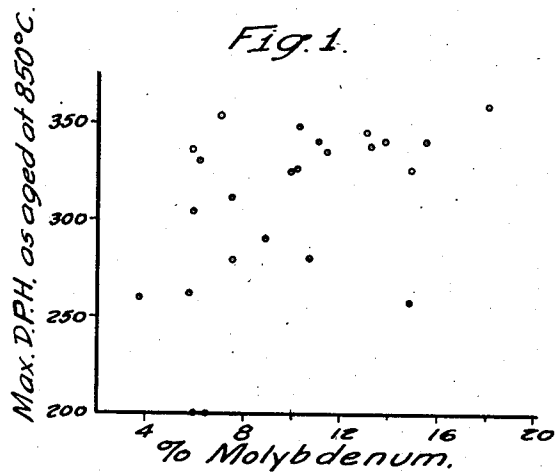
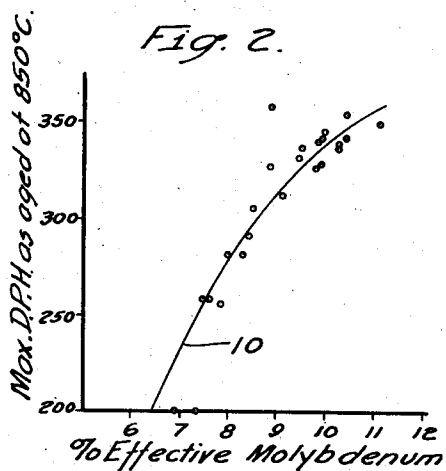
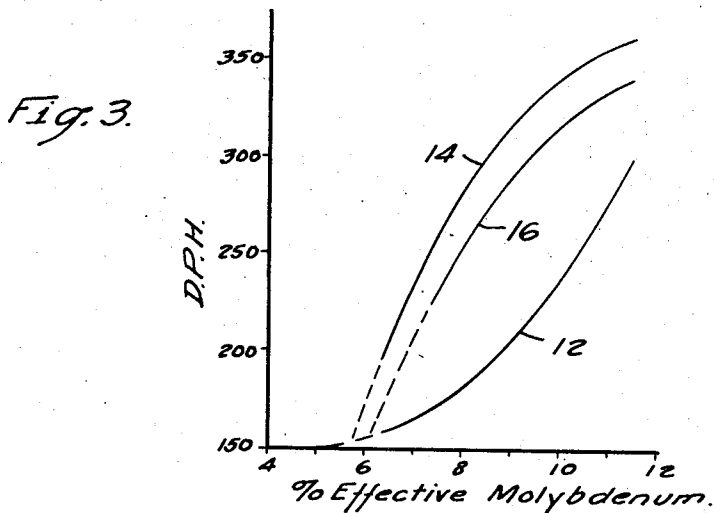
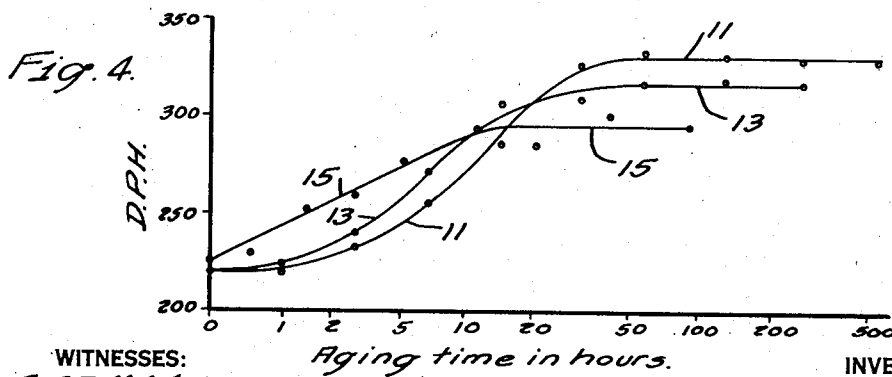


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HEAT RESISTANT ALLOYS

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2,403,128

HEAT RESISTANT ALLOYS

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This invention relates to alloys, and in particular to alloys having high strength and corrosion resistance at room and elevated temperatures.

