CREEP-RESISTANT NON-FERROUS ALLOYS

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Abstract

The article describes briefly creep phenomena and various metallurgical factors like grain size, alloy additions, dispersed phases, cold work, and heat treatment which influence creep properties. A review of the newer non-ferrous metal alloys like the aluminium-base, magnesium-base, copper-base, nickel-base, cobalt-base, chromium-base and others is presented in some detail depicting their particular significance and varied applications. A brief mention has also been made of the special significance of titanium-base and beryllium-base alloys stressing the need for development of those alloys specially in view of their industrial and strategic importance.

Introduction

IN the development of creep-resistant materials for high temperature applications, the non-ferrous metals have played an important part. Plain carbon steels are limited in use above a certain temperature, say 450°C., due to comparatively poor creep properties and low resistance to corrosion. Even at low temperatures up to about 300°C., where steels are strong, there are non-ferrous alloys like copper-base, magnesium-base and aluminium-base alloys which are more attractive than steels, because they have either better corrosion resistance or are less dense in addition to possessing good creep characteristics. Non-ferrous metals, when used as alloying elements with iron, not only increase its strength at high temperatures, but also enhance its resistance to corrosion. With the coming of turbo-jet engines where operating temperatures are as high as 800°C., the iron-base matrix is inferior in comparison to purely non-ferrous nickel-base, chromium-base and cobalt-base solid solution matrices.

Aircraft, steam power, chemical and petroleum industries are the main consumers of metals and alloys used at elevated temperatures. In view of the expected future expansion of these industries it is foreseen that there will be a considerable demand for this type of alloys in this country.

The purpose of this article is to review the newer non-ferrous creep-resistant materials, depict their particular significance and varied applications and emphasize the need for development of possible other types of alloys in view of their industrial and strategic importance.

Creep Phenomenon

Creep is the increasing deformation with time which occurs when a metal is stressed at a constant load while held at a constant temperature. There is no real limit of stress or temperature below which creep is absent, but the occurrence of creep during service is well known to be a more serious problem at about $\theta/3$ where θ is the melting point in degrees absolute. Creep tests are conducted to establish safe working stresses for materials subjected to sustained loading. The creep strength is defined by the maximum stress that can be applied at a given temperature without causing flow of the material at a rate exceeding a given limit or not exceeding a certain amount of extension (say 0·1 per cent) in a specified number of hours (say 1000 hr.).

The plot of strain with time at constant load (ideally constant stress) and constant temperature is called the creep curve. The creep curve is usually divided into the following four parts as shown in Fig. **1**: (1) an initial extension, (2) a stage during which

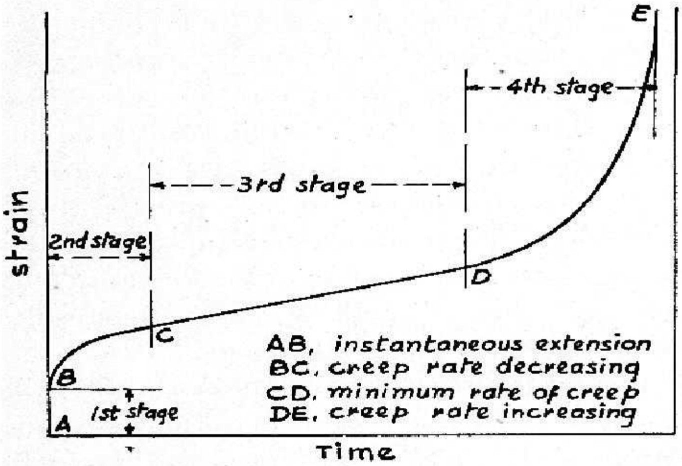

FIG. 1 — CREEP CURVE

creep rate decreases, (3) a stage in which the creep rate remains constant, and (4) a stage in which the creep rate increases till the fracture occurs.

When temperature is raised for a given stress or when stress is raised for a given temperature, the creep rates during the primary and secondary stages of creep as well as the duration of the secondary creep stage are all varied very appreciably, as shown by Griffiths[1].

