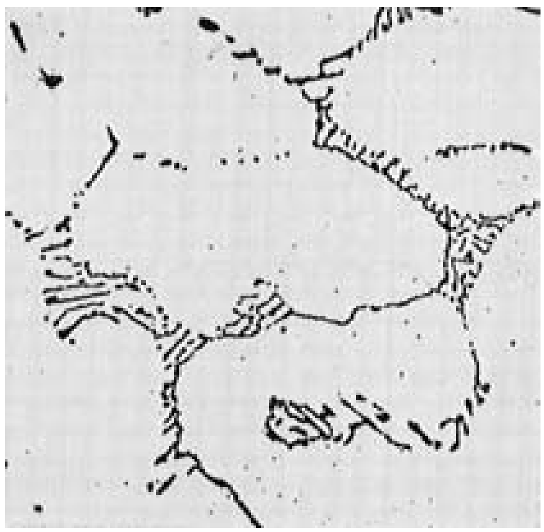


Figure 1. *Microstructure of as-cast Alloy IN-519. (Etchant-Murakami's reagent). 400X*

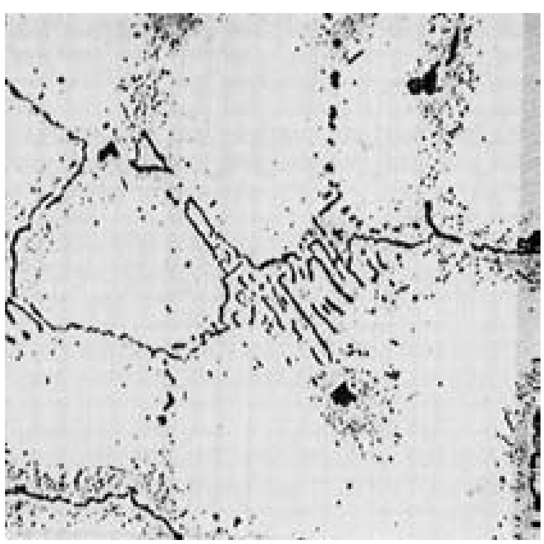


Figure 2. *Microstructure of Alloy IN-519 after 2000 hours at 800°C. (Etchant-Murakami's reagent). 400X.*

Table 1. Alloy IN-519. Chemical composition, weight per cent.

	Carbon	Silicon	Manganese	Chromium	Nickel	Niobium	Sulphur	Phosphorus	Iron
Nominal	0.30	0.75	0.75	24.0	24.0	1.5	0.015	0.015	Balance
Recommended range	0.25–0.35†	1.0 max*	1.0 max	23.0–25.0	23.0–25.0	1.4–1.8	0.040 max	0.040 max	Balance

** 0.8 per cent max Si is preferred for retention of highest tensile ductility and toughness after long-term service exposure at elevated temperatures.*
† The proposed new edition of the German Standard SEW 595 stipulates carbon contents of 0.25–0.40 per cent and a range of 0.30–0.40 per cent carbon has been extensively and, as far as is known, satisfactorily adopted by German producers.

The progressive replacement of secondary chromium carbide by a fine, stable precipitate of niobium carbide with increasing additions of niobium to the 24Cr-24Ni type of steel is accompanied by a reduction in the amount of secondary carbide formed. Therefore, the improvement in stress-rupture properties passes through a maximum at a niobium/carbon ratio of about 5. This fact is recognized in the composition design of Alloy IN-519.

The structural stability of IN-519 has been studied in relation to the formation of sigma-phase after long-time exposure at temperatures in the range 600–1000°C. Of some 53 heats examined by Inco, 33 had compositions within the recommended range given in Table 1 while 20 others were made with silicon, manganese, chromium, nickel or niobium contents somewhat outside that range in order to assess the effects of variations in these elements more completely. The results showed that IN-519 has low susceptibility to formation of this embrittling phase. For example, after 5,000 hours exposure at 800°C – a critical temperature for sigma-phase formation – 30 of the 33 alloys having compositions within the recommended range were completely free from sigma-phase, as judged by optical microscopic examination, while the three remaining alloys had only the smallest detectable trace. The most notable effect of variations in composition outside the recommended range was that attributable to silicon. Increasing the silicon content from 1.0 to 1.8 per cent resulted in the formation of sigma-phase in amounts varying from a trace to 25 ^{vol}/o when the nickel/chromium ratio was equal to or less than unity. However, at nickel/chromium ratios above unity the effect of silicon in promoting sigma formation was reduced, to the extent that no sigma-phase was formed in alloys containing 1.0 to 1.3 per cent silicon.

To ensure low susceptibility to sigma-phase formation it is desirable, therefore, to conform to the upper limit of 1.0 per cent silicon given in Table 1 and to maintain the nickel/chromium ratio at unity or above. The preferred maximum of 0.8 per cent silicon mentioned in Table 1 for the retention of highest ductility after long-term exposure at elevated temperatures is also to be preferred for avoiding sigma-phase formation.

Mechanical properties

Tensile and impact properties

Representative tensile test data from room-temperature and short-time elevated temperature tests on as-cast samples of Alloy IN-519 from five centricast commercial tubes are shown in Figure 3. Comparison of these results with published data for as-cast HK-40 steel indicates that the ductility of IN-519 is generally superior at temperatures up to 900°C, while the 0-2 per cent proof stresses and tensile strengths of both alloys are similar.

Figure 3 also shows the effect of prolonged ageing at 800°C on the tensile properties of IN-519. These data indicate that only slight lowering of room-temperature ductility occurs after long-term service exposure, the elongation being typically about 12 per cent in contrast to the behaviour of HK-40 steel which usually has elongation values below 5 per cent after such treatment. The room-temperature tensile stress values of IN-519 remain unaffected by prior ageing at 800°C and no adverse effects of this treatment are shown in the tensile properties at elevated temperatures.