At the present time there are a number of alloys available which are known to the trade as heat resistant alloys. The known alloys, however, usually have one or more disadvantages in that the strength at elevated temperatures is insufficient for many modern applications or the oxidation resistance is poor or the alloy cannot be readily forged. Among the known heat resistant alloys, the iron-nickel-chromium alloys have been generally considered as superior alloys, the chromium imparting oxidation resistance while the nickel tends to maintain the alloys austenitic, that is, having a face-centered-cubic crystal structure. Although superior to the ferritic iron-chromium alloys, nevertheless, the strength of the austenitic iron-nickel-chromium alloys diminishes quite rapidly with an increase in temperature, it being found, for example, that alloys of the iron base type containing 25% chromium and 20% nickel have only half the strength at 650° C. that they have at room temperature. Further, the available alloys are also relatively weak at room temperature, the specific 25-20 alloy referred to hereinbefore having a tensile strength of only 82,000 pounds per square inch at room temperature.

Certain alloys have been produced in which the elements such as beryllium, titanium and aluminum have been utilized to impart precipitation hardening characteristics. These elements however are not satisfactory since alloys containing and depending only upon such precipitation hardening elements for their hardness do not have the characteristic of permanently retaining such hardness when subjected to extended heating at elevated temperatures, such as are contemplated as the working temperatures for the alloy of this invention.

It is an object of this invention to provide an alloy having oxidation resistance and high strength at elevated temperatures.

Another object of this invention is to provide an alloy capable of substantial precipitation hardening and having oxidation resistance and high strength at elevated temperatures.

A further object is to provide an austenitic alloy having high strength at room temperature.

A more specific object of the invention is to provide an austenitic alloy containing nickel, chromium, molybdenum and manganese which can be forged and precipitation hardened.

Another object of this invention is to provide a precipitation hardened alloy having the characteristic of retaining its high temperature properties after prolonged or repeated exposure to elevated temperatures.

Other objects of this invention will become apparent from the following description when taken

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in conjunction with the accompanying drawing, in which:

Figure 1 illustrates the maximum hardness obtained by heat treatment in alloys of this invention with respect to the molybdenum content.

Fig. 2 is a graph, the curve of which illustrates the maximum hardness of the alloys of this invention in terms of a relation between the alloying constituents.

Fig. 3 is a graph, the curves of which illustrate the hardness obtained in terms of the relation of the constituents of the alloys of this invention after different heat treatments, and

Fig. 4 is a graph, the curves of which illustrate the hardness obtained on a particular alloy of this invention as heat treated for different periods of time.

We have found that alloys of the heat resistant type can be produced having higher strength and good corrosion and oxidation resistance at both room and elevated temperatures, the higher strength being imparted to the alloys by precipitation hardening treatment. In general this application is directed to alloys containing primarily chromium, nickel, molybdenum and manganese which are precipitation hardened by quenching them from a high temperature and thereafter aging them at a somewhat lower temperature to give the alloys high strength at room and elevated temperatures.

In particular, the heat treatment which has been found suitable for developing the desired characteristics in the alloy of this invention comprises quenching the alloy from a temperature between 1000° C. and 1300° C. and aging it at a temperature between 700° C. and 1000° C., the aging temperature usually being at least 200° below the quenching temperature. Preferably the heat treatment comprises quenching from a temperature between 1040° C. and 1260° C. and aging the quenched alloy at a temperature between 750° C. and 950° C.

For some types of service however, where the creep rate at operating temperatures must be very low, the alloys of this invention may be utilized in either the "as quenched" or "under aged" state. By "under aged" is meant the aging to less than maximum hardness for the aging time interval chosen. We have found that in this incompletely aged condition the rate of creep is lower than as aged to maximum hardness prior to service.

Generally the period of time of aging the alloy depends upon the aging temperature. Practically, however, the aging temperature for any particular alloy is usually selected to produced maximum hardness in a particular time. Thus, a time of 20 hours has been selected as a commercially practical aging time and the aging temperature is adjusted accordingly. However, as will be apparent from Figure 4 of the drawing, referred to hereinafter, higher hardness can

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be obtained on any of the alloys if they are aged for longer periods of time at lower temperatures.