Metallurgical Factors Influencing Creep

Creep is an extremely structure-sensitive property and is affected by minor variations in metallurgical condition in a very pronounced degree. Important factors which affect creep are:

1. Grain size
2. Alloy additions and dispersed phases
3. Cold-working, recovery and recrystallization
4. Heat treatment

A study of the alloys used at temperatures above 800°C. shows that with one or two exceptions such as nickel-molybdenum alloys the major components of the alloys are usually two or more of the elements nickel, chromium, iron or cobalt. Also with the exception of chromium-base alloys the matrix of most of the alloys, e.g. the nickel-chromium alloys and cobalt-base alloys, is the austenitic face-centred cubic solid solution of a combination of the above elements. Creep resistance is developed in this matrix in nearly all the alloys by the addition of elements such as molybdenum, tantalum, titanium, aluminium, etc., which strengthen the alloys by the precipitation of either carbides or intermetallic phases during service at high temperatures or during a preliminary heat treatment.

It is also evident that there is a rough correlation between the melting point of an alloy and the temperature range of its usefulness for creep resistance.

1. *Grain Size* — The grain size and grain boundary condition of a material influence its creep behaviour. It is well known that when a strong metal is stressed at room temperature, the fracture takes place within the grains, while at elevated temperatures and for longer fracture times the fracture occurs around the grains. This shows that in a metal the grains are weaker than the grain boundaries at room temperature and the grains are stronger than the grain boundaries at elevated temperatures. From this it follows that a metal with a fine-grained structure will possess the greatest creep resistance at low temperatures and a coarse-grained structure will have superior creep strength at higher temperatures. This does not necessarily apply to alloys where other factors may mask the effects of the grain size.

There will, however, be a temperature for a given metal at which the grain and the grain boundary will have the same strength. This temperature is called the equi-cohesive temperature. It varies with the rate of strain. For slow strains it is more or less equivalent to the temperature of recrystallization. Coarse-grained metals should, therefore, possess the maximum creep strength at temperatures above the lowest temperature of recrystallization, whereas at temperatures below this, the fine-grained alloys should be superior. This point is illustrated by the work of Clark and White[2]

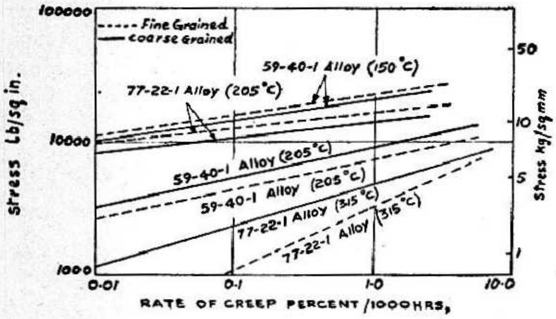

FIG. 2 — INFLUENCE OF GRAIN SIZE ON RATE OF CREEP OF HOT-ROLLED COPPER-ZINC-TIN ALLOYS (CLARK & WHITE)

on two copper-zinc-tin alloys in both the fine and coarse-grained conditions, as shown in Fig. 2.

2. *Alloy Additions and Dispersed Phases* — Even small quantities of solute elements strain the parent lattice and restrict the development of slip processes, hence reducing both primary and secondary creep[3]. This is particularly true when the diameter of the solute atoms differs appreciably from that of the solvent. For large concentration of solute atoms a different effect may arise[4]. At a constant elevated temperature the increasing atomic mobility in the lattice caused by increasing alloying additions will tend to make the melting point of the alloy closer to the chosen temperature, thus lowering the creep resistance.

Reinforcement of a parent lattice can be effected by a fine dispersion of a second phase. Such a phase must be strong and metallurgically stable in order that it may be an effective strengthener. Fine dispersions are often strong but metallurgically unstable, whereas coarse dispersions are mechanically weaker but metallurgically stable. The optimum condition, therefore, is one in which the particles are as fine as is compatible with a relatively stable condition. The optimum dispersions for any temperature will depend upon the time that the material must be in service. Materials that appear to be superior in tests of a few hundred hours are often weaker in tests which last several thousand hours. The optimum structure is coarser for higher temperatures or longer times. Results illustrating this point are given by Jenkins, Bucknall and Jenkinson[5], who investigated the creep properties in various stages of hardening of a precipitation-hardenable copper-nickel-silicon alloy containing about 2·4 per cent nickel and 0·65 per cent silicon. Table 1 shows the results obtained by these investigations.