Room-temperature Charpy V-notch impact values of Alloy IN-519 in the as-cast condition and after prolonged exposure at temperatures in the range 800–1000°C are shown in Figure 4 (Page 6). Some loss of toughness occurs after high-temperature ageing, but a useful level of impact strength is still retained and the results are in accord with microstructural observations that little or no sigma-phase is formed.

Stress-rupture properties

The results of 339 stress-rupture tests (46 of them on welded specimens) on Alloy IN-519 at temperatures in the range 700-1100°C are presented as a Larson-Miller plot in Figure 5 (Page 7) showing a single (mean) master curve* from which rupture-stresses may be derived by extrapolation to longer for shorter times than those covered by the available test data. These data represent 18 heats of IN-519 from eight commercial suppliers and the tests were made in five test-houses for times extending up to 42,312 hours. Therefore, the results may be considered as representative of the alloy for the normal variations in production and testing likely to be encountered in practice.

Figure 5 (Page 7) also shows 95 per cent confidence limits for the prediction of probable variations in test data, while the inset chart of that diagram gives the distribution of rupture-lives for the tests made.

Stress rupture vs. rupture-life test results are plotted in Figure 6 (Page 8) for temperatures of 700°, 800°, 900° and 1000°C, together with 95 per cent confidence limits corresponding to those shown in Figure 5 (note: the latter also covers tests at other temperatures).

The mean and minimum stresses giving various rupture-lives for Alloy IN-519 at several temperatures have been derived from the Larson-Miller plot shown in Figure 5 and are compared in Table 2 (Page 6) with the corresponding stresses for HK-40 steel, similarly derived from test data extending up to 21,700 hours on material from 12 commercial heats. This comparison indicates the superior rupture-strength of IN-519. It should be noted by comparison of Figure 6 (Page 8) and Table 2 (Page 6) that the derivation of long-time rupture-stresses for IN-519 involved some extrapolation of the available data to longer rupture times. This extrapolation becomes more problematic the higher the test temperature, since there are fewer data points available giving values greater than 25 for the parameter ‘P’ (i.e., equivalent to 10^5 hours at 920°C) in the Larson-Miller plot which forms the basis of the extrapolation. Rather more extrapolation of the stress/rupture-life test data was incurred in deriving some of the long-time rupture stresses in Table 2 for HK-40 steel.

Stress-rupture ductility is an important parameter affecting the performance of stressed components in high-temperature service and Figure 7 (Page 9) compares values for IN-519 and HK-40. Insufficient data are available to provide a clear indication of the relative merits of the two materials at rupture lives in excess of 10,000 hours, but the general trend of the results suggests that IN-519 retains higher ductility, while at lower rupture-lives its superiority in this respect is more clearly evident.

Creep properties

The time taken to produce a total plastic strain of 1 per cent is plotted as a function

* See appendix for the method used to derive the mean curve in the Larson-Miller plot.

of stress at various temperatures in Figure 8 (Page 9). These data do not provide a measure of the steady state minimum creep rate since they take into account the initial plastic strain on loading the test piece and also the primary creep extension in addition to steady state creep extension. Limited data for minimum creep rate are given in Table 3 (Page 7).

Weldability

Alloy IN-519 can be welded by a variety of commercial processes, both manual and automatic. In commercial practice manual metal arc, TIG and MIG welding have all been used successfully; bare filler wires and coated electrodes are commercially available.

To ensure good weldability the carbon, niobium and phosphorus contents of the filler material are carefully controlled. The desirable levels of carbon and niobium to avoid weld-metal cracking are inter-related as shown in Figure 9 (Page 10). Niobium is preferably kept in the range 1.4 to 1.8 per cent, as in the parent alloy, while carbon is held to the slightly lower maximum level of 0.33 per cent compared with the 0.35 per cent upper limit of the range recommended for the parent material. In fact, it is preferable if the carbon content of the weld metal does not exceed 0.3 per cent. Similarly, the control of phosphorus in the filler material is slightly more stringent than in the parent alloy and the content should be less than 0.02 per cent. Even with correct levels of carbon and niobium hot-cracking of the weld metal can occur if the phosphorus content is too high. Additionally, filler metal silicon contents below 0.8 per cent are preferable for optimum weldability.

Heat-affected-zone cracking of IN-519 parent metal has not been observed in castings having compositions within the recommended range. However, some HAZ cracking has been observed in cast tubes of 24Cr-24Ni-Nb steel with carbon contents of 0.42 and 0.46 per cent.

In comparison with the welding of HK-40 steel the welding of IN-519 may require greater control of heat input since the niobium-containing alloy is slightly more susceptible to hot-cracking. However, providing care is taken in this respect, coupled with the aforementioned compositional control, completely sound welds are obtainable. Control of the interpass temperature to less than 200°C has generally given crack-free weld-joints. In contrast, one instance of HAZ cracking has been encountered when the interpass temperature was allowed to rise to 400°C.

In commercial welding practice the TIG process has been predominantly employed with IN-519 centri-cast tubes, employing filler material from wire or cast sticks of essentially matching composition. Root runs have been made autogenously or by TIG deposition of added filler metal. Additionally, both the MIG and manual metal arc processes have been used for filling runs.