The proportions of the constituents of the alloy may be varied over wide ranges in a predetermined manner as will be explained more fully hereinafter but in order that the resulting alloy may be forgeable, it is essential that the molybdenum content should be maintained at not more than 20%. In general, the alloy composition may range from 16% to 28% chromium, from 20% to 60% nickel, from 4% to 20% of molybdenum, from traces up to 3% of manganese with the balance iron and not more than 1% of impurities such as carbon and the deoxidizers, silicon, vanadium, titanium and/or aluminum. The manganese is included to improve work-

ability. In the alloy of this invention, the molybdenum content is maintained at not less than 4% in order to insure precipitation hardening characteristics, it being found that molybdenum in the range 4% to 20% is a very active precipitation hardening agent in the alloy. While molybdenum is employed as the precipitation hardening agent the other alloying elements have an effect on the characteristics of the alloy and the relation of the alloying constituents in the alloy must be carefully controlled as will be explained hereinafter.

It is preferred to maintain the carbon content of the alloy at less than 0.2%. This is because it has been found that carbon in amounts above 0.2% is harmful in that it forms carbides with chromium and molybdenum, thereby lowering both oxidation resistance and response to precipitation hardening treatment.

The minimum nickel content is given as 20% in order that the resulting alloy will have an entirely austenitic structure. Alloys having lower nickel contents and containing chromium and molybdenum in varying effective amounts may contain the ferritic or sigma phases after having been subjected to precipitation hardening heat treatment whereas the alloys of this invention are free of the sigma phase. Although the upper limit of the nickel range has been given here-

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inbefore as 60%, because of metallurgical economies it is preferred to utilize 52% as the upper limit of nickel where the chromium and molybdenum are introduced into the alloy in the form of ferro-alloys. This, however, is not a limiting factor as it may be desirable to form the alloys of this invention from pure chromium and molybdenum.

The chromium is primarily utilized for imparting corrosion and oxidation resistance to the alloy, it being found that not less than 16% chromium is necessary in the present alloy for giving the required corrosion and oxidation resistance to the alloys which will permit its use at temperatures up to 870° C. (1600° F.). The upper limit of 28% is established for the chromium content since it has been found that no advantage in tensile strength and other desirable characteristics can be obtained by increasing the chromium content beyond this point. In general, from our investigation it can be said that the chromium content required for imparting a high degree of corrosion and oxidation resistance to the alloy of this invention is equal to or is greater than $[27-0.2 (\% \text{ Ni})]$. The actual chromium content needed for a particular application will depend, in addition to the nickel, on the service temperature and the life desired at that temperature.

The chromium and molybdenum are readily introduced into the melt in forming the alloy by utilizing a 70% ferro-molybdenum and a 70% ferro-chromium alloy. Such alloys are available and are a more economical medium for obtaining a given molybdenum and chromium content than by the addition of pure metals. Where such ferro alloys are used as the addition agents for molybdenum and chromium, the associated iron content is 43 (% Mo + % Cr). As will be apparent the cost of the alloy is decreased as the iron content is increased. However, it has been found that the best physical properties are obtained with a low iron content.

As representative of alloys within the broad range given hereinbefore, reference may be had to the following table:

Table I

Alloy No.	Composition, weight percent				Hardness ¹ as quenched from 1150° C.	Max. hardness ¹ as aged at—		Charc. temp., ° C.	Forgeability
	Ni	Cr	Mo	Mn		850° C.	950° C.		
3067	29.5	19.4	6.0	1.5	160	200		900	Good.
3069	58.8	20.2	14.8	1.3	233	258		900	Do.
4060	30.1	17.4	15.4	0.7	256	340	290	820	Fair.
4063	30.0	25.0	15.0	0.7					No good.
4066	29.5	25.4	10.3	0.7	268	347	324	870	Fair.
4067	30.0	22.0	15.0	0.7					Poor.
4069	53.9	18.0	17.9	0.8	240	357	311	925	Good.
4090	45.8	25.0	18.0	0.7					No good.
4105	50.5	25.2	13.8	0.7	240	337	300	900	Fair.
4111	31.5	23.0	10.2	0.7	224	327	293	945	Good.
4116	53.2	24.2	10.7	0.7	210	290	240	900	Do.
4117	51.8	27.3	8.9	0.7	200	290	235	900	Do.
4134	20.5	24.8	7.1	0.7	247	353	335	950	Fair.
4135	40.9	25.2	7.6	0.7	178	290	255	960	Good.
4136	30.8	24.2	7.6	0.7	198	312	295	945	Do.
4161	30.4	24.7	4.0	0.7	175	260	225	950	Do.
4162	30.5	24.6	6.0	0.7	194	304	290	950	Do.
4163	30.6	27.3	5.9	0.7	224	336	315	950	Do.
4165	30.4	24.7	6.2	2.5	212	329	307		Do.
4189	40.5	25.3	6.0	1.1	171	263			Do.
4209	47.6	25.0	13.0	0.7	266	344			Fair.
4210	40.8	25.0	11.0	0.7	245	340			Good.
4211	35.9	24.5	9.9	0.7	250	325			Do.
4218	39.7	21.7	13.2	0.6	277	338			Do.
4229	35.0	23.5	11.4	0.7	255	335			Fair.
4290	20.3	17.8	6.4	0.7	173	200			Good.
4374	25.1	22.8	8.0	2.1	209				Do.
4375	30.0	24.2	7.9	2.1	235				Do.
4540	50.0	20.0	15.0	2.0	231				Do.
4545	59.0	20.0	18.8	2.0	214				Do.
M-156	48.4	19.9	14.8	0.7	225	325	290	950	Do.