The results show that in the normal tensile test the fully hardened material was the strongest at all the three temperatures. In creep tests, however, this was only true at 200°C. at which temperature the atomic mobility was low. At 300° and 450°C. the slowly cooled material was the strongest in the 1000 hr. tests.

Solute elements which are likely to produce precipitation-hardening or carbide phases are the sources of dispersed phases. These elements are tungsten, molybdenum, titanium, columbium, carbon, etc. These elements either form carbides or intermetallic compounds which, when dispersed properly, strengthen the solid solution matrix. The carbides are generally better strengtheners than the intermetallic compounds.

3. *Cold-working, Recovery and Recrystallization* — Growth of new strain-free crystals takes place when a cold-worked metal is heated to above a certain critical temperature. This process is called recrystallization. Recrystallization takes place in three steps, viz. recovery, nucleation of new strain-free crystals and finally grain growth. Consequently the effect of cold-working on the creep behaviour will be important only below the recrystallization temperature. The work of Zschokke and Niehus[6] on chromium-nickel steel containing small amounts of titanium and tungsten shows that cold-work to a certain limit produces a beneficial effect by reducing the amount of creep in the primary stage and the steady stage. Further, the work of these authors shows that for each test temperature there is an optimum degree of cold-working for producing

TABLE 1 — COMPARISON OF TENSILE AND CREEP PROPERTIES OF AN AGE-HARDENABLE COPPER-NICKEL-SILICON ALLOY IN VARIOUS INITIAL CONDITIONS (JENKINS, BUCKNALL & JENKINSON)

Temperature of test, °C.	Stress to bring about rupture in 0·1 hr.					
	Slowly cooled from 900°C.		W.Q. from 900°C.		Fully hardened W.Q. + 2 hr. at 500°C.	
	tons/sq. in.	kg./sq. mm.	tons/sq. in.	kg./sq. mm.	tons/sq. in.	kg./sq. mm.
200	14·50	22·80	15·8	24·9	35·50	55·90
300	12·70	20·00	15·6	24·6	25·00	39·40
450	8·40	13·20	10·3	16·2	12·20	19·20
			1000 hr.			
200	14·00*	22·00	16·0*	25·2	22·00	34·60
300	8·80	13·90	7·2	11·3	6·60	10·40
450	3·55	5·59	2·3	3·6	1·85	2·91

*Specimens slowly loaded during previous 2-3 hr.
W.Q. = Water-Quenched.

maximum creep resistance and this optimum degree of cold-work decreases with increasing temperature of creep test.

What is said above applies whether the cold-work is performed at room temperature or for convenience or incidentally at higher temperatures. Since creep in the primary stage is accompanied by strain-hardening, it is natural that the temperature of the creep test is sufficiently raised; such strain-hardening may be followed by recovery and re-crystallization processes. From creep experiments on cold-worked lead, Greenwood and Worner[7] have shown that during the process of recrystallization, the creep curve is modified; accelerated creep occurs during recrystallization and is followed by a period of relatively slow creep characteristic of the recrystallized material. The experiments of Schmidt and Wassermann[8] on cold-worked copper also confirm the above findings.

Sully, Cale and Willoughby[9] attribute the cause of tertiary creep and fracture to the process of recrystallization and recovery. On the other hand, Jenkins and Mellor[10] have shown that recovery and recrystallization during creep tests may take place much below the minimum recrystallization temperature.

4. *Heat Treatment* — The heat treatment used for high-temperature materials should be such as to yield an initially strain-free material having a relatively stable metallurgical structure, as a metallurgical condition of maximum strength is by itself insufficient from the point of view of good service performance. Often the high-strength conditions under the influence of stress undergo structural changes resulting in high creep rates. A stable metallurgical condition may be achieved by an isothermal overageing heat treatment at or just above the service temperature, or by a very slow cooling operation from a temperature higher than the service temperature.