Weld preparations have been dictated by the particular experience of individual companies. In general, however, a single U preparation has been used for centricast tubes, with a 2-4 mm root face, a land between 0 and 4 mm, and a root radius of about 3 mm. The bevel angle is sometimes dictated by the process and is typically 15° for TIG welding, or 25° for manual metal

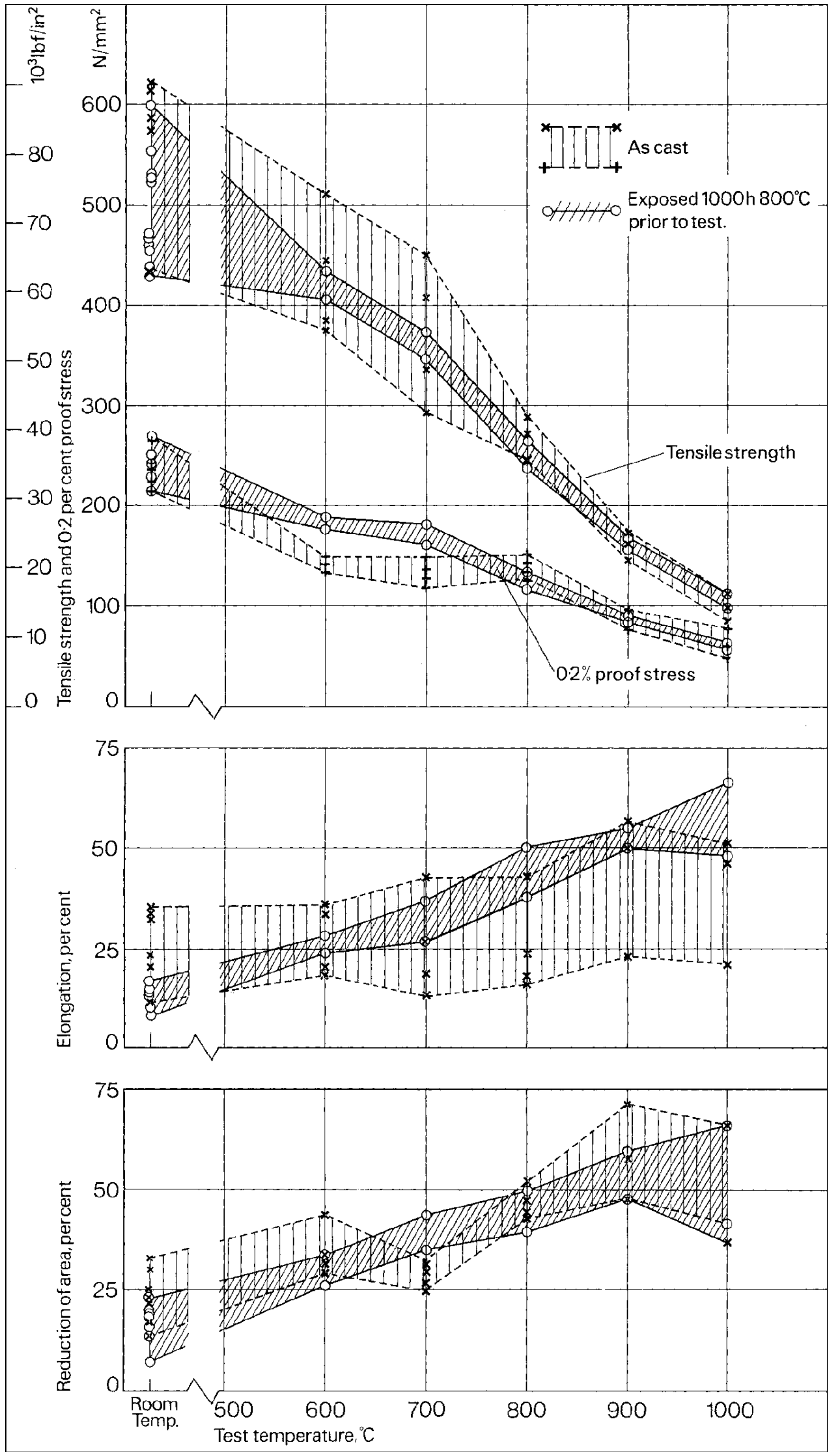


Figure 3. *Representative tensile properties of Alloy IN-519 as a function of test temperature: as-cast, and after prolonged exposure at 800°C.*

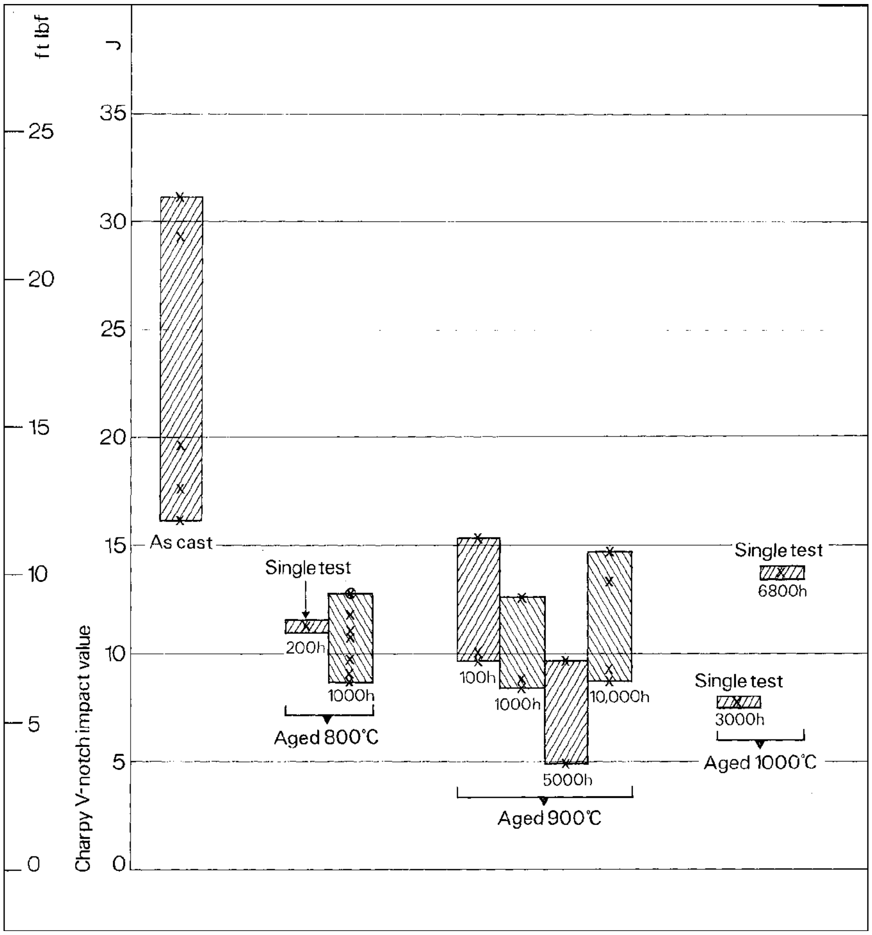


Figure 4. *Effect of exposure at 800–1000°C on the room-temperature impact resistance of Alloy IN-519.*

arc welding to allow better access. For autogenous TIG welding of the root a closed butt configuration is used.