¹ Diamond pyramid or Vickers hardness.

In the foregoing table each of the alloys listed contain about 0.4% silicon and about 0.1% carbon with the balance of the alloying constituent being iron with negligible amounts of the deoxidizers and other impurities. The heat treatment applied is indicated as comprising quenching the alloys from 1150° C. and subjecting them to different aging treatments consisting of aging them at 850° C. and at 950° C.

Referring to Fig. 4 of the drawing, there is illustrated typical hardness curves for a representative alloy of this invention. These curves are based on alloy #4111 given in Table I and which has been quenched from 1150° C., curves 11, 13 and 15 representing the hardness of the alloy as aged at 850° C., 900° C. and 950° C. respectively for different periods of time. As illustrated the maximum hardness for this particular alloy as aged at 950° C. is obtained after 20 hours of aging.

In aging the alloys an accurate record was kept of the aging temperature at which maximum hardness is reached in 20 hours and this temperature is listed in the table as the characteristic temperature. Such characteristic temperature indicates the relative thermal stability of the group of alloys as a whole and also measures the relative stability of the individual alloys.

As is evident, the variable nickel, chromium, molybdenum constituents have an effect on the hardness of the resulting alloys. In order to relate these elements with respect to the hardness, an empirical formula has been derived, the terms of which must be satisfied in producing the alloy of this invention having the desired degree of precipitation hardening and required forging characteristics. In this formula, the respective contributions of molybdenum, chromium, manganese and nickel to the precipitation hardening are evaluated quantitatively, and from it a number, called for convenience, the percent effective molybdenum content, is calculated. This formula is

$$\% \text{ effective molybdenum} = \frac{1}{2} \left[\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5 \right]$$

From the formula, it is evident that the elements chromium and manganese act to increase the molybdenum hardening effect while nickel decreases such effect.

The following Table II gives the percent effective molybdenum content found in accordance with the foregoing formula for the alloys of Table I.

Table II

Alloy No.	Percent eff. Mo.	Forgeability
4083	13.3	No good.
4089	12.8	Do.
4087	12.1	Poor.
4086	11.1	Fair.
4080	10.4	Do.
4134	10.4	Do.
4105	10.2	Do.
4229	10.2	Do.
4209	10.0	Do.
4374	10.0	Good.
4375	10.0	Do.
4545	10.0	Do.
4111	9.9	Do.
4210	9.9	Do.
4211	9.8	Do.
4218	9.8	Do.
4163	9.5	Do.
4165	9.4	Do.
4540	9.2	Do.
4136	9.1	Do.
4090	8.9	Do.
M-156	8.8	Do.
4162	8.5	Do.
4117	8.4	Do.
4135	8.3	Do.

Alloy No.	Percent eff. Mo.	Forgeability
4116	8.0	Do.
3989	7.9	Do.
4189	7.7	Do.
4161	7.5	Do.
4290	7.3	Do.
3987	6.9	Do.

Referring to Fig. 1 of the drawing, there is plotted the actual hardness of the alloys as listed in Table I as aged at 850° C. against the actual molybdenum content of the different alloys. It is apparent that there is no consistent relation between hardness as aged and actual molybdenum content, the scatter being the result of the effects of the variable nickel, chromium and manganese contents on the precipitation hardening. However, by utilizing the empirical formula given for the effective molybdenum content a well defined relation between maximum hardness and the effective molybdenum content is obtained as illustrated by curve 10 of Fig. 2.