Almost all the important creep-resistant alloys are precipitation-hardened, i.e. by an appropriate heat treatment either before or during service, a constituent differing from the matrix is dispersed throughout the structure in a finely divided form. Such a fine dispersion helps in hindering the initiation and propagation of slip processes and thus enhances the creep resistance of the alloys.

Non-ferrous-base Creep-Resistant Alloys

Aluminium-base Alloys — Because of their lightness, strength, ductility and resistance to corrosion, aluminium-base alloys constitute an important class of creep-resistant material. With the development of jet-propelled airplanes, considerable interest has arisen in the creep properties of aluminium alloys at temperatures up to 200°C. The alloys used for creep resistance are either age-hardening type or wrought alloys, the former being the stronger type.

The first age-hardening alloy was discovered by Wilm in 1911. It contains 4 per cent copper, 0·55 per cent magnesium, 0·4 per cent silicon, 0·6 per cent manganese, and 0·4 per cent iron. There are many other aluminium-copper alloys derived from the basic duralumin composition but differing slightly in their response to heat treatment and maintenance of strength at high temperatures. Compositions of a few American alloys are given below and creep properties due to Flanigan, Tedsen and Dorn[11] are shown in Fig. 3.

	Cu, %	Cr, %	Mg, %	Mn, %	Si, %	Zn, %
24S	4·5	—	1·5	0·6	—	—
R301	4·5	—	0·4	0·8	1·0	—
75S	1·6	0·3	2·5	0·2	—	5·6

In addition to these aluminium-copper alloys, age-hardening alloys are known in the

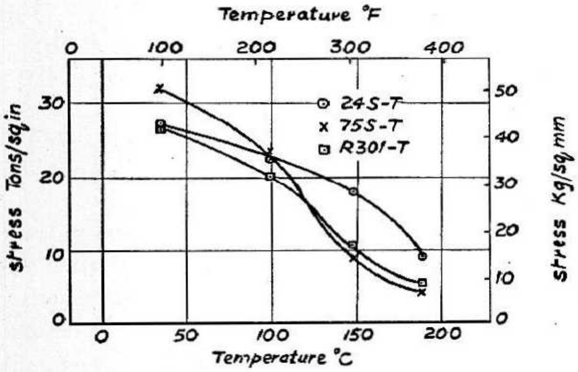

FIG. 3 — STRESS FOR MINIMUM CREEP RATE OF 10^{-5} IN./IN./HR. FOR HEAT-TREATED ALUMINIUM ALLOY SHEET (FLANIGAN, TEDSEN & DORN)

aluminium-zinc-magnesium system, containing 2-4 per cent magnesium and 5-7 per cent zinc, and in the aluminium-silicon series containing 11-13 per cent silicon, up to 1 per cent manganese, magnesium, copper or nickel.

The wrought aluminium alloys usually contain copper, nickel, iron or magnesium. The earliest alloy of this type was γ alloy containing copper 4 per cent, magnesium 1·5 per cent, silicon 0·7 per cent, nickel 2 per cent, iron 0·6 per cent. From this basic composition a number of alloys of very similar composition, the RR alloys, have been developed. One of the best known of these alloys is RR56, composition of which is:

Cu, %	Mg, %	Si, %	Ni, %	Ti, %	Fe, %
2·09	0·57	0·54	1·44	0·07	1·26

This alloy has outstandingly good creep properties at elevated temperatures and is capable of withstanding over twice the stress of 24S for the same rate of steady state creep.