Laboratory trials by Inco have also demonstrated the feasibility of autogenous plasma-arc welding for the forming of a root bead. Such root runs have been made by melting through a 3.2 mm root face having a 1.6 mm root gap, using 200 amps at a welding speed of 0.47 m/min, with argon + 7.5 per cent hydrogen as the plasma gas.

Weld-joint properties

Stress-rupture data for TIG welds made in IN-519 centricast tubes of commercial manufacture, using cast stick filler material matching the composition of the parent metal, are shown in Figure 6. These data show the weld joints to have stress rupture strengths similar to those of the parent tubes. Similar data for TIG welds have also been reported elsewhere [(2)].

In stress-rupture tests at 900°C and 1000°C on coated-electrode weld joints, rupture-strength joint efficiencies of 70–100 per cent have been obtained.

The stress-rupture properties of weld-joints in Alloy IN-519 may be contrasted with comparable joints in HK-40 steel for which TIG welds give a lower weld-efficiency of about 80 per cent, while HK-40 weldments prepared with conventional basic-coated electrodes usually have a joint efficiency of only about 60 per cent. However, it should be noted that recent tests on welds made with rutile-coated electrodes of appropriate composition have indicated that manual metal arc welds can be made in HK-40 steel giving joint efficiencies of 70–80 per cent.

The generally superior stress-rupture

Table 2. Comparison of derived-rupture-stresses* for various rupture lives of Alloy IN-519 and HK-40 steel.

Test Tempera-ture (°C)	Duration (hours)	Mean derived-rupture-stress				Minimum derived-rupture-stress (77% of mean)				Ratio of derived -rupture-stress IN-519/ HK-40†
		IN-519		HK-40		IN-519		HK-40		
		N/mm²	lbf/in²	N/mm²	lbf/in²	N/mm²	lbf/in²	N/mm²	lbf/in²	
800	1,000	78.5	11385	71.7	10392	60.4	8766	55.2	8002	1.10
	3,000	68.3	9907	59·0	8563	52.6	7628	45.5	6594	1.16
	10,000	58.0	8406	47.4	6874	44.6	6473	36.5	5293	1.22
	30,000	49.4	7158	38.5	5587	38.0	5512	29.7	4302	1.28
	100,000	40.9	5932	30.5	4418	31.5	4568	23.5	3402	1.34
900	1,000	44.5	6451	36.7	5325	34.2	4967	28.3	4100	1.21
	3,000	36.6	5312	29.0	4207	28.2	4090	22.3	3239	1.26
	10,000	29.2	4233	22.2	3220	22.5	3259	17.1	2479	1.31
	30,000	23.4	3396	17.3	2502	18.0	2615	13.3	1927	1.36
	100,000	18.1	2631	13.0	1882	14.0	2026	10·0	1449	1.40
1000	1,000	21.9	3172	17.5	2539	16.8	2442	13.5	1955	1.25
	3,000	16.9	2454	13.2	1916	13.0	1890	10.2	1475	1.28
	10,000	12.6	1821	9.6	1391	9.7	1402	7.4	1071	1.30
	30,000	9.4	1367	7.1	1030	7.3	1053	5.5	793	1.33
	100,000	(6.8)	(981)	5.0	732	(5.2)	(755)	3.9	564	1.34

** Rupture stresses were derived from Larson-Miller plots of available test data. Values in parentheses were derived by extrapolation beyond the highest value of the Larson-Miller parameter plotted in Figure 5.*
† Minimum derived-rupture-stresses, taken as the lower 95 per cent confidence limit, were 23 per cent lower than the mean derived-rupture-stresses for both IN-519 and HK-40. Thus the mean- and the minimum-stress ratios of the two materials are the same.