Similar results are found when the effective molybdenum content is also plotted against the hardness of the alloys as quenched from 1150° C. and as quenched and then aged at 950° C. Representative curves of such relations are given in Fig. 3 in which curve 12 represents the hardness in terms of the effective molybdenum content of the alloy as quenched from 1150° C., curve 14 represents the hardness in terms of the effective molybdenum content for the alloys as quenched from 1150° C. and aged at 850° C. and curve 16 represents the hardness in terms of the effective molybdenum content for the alloy as quenched from 1150° C. and aged at 950° C. From these curves it is seen that the precipitation hardening effect commences at an effective molybdenum content of about 6% and does not become appreciable until the effective molybdenum content reaches 8%. It is therefore preferred to maintain the lower limit of effective molybdenum content at not less than 8%.

In Table II, the alloys of Table I are listed in order of decreasing effective molybdenum content so as to illustrate the relation between forgeability and effective molybdenum content. We have found that a definite line of division in terms of the effective molybdenum content can be drawn between the alloys having poor and fair forging characteristics at an effective molybdenum content of 11.5%. However, for the purpose of this invention it is preferred to limit the upper limit of the effective molybdenum content to 11% because alloys with an effective molybdenum content greater than 11% contain an excessive amount of undissolved hardening constituent in the "as quenched" condition. As may be seen by referring to Fig. 3, the "as quenched" hardness increases rapidly above 11% effective molybdenum content to a value which greatly reduces machinability and hence impairs the utility of the alloy. For the reasons stated it is, therefore, desired to maintain the effective molybdenum content between 8% and 11% as given in the formula hereinbefore.

While all the alloys within the range given hereinbefore and which satisfy the terms of the equation for the effective molybdenum content have good corrosion resistance and high strength, it is found that certain of the alloys have an exceptional high strength in excess of 29,000 lbs. per square inch at an elevated temperature of about 870° C. Through numerous experiments it

has been established that these alloys have compositions which fall within the more specific range of 30% to 60% nickel, 16% to 28% chromium, 8% to 20% molybdenum and from traces up to 3% of manganese with carbon less than 0.2% and the balance iron and incidental impurities and that such alloys satisfy the relation of the formula for the effective molybdenum content given hereinbefore. Results of tensile tests made at 870° C. with a strain rate of 0.017 inch per inch per minute on a number of alloys including the more specific range given hereinbefore are given in the following table:

Table III

Alloy No.	Composition, wt. percent				Percent eff. Mo	Tensile strength, #/sq. in.	Percent elongation	Percent red. area
	Ni	Cr	Mo	Mn				
4090...	53.9	18.0	17.9	0.8	8.9	36,900	54	84
4111...	31.5	23.0	10.2	0.7	9.9	29,100	42	62
4135...	40.9	25.2	7.6	0.7	8.3	28,600	30	35
4161...	30.4	24.7	4.0	0.7	7.5	24,000	15	20
4162...	30.5	24.6	6.0	0.7	8.5	28,200	9	12
4165...	30.4	24.7	6.2	2.5	9.4	23,800	34	58
4189...	40.5	25.3	6.0	1.1	7.7	27,200	14	14
4209...	47.6	25.0	13.0	0.7	10.0	31,500	26	40
4210...	40.8	25.0	11.0	0.7	9.9	31,100	15	18
4211...	35.9	24.5	9.9	0.7	9.8	30,600	13	14
4218...	39.7	21.7	13.2	0.6	9.8	31,600	18	27
M-156...	48.4	19.9	14.8	0.7	8.8	35,300	7	8

The alloys were heat treated to produce maximum hardness in an aging period of 20 hours and then stabilized for 20 hours at a temperature of 870° C. (1600° F.) prior to the testing. By referring to Table III, it is apparent that a number of the alloys in the specific composition range did not have the required strength of 29,000 pounds per square inch at 870° C. even though they satisfy the requirement of the formula for effective molybdenum content.