Magnesium-base Alloys — Pure magnesium creeps at room temperature, but when alloyed with certain metals, its resistance to creep increases. In recent years the development of magnesium alloys has taken an important position due to their use in light-weight aircraft engines. The small amount of alloying elements used are silicon, aluminium, zinc, manganese and cerium. These alloys are used both in the cast and wrought conditions. The composition of various alloys used and their creep strength at different temperatures are shown in Tables 2 and 3 due to Vosskuhler[12]. The tables show that the wrought alloys are far superior to the cast alloys at room temperature and slightly elevated temperatures. The same results were obtained by Moore and McDonald[13] who showed in addition that the stress required to cause rupture in 1600 hr. is above the yield strength for nearly all the alloys. Above a temperature of 100°

TABLE 2 — CREEP STRENGTH OF CAST MAGNESIUM ALLOYS (VOSSKUHLER)

Alloy	Treatment	Stress (tons/sq. in.) to produce permanent set of 0·1% after 200 hr. at temperatures of			
		30°C.	100°C.	150°C.	200°C.
Sandcast AM503 (2 Mn)	As cast	1·33	1·02	0·95	0·89
CMSi (1 Si)	As cast	2·22	1·78	1·40	1·02
AZ31 (coarse) (3 Al, 1 Zn)	As cast	2·10	1·78	—	1·46
AZ31 (fine)	As cast	3·05	2·35	2·16	1·52
AZF (3 Al, 3 Zn)	As cast	3·87	3·18	2·04	0·76
AZG (6 Al, 3 Zn)	As cast	5·14	2·60	1·27	0·76
AZG (200°C.)	10 hr. 200°C.	5·45	3·18	1·78	0·70
AZG (300°C.)	4 hr. 300°C.	4·70	3·62	1·33	0·64
A8 (8 Al)	As cast	5·08	3·37	1·40	0·51
A9 (8·5 Al, 0·5 Zn)	As cast	5·21	3·68	1·40	0·64
A9v	Homogenized	4·70	3·55	1·02	0·64
A9h	Precipitated	5·91	3·74	0·95	0·57
AZ91 (9·5 Al, 0·5 Zn)	As cast	6·22	3·37	1·15	0·44
Diecast A8	As cast	4·89	3·44	1·52	0·44
AZ91	As cast	5·78	3·81	1·21	0·32

TABLE 3 — CREEP STRENGTH OF WROUGHT MAGNESIUM ALLOYS (VOSSKUHLER)

Alloys	Treatment	Stress (tons/sq. in.) to produce permanent set of 0·1% after 200 hr. at temperatures of			
		30°C.	100°C.	150°C.	200°C.
AM503 (2 Mn)	Extruded once	6·79	2·35	1·46	0·95
AM503	Extruded twice	3·49	0·76	0·13	—
AM537 (2 Mn, 0·5 Ce)	Extruded in lab.	11·30	9·52	5·27	1·46
AM537	Extruded in works	7·56	5·46	5·27	1·59
AZ31 (3 Al, 1 Zn)	Extruded in works	9·52	2·98	0·48	—
Z1b (4 Zn)	Extruded in works	6·86	2·79	0·76	0·64
AZM (6 Al, 1 Zn)	Extruded in works	13·27	4·13	0·44	—
AZ855 (8 Al, 1 Zn)	Extruded in works	10·29	4·06	0·44	—
V1 (10 Al)	Extruded in works	14·60	4·25	0·32	—
V1w	Extruded in works and homogenized	14·86	4·06	0·19	—
Vih	Homogenized and hardened	12·70	2·54	0·38	—
AM6 (2 Mn, 6 Ce)	Extruded in works, homogenized and hardened	8·51	6·60	6·10	2·16

to 150°C. the cast alloys prove superior to the corresponding wrought alloys perhaps due to the recovery and recrystallization taking place in the former above these temperatures.

The wrought magnesium-aluminium alloys and the magnesium-aluminium-zinc alloys are the most creep-resistant magnesium alloys at temperatures up to 100°C., while above this temperature the magnesium-manganese and magnesium-manganese-cerium alloys prove better.

Murphy and Payne[14] investigating the effect of zirconium on the creep properties of magnesium-cerium alloys found that 0·4-0·5 per cent addition of zirconium improved the creep resistance of these alloys considerably.

The creep resistance of the improved magnesium-base alloys compares very favourably with some of the aluminium-base alloys, and in consequence of the formers' lower density the future scope of these alloys seems to be wider.