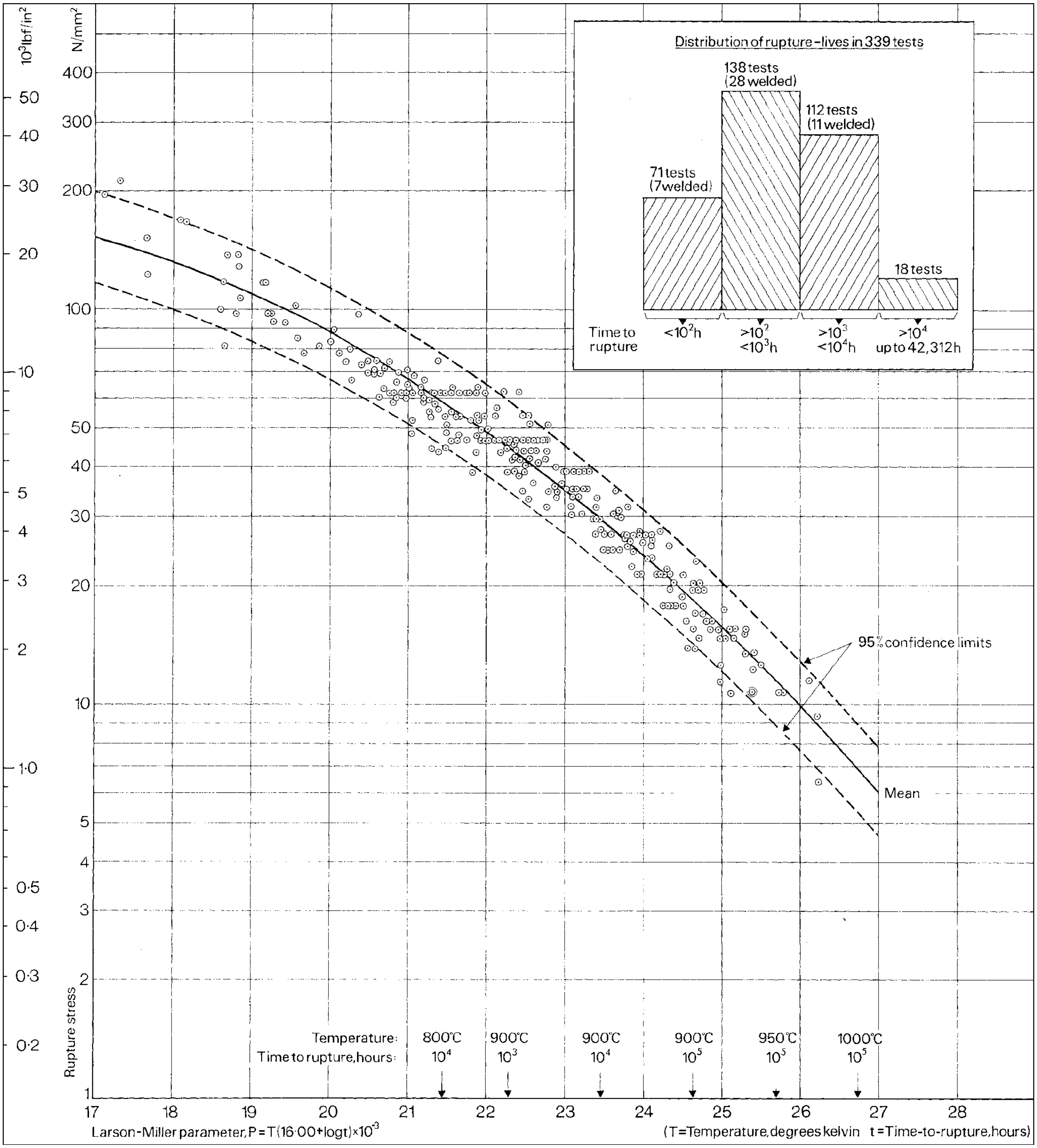


Figure 5. *Alloy IN-519. Larson-Miller stress-rupture relationship.*

Table 3. Alloy IN-519. Minimum creep rate/stress data.

Temperature °C	Minimum creep rate per cent/hour	Stress for given minimum creep rate	
		N/mm²	lbf/in²
900	0.001 0.0001	42.7 30.0	6200 4500
1000	0.001 0.0001	18.1 12.4	2620 1790

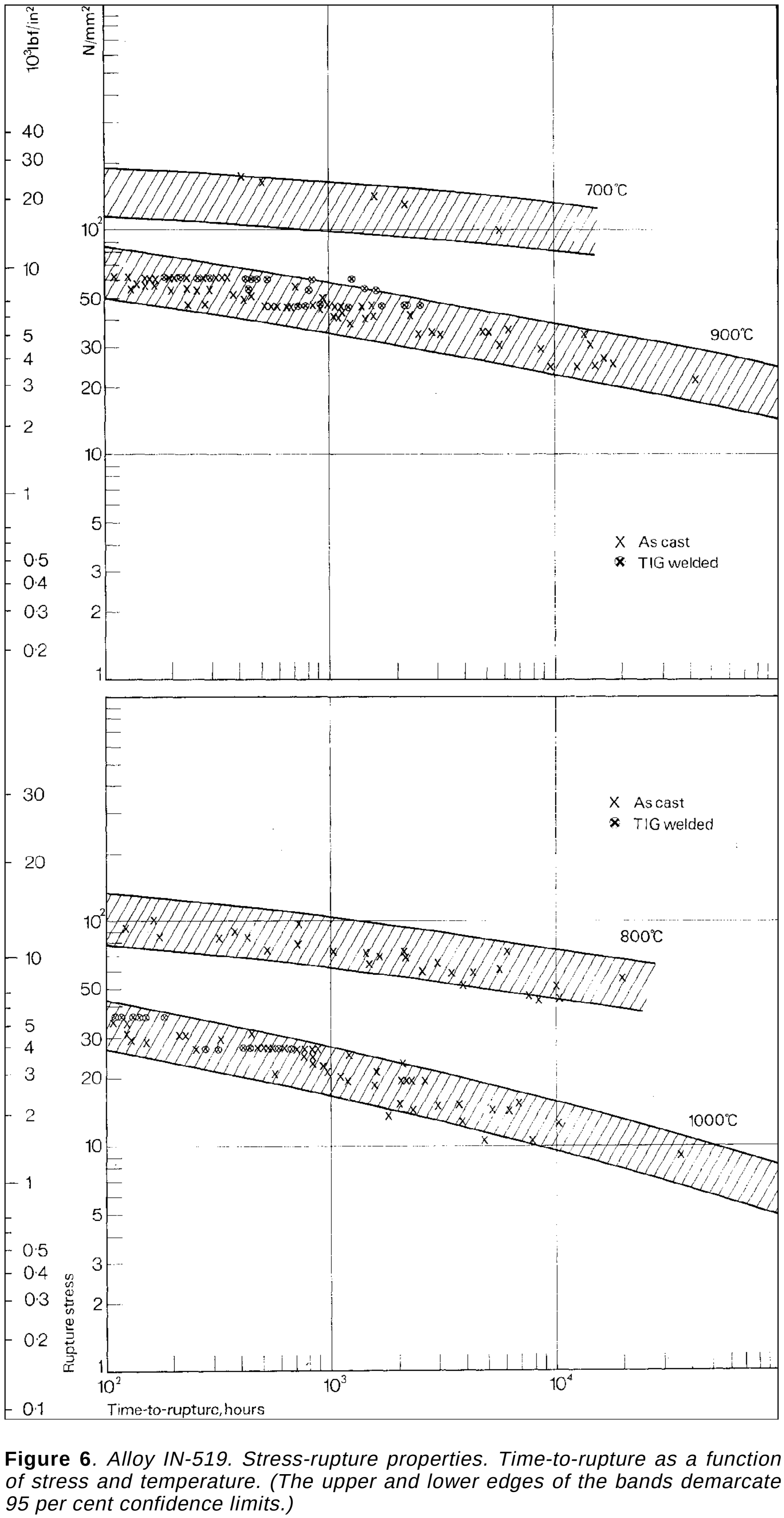


Figure 6. *Alloy IN-519. Stress-rupture properties. Time-to-rupture as a function of stress and temperature. (The upper and lower edges of the bands demarcate 95 per cent confidence limits.)*