We have found that the tensile strength at these elevated temperatures depends chiefly on the molybdenum content of the solid solution matrix, the precipitation hardening being effective at the lower temperatures. In the "as quenched" condition, the molybdenum content of the solid solution nearly equals the total molybdenum content of the alloy and during aging it decreases by the amount of molybdenum which is precipitated. If the aging were carried to a complete equilibrium condition, the solid solution would be depleted to the molybdenum content equivalent to 6% effective molybdenum. Practically, however, aging is carried only to the state of maximum hardness, at which point, an estimated 50% of the molybdenum has been precipitated. Hence, as aged to maximum hardness the molybdenum content in solid solution can be calculated from the equation:

$$\% \text{ Mo in S. S.} = \% \text{ Mo} - \frac{1}{2} (\% \text{ Mo available for precipitation})$$

$$\text{or} \quad \% \text{ Mo in S. S.} = \% \text{ Mo} - (\% \text{ eff. Mo} - 6)$$

If in the latter formula, the formula for the effective molybdenum is substituted, then

$$\% \text{ Mo in S. S.} = \frac{1}{2} [\% \text{ Mo} - 0.8 (\% \text{ Cr}) - 0.75 (\% \text{ Mn}) + 0.25 (\% \text{ Ni}) + 13.5]$$

When the percent molybdenum in solid solution calculated from the foregoing formula is greater than 6% for the alloys of this invention, then the tensile strength of the alloys at 870° C. will be in excess of 29,000 pounds per square inch.

By referring to the following Table IV, in which the relation between the constituents as found

by the solid solution molybdenum formula and the tensile strength at 870° C. are set forth, it is evident that only those alloys having a relation of the constituents thereof to give a solid solution content equal to or greater than 6 will have the required strength.

Table IV

Alloy No.	Approximate percent molybdenum in solid solution	Tensile strength at 870° C., pounds per sq. in.
4090...	15.0	36,900
M-156...	12.0	35,300
4218...	9.4	31,600
4209...	9.0	31,500
4210...	7.1	31,100
4111...	6.3	29,100
4211...	6.1	30,600
4135...	6.3	28,600
4189...	4.3	27,200
4162...	3.5	28,200
4165...	2.8	23,800
4161...	2.4	24,000

From this table it is apparent that the amount of molybdenum in solid solution in the alloy has a direct relation to the tensile strength of the alloy at such elevated temperatures. It is, therefore, essential that the alloy which is to be employed at temperatures up to 870° C. have the relation between its constituents which will satisfy both of the formulae for the effective molybdenum content and for the solid solution molybdenum content in order to have the required strength and good forgeability.

The alloys in this group which satisfy both the effective molybdenum and solid solution molybdenum formulae have a high resistance to creep. As a specific example, reference may be had to the alloy identified as M-156 in Table III which has a minimum creep rate of 2.4×10^{-4} inch/inch/hour at 650° C. under a stress of 40,000 pounds per square inch.

Where consideration must be given to the cost of the alloy and the requirements of service are such that the alloy will be subjected to temperatures below 800° C., then the composition is preferably within the range of 20% to 40% nickel, 16% to 28% chromium, 4% to 10% molybdenum, from traces up to 3% manganese and the balance iron and not more than 1% of incidental impurities. In these more economical alloys, the composition must also have a relation between its alloying constituents to satisfy the formula for the effective molybdenum content as in the previous examples in order to maintain forgeability and have good strength at temperatures up to 800° C. As representative of alloys within this classification, reference may be had to the following Table V:

Table V

Alloy No.	Composition, wt. percent				Percent eff. Mo	T. S., #/sq. in.	Percent elong.	Percent red. area
	Ni	Cr	Mo	Mn				
4162...	30.5	24.6	6.0	0.7	8.5	55,100	8	10
4163...	30.6	27.3	5.9	0.7	9.5	61,600	5	7
4165...	30.4	24.7	6.2	2.5	9.4	48,900	15	17
4374...	25.1	22.8	8.0	2.1	10.0	56,900	20	30
4375...	30.0	24.2	7.9	2.1	10.0	56,200	11	15

The tensile strength given in the foregoing table is that obtained at 760° C. (1400° F.) and with a strain rate of 0.017 inch per inch per minute on the alloys as aged to maximum hardness in 20 hours, and stabilized for 20 hours at 760° C.

Silicon and titanium additions within low limits act to increase the precipitation hardening of the alloy. This is because, qualitatively, these elements reduce the solid solubility of molybdenum and serve to increase the amount of molybdenum which is precipitated. Through numerous experiments it has been found that additions of silicon and/or titanium in amounts greater than those employed for deoxidizing purposes and preferably up to 2.5% silicon and/or 3% titanium in the resulting alloy, have an effect on the precipitation hardening which is additive to the effect of the chromium and manganese additions. It is therefore necessary to modify the formula for the effective molybdenum content given hereinbefore where the alloy contains either or both silicon and titanium as essential alloying elements to maintain the effective molybdenum content within the limits of 8% to 11% as established hereinbefore. This modified formula is as follows:

$$\% \text{ eff. Mo} = \frac{1}{2} [\% \text{ Mo} + 0.8(\% \text{ Cr}) + 0.75(\% \text{ Mn}) + 1.6(\% \text{ Ti}) + 1.2(\% \text{ Si}) - 0.25(\% \text{ Ni}) - 2]$$

In the following table a number of representative alloys containing either or both silicon and titanium are listed together with some of the properties of the alloys, it being understood that the balance of the alloying composition is iron and not more than 1% of impurities.