Copper and Copper-base Alloys — Pure copper finds extensive application in electrical conductors and its alloys for boiler stay rods and fire-boxes. In these applications strength and resistance to creep at atmospheric and elevated temperatures are of great importance.

The strength of copper used for electrical purposes is increased by the addition of other elements like cadmium and silver. Silver is added (0·05 per cent) where a high resistance to softening at elevated temperatures and high conductivity are required[15].

The creep resistance of phosphorized copper has been investigated by Burghoff and Blank[16]. Tapsell and Johnson[17] have compared the creep characteristics at 300° and 350°C. of arsenical copper and silver-arsenical copper. The alloy containing silver was found to be superior at all stresses at these temperatures and it was found to be most marked at stresses less than 2 tons/sq. in. corresponding to creep rates of the order of 10^{-5} in./in./day.

Parker and Ferguson[18] have shown that copper alloys containing 2·59 per cent cobalt, 0·46 per cent beryllium and 2·25 per cent beryllium have outstanding creep resistance at 200°C.

Among the most commonly used industrial copper alloys with higher percentages of alloying elements are the copper-zinc alloys, copper-nickel-zinc alloys, copper-tin alloys which sometimes also contain some zinc, the copper-aluminium alloys, the copper-silicon-tin alloys, copper-nickel-zinc and copper-nickel alloys.

Voce[19] gives details of creep investigations on the aluminium bronzes and shows their superiority to the ordinary zinc and tin-containing bronzes. The bronzes investigated contained 10 per cent aluminium, 10 per cent aluminium and 3 per cent iron and 10 per cent aluminium, 5 per cent iron and 5 per cent nickel.

Nickel-base Alloys — The most important class of creep-resistant materials for applications at temperatures above 600°C. are the alloys of nickel. The alloys are: (1) nickel-chromium alloys, (2) nickel-molybdenum alloys, (3) nickel-chromium-iron alloys, and (4) nickel-copper alloys.

Nickel-chromium Alloys — The use of nickel-base, nickel-chromium and nickel-chromium-iron alloys for applications requiring a high resistance to oxidation at high temperatures is only well known. The chromium content of these alloys is limited to 20 per cent because of hot-working difficulties above the limit. For lack of sufficient strength at temperatures above 500°C., these alloys can be used only below this temperature.

Attempts to improve the creep properties of the straight nickel-chromium alloys resulted in the development of the ' nimonic ' series in England and the ' inconel ' series in the U.S.A.

The ' Nimonic ' Series[20,21] — Nimonic 75 was the first alloy developed in this series and is used in the form of sheet for gas turbine flame tubes and as castings for nozzle guide vanes. The alloy contains approximately 20 per cent chromium, 0·05-0·2 per cent carbon and 0·2-0·3 per cent titanium. Maximum creep resistance for this alloy is obtained by a solution treatment at 1150°-1250°C. followed by a precipitation treatment at about 700°C.

Further research led to the development of the alloys nimonic 80 and nimonic 80A which find exclusive application for rotor blades in British gas turbine and jet engines. These alloys in addition to having good oxidation and creep resistance have also good fatigue properties at the service temperatures. The compositions of these alloys fall in the following range:

C, %	Mn, %	Si, %	Cr, %	Ti, %	Al, %	Fe, %	Ni, %
0·1 max.	1·0 max.	1·0 max.	19-22	1·5-3·0	0·5-1·5	5 max.	bal.

Table 4 compares the creep properties of nimonic 80 and nimonic 80A on the basis of stress to produce elongation of 0·1-0·5 per cent and shows the superiority of nimonic 80A in both short and long-term tests.

Nimonic 90 and 95 are improved alloys based on the nimonic series. The rupture stress of nimonic 80 for a life of 100 hr. is 20 tons/sq. in. at about 720°C. Nimonic 80A has the same strength at 750°C. while nimonic 90 has the same strength at 780°C. Though exact figures are not available for nimonic 95, it can be safely surmised that the same strength of 20 tons for 100 hr. can be expected at 800°C.