characteristics of IN-519 weld joints compared with those of HK-40 have prompted the suggestion that IN-519 filler metal can be used for the welding of HK-40 to provide welds having stress-rupture strengths matching those of the parent metal. In fact, trial welds in HK-40, made by Inco using IN-519 consumables, have given stress-rupture lives at given stress levels similar to those of unwelded HK-40, with failure occurring in the parent metal.

In common with experience in welding other high-carbon austenitic heat-resisting alloys, the room-temperature ductilities of weld deposits in IN-519 are less than those of the parent metal, whilst tensile strengths of the deposited alloy are higher. However, TIG weld deposits tend to have higher ductilities than manual metal arc deposits. For example, elongations of 8–15 per cent and 4–8 per cent have been obtained in TIG and MMA deposits, respectively, on a 50 mm gauge length, in tensile tests transverse to the joints, whereas elongations for the parent metal are typically 15–20 per cent.

Thermal fatigue resistance

The ability of a heat-resisting alloy to withstand cyclic thermal stresses without ultimate cracking ensuing is an important factor in determining the service life of components used in intermittent high-temperature duty although primarily designed on the basis of the properties of the alloy at high temperatures. The stresses developed on heating to and cooling from the service temperature depend on several factors, including the design, rate of temperature change, thermal physical properties of the alloy and its ability to yield locally, thus avoiding the generation of high stress concentrations. The thermal fatigue life of individual components as a result of these combined effects is difficult to predict from laboratory test data on simple test specimens. Therefore, tests that have been devised generally provide a comparative measure of the resistance of different alloys to cracking when subjected to a number of cycles of rapid heating and cooling, but it must be emphasized that the results obtained are only strictly valid for the particular test conditions employed. The results of one form of test in which the behaviour of Alloy IN-519 and HK-40 steel were compared are given in Table 4 (Page 10)[2].

Corrosion resistance

High-temperature oxidation

Alloy IN-519 has similar oxidation resistance to HK-40 steel at temperatures up to 1000°C as shown by the results of short-time static and cyclic oxidation tests given in Table 5 (Page 10). At those temperatures the weight loss of IN-519 after mechanical descaling is within the limit(s) prescribed for heat-resisting material in Stahl-Eisen-Werkstoffblatt 470. The latter defines a material as heat-resistant at a temperature 'X', if the average weight loss by scaling does not exceed 1 g/m^2h at that temperature and does not exceed 2 g/m^2h at a temperature of X + 50°C, when heated in air at those temperatures for five cycles of 24 hours each. Cooling to room temperature is effected after each heating cycle and the test sample is finally descaled mechanically.

With increasing test temperature above 1000°C the oxidation resistance of IN-519 becomes less than that of HK-40; however the difference only becomes significant at temperatures well in excess of the temperature range of application for reformer tube service.

Carburization

Alloy IN-519 is not intended for use under severely carburizing conditions as are produced in ethylene pyrolysis furnaces. However, the alloy does have adequate carburization resistance in moderately carburizing environments which may sometimes be encountered in steam-hydrocarbon reforming furnaces.

Laboratory tests at the Inco European Research and Development Centre have shown that the carbon pickup in IN-519 heated in a solid pack-carburizing medium is similar to that of low-silicon HK-40 steel, but is higher than that of high-silicon grades of HK-40 (Table 6) (Page 10).

Stress-corrosion cracking characteristics

Stress-corrosion cracking problems in reformer catalyst tubes have been largely overcome by suitable design. However, the reader who may be interested in this aspect of material performance should refer to the results of laboratory tests in various chemical media reported elsewhere[3]. That investigation indicated that the stress-corrosion cracking resistance of Alloy IN-519 is equal or superior to that of HK-40 steel depending on the environmental test conditions.