Table VI

	Composition, weight percent						Percent eff. Mo	Hardness as quenched from 1150° C.	Max. hardness as aged at 850° C.	Tensile strength, #/sq. in.	Percent el.	Percent R. A.
	Ni	Cr	Mo	Mn	Si	Ti						
3986	30.0	18.0	10.0	1.3	0.5	2.8	10.6	263	368			
4056	30.4	18.9	10.1	0.7	1.1	2.0	10.3	232	308			
4088	30.4	22.3	10.3	0.7	0.6	1.0	10.7	265	360			
4131	30.4	24.8	6.2	0.7	0.6	0.5	9.2	194	312			
4142	31.6	24.7	5.6	0.7	1.9		9.1	225	338	93,200	14	18
4164	30.8	25.0	6.2	0.7	0.9	0.9	9.7	238	335	110,800	13	18
4186	30.2	25.5	6.1	2.1	1.2		10.0	205	316			
4285	26.3	22.8	4.1	2.1	2.2		9.0	198	265	74,800	16	18
4308	21.1	21.2	6.3	2.0	1.5		9.6	240	292			
4309	25.1	23.0	6.0	2.0	2.0		10.0	224	298	91,100	9	11
4310	30.0	24.1	6.1	2.1	2.1		10.0	221	302	95,700	6	8
4341	20.2	17.6	6.0	2.0	2.0		8.5	174	252	70,000	35	57
4342	25.2	19.8	8.1	2.1	2.0		9.8	212	295	84,700	26	39
4343	30.2	22.0	8.0	2.1	2.0		10.0	234	320	90,000	15	24
M-120	29.8	25.3	6.1	0.7	0.6	0.3	9.3	200	328	96,000	11	13
M-138	42.2	22.5	11.6	1.7	1.6		10.1	247	325			

In the table the effective molybdenum as calculated by the formula for the alloys containing silicon and/or titanium is given. It is of course apparent that where titanium is not present, that the titanium factor in the formula becomes zero and can be ignored. By utilizing the formula the optimum compositions can be selected from the infinite number which it is possible to form in the broad ranges given for the different alloying elements, thereby reducing the possible combinations to include a relatively small number of correctly balanced compositions.

The tensile strength recorded is that obtained at 650° C. (1200° F.) with a strain rate of 0.017 inch per inch per minute. The precipitation hardened alloys containing silicon and/or titanium within the ranges given are particularly useful at temperatures in the neighborhood of 650° C., where the effects of the precipitation hardening predominate as opposed to those alloys which are to be employed at the higher temperatures in the neighborhood of 870° C. where the amount of molybdenum in solid solution is of primary importance. In these austenitic alloys the relatively small amounts of silicon and/or titanium

replace a larger amount of the molybdenum, thereby giving a more economical alloy with little or no loss in tensile strength at temperatures of 650° C.

Where expense is no criterion, then an alloy composed of 59% nickel, 20% chromium, 20% molybdenum, 0.6% manganese and the balance deoxidizers plus impurities, can be advantageously employed, it being found that such an alloy can be cast and precipitation hardened by the treatment given hereinbefore to a hardness in excess of 300 DPH. If it is desired to achieve maximum strength at 870° C. in forgeable alloys then a composition such as alloy No. 4545 listed in Table I can be used. In both of these alloys iron is present only as an impurity. In this type of alloy it is preferred to maintain the composition within the ranges of 52% to 60% nickel, 16% to 28% chromium, 8% to 20% molybdenum, from traces up to 3% manganese with less than 1% of impurities including iron, with the alloying components having the relation satisfying the equations for the percent effective molybdenum and percent molybdenum in solid solution.

In all of the alloys referred to hereinbefore, manganese is present in order to improve workability of the alloy. Further, although the nickel content is given within certain specific ranges, the actual nickel content of the specific alloys listed includes incidental cobalt, it being found

that the nickel metal contained about 1% cobalt as is usual in the nickel supplied to the trade.