Inconel Series — The American counterparts of the creep-resistant nickel-chromium alloys are the alloys K-42-B, age-hardenable inconel and refractaloy 26. In age-hardenable inconel the base is the well-known inconel 14 per cent chromium, 6 per cent iron alloy. From data given by Cross and Simmons on the basis of time to rupture properties at 815°C. the age-hardenable inconel alloy is roughly equivalent to nimonic 80. K-42-B is more creep-resistant and refractaloy is better than the K-42-B alloy.

Nickel - molybdenum Alloys — Nickel-molybdenum alloys find application primarily as corrosion-resistant material against sulphuric acid. The alloys have high strength and when suitably alloyed they retain their strength at temperatures as high as 800°C. The alloys used in high temperature applications are Hastelloy B and Hastelloy C and have the following composition:

	C, %	Mo, %	Fe, %	Ni, %	Cr, %	W, %
Hastelloy B	0·12	26-30	4-7	bal.	—	—
Hastelloy C	0·15	15-19	4-7	bal.	13-16	3·5-5·5

Hastelloy B is age-hardenable and for creep-resistant applications is usually given a heat treatment consisting of a solution treatment of 30 min. at 1150°C. followed by air-cooling and a subsequent ageing treatment of 72 hr. at 930°C. Due to the high molybdenum content of these alloys, this alloy withstands reducing conditions better than oxidizing conditions. In an oxidizing atmosphere its use should be limited to temperature below 750°C.[22] This alloy has found successful application in gas turbines in both cast and wrought forms.

In Hastelloy C, chromium is added to improve the resistance to oxidation and because of this it can be used in oxidizing atmospheres at temperatures up to 1150°C., when relatively free from stress. It is used in the

TABLE 4 — CREEP PROPERTIES OF NIMONIC 80 AND NIMONIC 80A

Time, hr.	Temp., °C.	Stress (tons/sq. in.) to produce 0·1% extension		Stress (tons/sq. in.) to produce 0·5% extension		Stress (tons/sq. in.) to produce fracture	
		Nimonic 80	Nimonic 80A	Nimonic 80	Nimonic 80A	Nimonic 80	Nimonic 80A
100	650	21·0	26·0	26·5	29·5	28·0	30·0
—	750	10·0	14·5	14·5	17·0	15·0	17·5
10000	650	12·0	—	15·5	18·0	16·0	18·5
—	750	—	—	4·0	5·5	4·5	6·0

form of both sheet and wire. Though this alloy does not compare favourably with Hastelloy B in short-term creep tests, its performance is nearly equal in long-term tests.

Cobalt-base Alloys — The creep-resistant cobalt-base alloys are all essentially cobalt-chromium alloys to which other elements are added to confer special properties. Most of the alloys are not forgeable and are used in the as-cast condition. The first cobalt-base alloy to be developed as a high-temperature material was vitallium and the other cobalt-base alloys were developed from this alloy. The composition of this and other cobalt-base alloys along with their 1000 hr. rupture strength from 1200° to 1800°F. is given in Table 5[23].

Since these alloys are used in the as-cast condition, the casting conditions have important influence on their creep resistance as these conditions ultimately control the grain size[24,25]. The cooling rate of the cast alloy controls the ageing process. If overageing has taken place during cooling, a subsequent heat treatment is beneficial, otherwise not. In consequence the effects of heat treatment on the creep properties of cast cobalt-base alloys are obscure.

Grant[24] has shown that the creep properties of these alloys are considerably influenced by the spacing of their carbide net-work and the grain size.

Chaston and Child[26] describe a new cobalt-base alloy containing about 10 per cent chromium, 10 per cent tantalum and 0·3 per cent carbon. This alloy is reported to be suitable for service as castings at about 900°C.