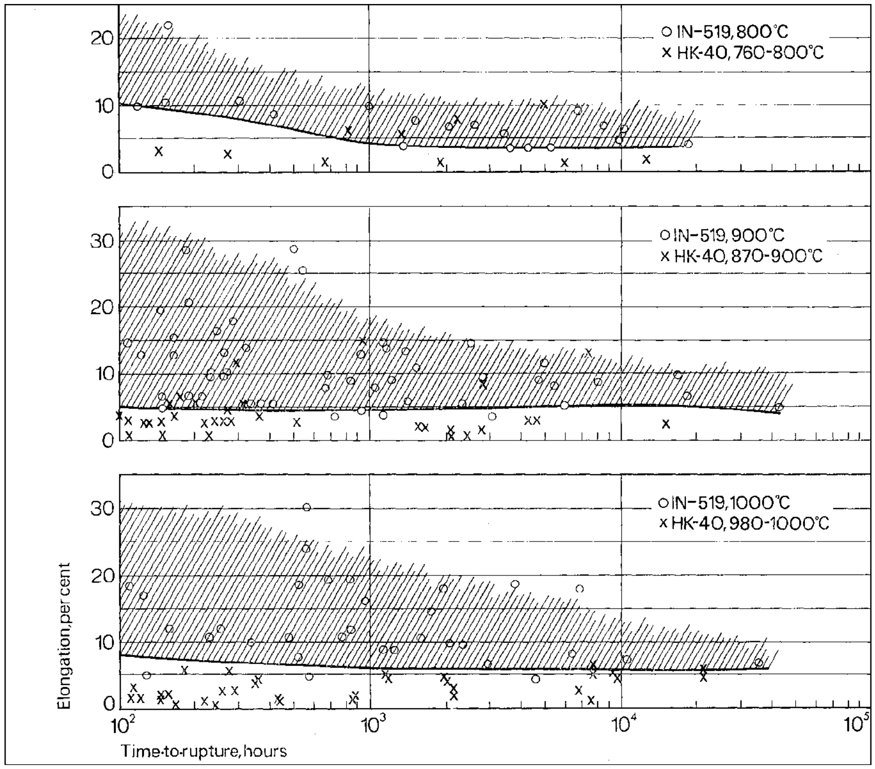


Figure 7. *Stress-rupture ductility of Alloy IN-519, in comparison with HK-40 steel.*

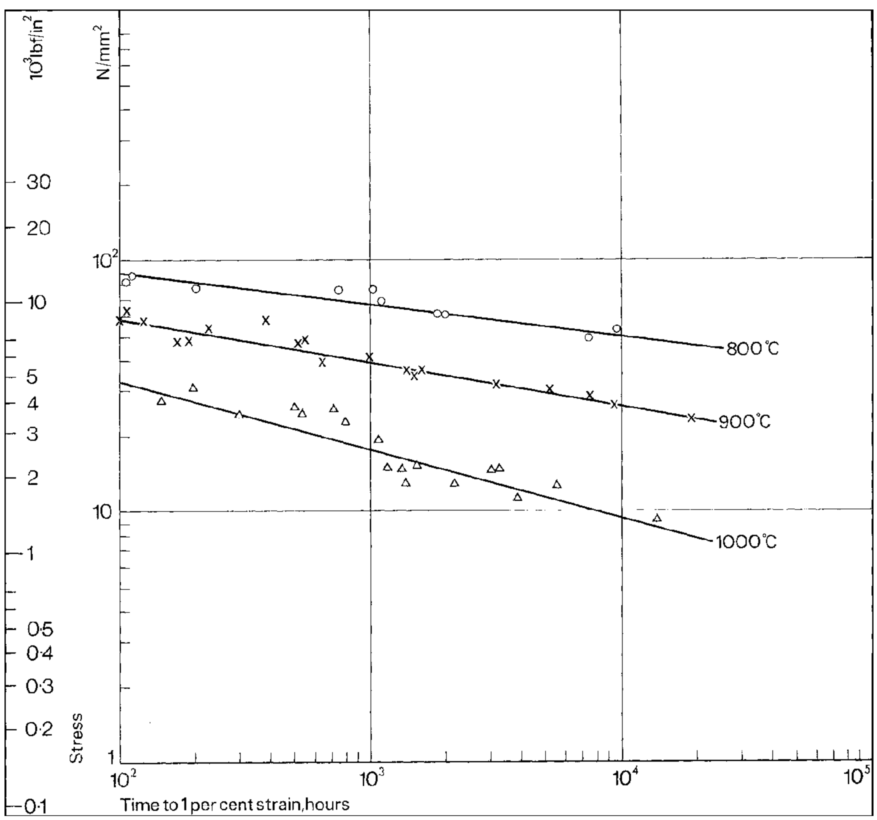


Figure 8. *Alloy IN-519. Creep properties. Time to 1 per cent total strain as a function of stress and temperature.*

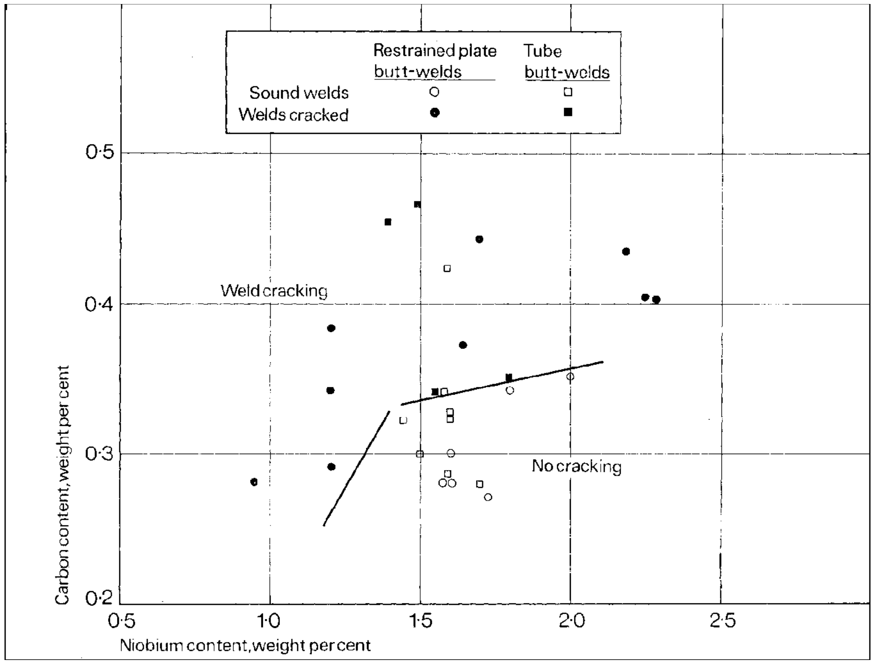


Figure 9. *Inter-relationship between carbon and niobium on the weld-cracking behaviour of 24Cr-24Ni steel weld deposits in restrained plate and tube butt-weld cracking tests.*

Table 4. Resistance to thermal fatigue: cyclic heating and cooling test results.

Material	Temperature cycle	Number of cycles to crack initiation	
IN-519 HK-40	Cylindrical specimen heated on one side to 1100°C and quenched in water	50, 30,	50 30

Table 5. Oxidation resistance of IN-519 and HK-40.