Chromium-base Alloys — By virtue of the fact that chromium is extremely resistant to oxidation it has been a common addition to high-temperature creep-resistant alloys. Chromium-base alloys have been studied to some extent at temperatures in the range of 875°-925°C.[27] Chromium-iron-molybdenum alloys have been found to possess the best combination of strength and ductility. The

TABLE 5 — COMPOSITION AND RUPTURE STRENGTHS OF COBALT-BASE ALLOYS AND 'INCONEL-X' (FREEMAN *et al.*)

ALLOY	CHEMICAL COMPOSITION, %											TYPICAL 1000 HR. RUPTURE STRENGTHS				
	C	Si	Mn	Cr	Ni	Co	Mo	W	Cb	Fi	Ti	1200°F.	1350°F.	1500°F.	1600°F.	1800°F.
Vitallium	0·30	0·6	1·0	25	3	61	5·5	—	—	2·0	—	43000	22000	14000	13000	7000
61	0·45	0·6	0·6	25	—	70	—	5·0	—	1·0	—	47000	27000	22000	12000	5400
X-40	0·50	0·7	0·6	25	10	55	—	7·0	—	1·0	—	46000	33000	23000	18000	9800
S816	0·45	0·5	0·7	20	20	45	4·0	4·0	4	3·0	—	44000	29000	21000	13000	6500
NR90	0·50	1·0	0·7	25	19	44	4·6	5·3	—	0·5	—	—	35000	23000	—	—
Inconel-X	0·05	0·4	0·5	15	73	—	—	—	1	7·0	2·5 (Al. 2·07)	69000	42000	18000	—	—

best alloys in this system as judged by compression creep tests lie between the compositions 60 per cent chromium, 15 per cent molybdenum and 25 per cent iron, and 60 per cent chromium, 25 per cent molybdenum and 15 per cent iron. The creep resistance was increased and the very limited ductility decreased as the molybdenum/iron ratio was increased from the former to the latter composition. The properties in tensile creep tests are very variable and the conclusion has been reached that these alloys are abnormally sensitive to minor casting defects and do not justify development.

Possible New Types of Creep-Resistant Alloys

Titanium-base Alloys — Titanium is already being used as a minor addition for the production of certain well-known creep-resistant alloys and the efficacy of titanium-containing carbides in austenitic steels and of titanium as a hardening addition to the nimonic alloys is only too well known.

The density of titanium is only 4·5, which is intermediate between the density of light metals aluminium and magnesium and the higher density of the copper and nickel alloys. This is of special significance where stress causing creep arises from the motions of the creep-resistant article, e.g. turbine blades. Though titanium does not have intrinsically a high resistance to oxidation because of its low density, its alloys may find a useful field of application specially in the temperature range of 250°-500°C. where the present light alloys are not adequate enough.

Beryllium-base Alloys — Beryllium, which has a melting point higher than those of aluminium and magnesium and a density near that of magnesium, could be considered to be a promising metal which could be used as an alloy constituent. Though at one time great interest was evinced in the development of these alloys, little work seems to have been accomplished. In view of the centrifugal forces involved in most service conditions, the metal beryllium with a relatively high melting point and low density and more than all our abundant resources should be incentive enough for the development of beryllium-base alloys.

Vanadium-base Alloys — As pure vanadium has not been available in any quantity, it has received little attention from metallurgists. The high melting point of vanadium and rather low density compared to steels and copper alloys are encouraging factors enough to justify the study and development of such alloys, specially in our country in view of our resources, provided the metal can be produced economically.

Zirconium-base Alloys — Though zirconium metal still remains, from the point of view of price, a precious metal, ductile high purity metal is available. Its high melting point and medium density (6·4) are encouraging factors warranting study and development.

Conclusions

In the foregoing pages an attempt has been made to depict the role of non-ferrous metals in the development and production of creep-resistant materials. With the great accent today on faster speeds and high operating temperatures the search for new and better alloys has become a dominating and strategic interest. India's development of non-ferrous metals and alloys is very much in its infancy.

Of the metals nickel, cobalt, chromium, titanium, cerium, zirconium, copper, aluminium and magnesium which are significant in creep-resistant alloys, our resources as regards nickel and cobalt are nil while those of copper are meagre. On the other hand, aluminium, magnesium, chromium and titanium could be said to be abundant but, except for aluminium and copper, are at present not being produced. It needs hardly be stressed that the production of these and other non-ferrous metals like beryllium, vanadium and zirconium and the development of new and better creep-resistant alloys are not only of industrial but strategic importance.

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