Alloy	Test temperature °C	Cyclic tests[1]		Static tests[2]	
		Weight loss after descaling		Weight loss after descaling	
		mg/cm²	g/m²h	mg/cm²	g/m²h
IN-519	900 1000 1050 1100	0.6, 3.1, 3.2 7.5, 8.7, 9.3 11.5, 24.2 56, 82	0.05, 0.26, 0.27 0.62, 0.73, 0.78 0.96, 2.02 4.7, 6.8	0.7, 2.9 4.6, 5.4 13.4 19.5, 22.9	0.07, 0.29 0.46, 0.54 1.34 1.95, 2.29
HK-40 (1.3–1.6% Si)	900 1000 1050 1100	2.2, 4.0 3.8, 7.0 13.0 9.9, 13.0	0.2, 0.3 0.32, 0.58 1.08 0.84, 1.08	0.3, 1.9 3.1, 4.9 5.1 8.0, 8.4	0.03, 0.19 0.31, 0.49 0.51 0.8, 0.84

(1) 5 cycles of 24 hours each at test temperature, cooled to room temperature between each cycle.
(2) 100-hour continuous test.

Specimens of 7.6 mm diameter × 13 mm long were used for each type of test.

Table 6. Carburization test results (1000 hours at 1025°C in solid carburizing medium).

Depth below surface, mm	Carbon pickup, weight per cent		
	IN-519 (0.32C, 0.95Si)	HK-40 (0.43C,1.03Si)	HK-40 (0.37C, 1.85Si)
0–1 1–2 2–3 3–4	0.36 0.25 0.16 0.11	0.32 0.20 0.13 0.11	0.13 0.11 0.08 0.07

Physical properties

Typical physical property data of Alloy IN-519 are given in Tables 7-12.

Table 7. Alloy IN-519. Physical properties.

Melting range:	
Solidus	1349°C
Liquidus	1367°C
Specific gravity	7.92
Specific heat	Table 8
Electrical resistivity	Table 9
Thermal conductivity	Table 10
Thermal expansion	Table 11
Modulus of elasticity (Dynamic)	Table 12

Table 8. Alloy IN-519. Specific heat values.

Temperature °C	Specific heat, c	
	J/kg K	cal/g °C
20	452 (419 measured)	0.108 (0-100 measured)
100	473	0.113
200	502	0.120
300	528	0.126
400	553	0.132
500	582	0.139
600	607	0.145
700	636	0.152
800	662	0.158
900	691	0.165
1000	717	0.171
1100	741	0.177

Calculated from $c = \frac{3R(1 + \beta T)}{A}$ *cal/g °C* [4]

3R = 5.96
$\beta = 6 \times 10^{4}$
T = temperature °C
A = 55.8, the 'average atomic weight' of the alloy.

Table 9. Allay IN-519. Typical electrical resistivity values.

Temperature °C	Electrical resistivity, microhm cm
24	97.1
100	101.0
200	105.9
300	109.3
400	112.4
500	115.4
600	117.8
700	119.3
800	120.8
900	123.5
1000	124.4

Table 10. Alloy IN-519. Thermal conductivity values.

Temperature °C	Thermal conductivity, λ	
	W/mK	cal/cm s °C
24	12.7	0.0303
100	14.1	0.0337
200	15.8	0.0377
300	17.5	0.0418
400	19.2	0.0459
500	20.7	0.0494
600	22.3	0.0533
700	24.0	0.0573
800	25.6	0.0611
900	26.9	0.0642
1000	28.5	0.0681

Calculated from $\lambda = \frac{2.2T \times 10^{-8}}{\rho} + 0.06$ *J/cm s °C* [5]

T = absolute temperature
ρ *= electrical resistivity, microhm cm*

Table 11. Alloy IN-519. Typical mean coefficients of linear thermal expansion.

Temperature °C	Mean coefficient of linear expansion, 10^{-6}/K
20–100	12.9
20–200	14.4
20–300	15.7
20–400	15.8
20–500	16.3
20–600	16.8
20–700	17.0
20–800	16.8
20–900	16.9
20–1000	17.1

Table 12. Alloy IN-519. Typical modulus of elasticity values (Dynamic determination).

Temperature °C	Modulus of elasticity			
	Heat 1		Heat 2	
	GN/m^2	10^6lbf/in^2	GN/m^2	10^6lbf/in^2
20	168	24.4	152	22.0
100	163	23.6	147	21.3
200	156	22.6	141	20.4
300	148	21.5	135	19.5
400	141	20.5	128	18.6
500	135	19.6	121	17.5
600	128	18.6	114	16.5
700	121	17.5	107	15.5
800	112	16.3	~ 102	~ 14.8
900	-	-	~ 99	~ 14.4
1000	-	-	~ 96	~ 14.0
1100	-	-	~ 92	~ 13.4

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Appendix: Derivation of the Larson-Miller mean curve

The method used optimizes the parameric constants of a second order polynomial equation of the Larson-Miller parameter, P, by minimizing the sum of the squares of the deviation of the actual data points from the equation of best fit. For the data on Alloy IN-519 this equation is:

$$\log \text{stress } (N/mm^2) = 0.667894 + 0.234009\, P\text{-}0008526\, P^2$$

where $P = T\,(C + \log t) \times 10^{-3}$

and T =Temperature, degrees Kelvin

C, the Larson-Miller constant, = 16.0

t=Time-to-rupture, hours.

The standard error of the estimate is 0.056626 and 95 per cent confidence limits (±twice the standard error) are as shown in Figure 5.

As with all methods of extrapolation the method used in this publication makes certain assumptions on the form of the stress/temperature/rupture-time relationship, and also uses equally weighted data points. Other methods of extrapolation may give different values for stresses derived from the same test data, in comparison for example with the stresses quoted in Table 2. The latter were derived using the same principles of extrapolation for both IN-519 and HK-40 steel.