The alloys of this invention are austenitic, that is, they have a face-centered-cubic crystal structure and have exceptional corrosion resistance and high strength at elevated temperatures, the composition of the alloy being determined by the temperature to which the alloy will be subjected in industry and the cost that the application can absorb. The alloy having the higher nickel content and illustrated by certain specific compositions in Table III and whose alloying constituents have a relation which will satisfy the formulae for the effective molybdenum content and the solid solution molybdenum content are particularly applicable for use in gas turbines where it is necessary to employ an alloy having relatively high tensile strength and a high degree of oxidation resistance. Further, these alloys are particularly adapted for use as parts of turbines where the temperature gradients range from the maximum down to as low as room temperature and where the turbine parts may be subjected to stresses which vary inversely with the temperature. These particular alloys have adequate

strength at all temperatures up to 870° C. (1600° F.) with the advantage over previous known alloys increasing as the temperature approaches 870° C.

All of the alloys of this invention have an unusual thermal stability at the operating temperatures at which they are to be employed as disclosed hereinbefore, giving a particularly long life in industrial applications.

Although this invention has been described with reference to a particular embodiment thereof, it is, of course, not to be limited thereto except insofar as is necessitated by the scope of the appended claims.

We claim as our invention:

1. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy comprising 20% to 60% nickel, 16% to 28% chromium, 4% to 20% molybdenum, less than 0.20% carbon, from traces up to 3% manganese, and the balance iron except the usual contaminants in common amounts, the alloy being precipitation hardened and having the relation among the alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

2. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy containing 20% to 52% nickel, 16% to 28% chromium, 4% to 20% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron except for the usual contaminants in common amounts, the alloy being a precipitation hardened austenitic alloy and having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

3. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of an age hardened alloy comprising 20% to 52% nickel, 16% to 28% chromium, 4% to 20% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron except from the usual contaminants in common amounts, which has been quenched from a temperature between 1040° C. and 1260° C. and aged at a temperature between 750° C. and 950° C. the alloy having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

and being austenitic.

4. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy comprising 30% to 60% nickel, 16% to 28% chromium, 8% to 20% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, the alloy being precipitation hardened and having the relation among its alloying components that the chromium is greater than $27 - 0.2 (\% \text{ Ni})$,

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

and

$$\frac{1}{2} [\% \text{ Mo} - 0.8 (\% \text{ Cr}) - 0.75 (\% \text{ Mn}) + 0.25 (\% \text{ Ni}) + 13.5]$$

is greater than 6%.

5. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy comprising 30% to 60% nickel, 16% to 28% chromium, 8% to 20% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, which has been quenched from a temperature between 1040° C. and 1260° C. and aged at a temperature between 750° C. and 950° C., the alloy having the relation among its alloying components that the chromium is greater than $27 - 0.2 (\% \text{ Ni})$,

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

and

$$\frac{1}{2} [\% \text{ Mo} - 0.8 (\% \text{ Cr}) - 0.75 (\% \text{ Mn}) + 0.25 (\% \text{ Ni}) + 13.5]$$

is greater than 6%.

6. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a precipitation hardened austenitic alloy comprising 20% to 40% nickel, 16% to 28% chromium, 4% to 10% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron and incidental impurities, the alloy having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

7. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of an age hardened alloy comprising 20% to 40% nickel, 16% to 28% chromium, 4% to 10% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, the alloy having the relation among its alloying components that the chromium is greater than $27 - 0.2 (\% \text{ Ni})$, and

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

8. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy consisting of 20% to 60% nickel, 16% to 28% chromium, 4% to 20% molybdenum, from traces up to a 3% manganese, from traces up to 2.5% silicon, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, the alloy being precipitation hardened and having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) + 1.2 (\% \text{ Si}) - 0.25 (\% \text{ Ni}) - 2] = 8\% \text{ to } 11\%$$

9. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy consisting of 20% to 60% nickel, 16% to 28% chromium, 4% to 20% molybdenum, from traces up to 3% manganese, from traces up to 2.5% silicon, from traces up to 3% titanium, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, the alloy being a precipitation hardened austenitic alloy and having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) + 1.6 (\% \text{ Ti}) + 1.2 (\% \text{ Si}) - 0.25 (\% \text{ Ni}) - 2] = 8\% \text{ to } 11\%$$

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10. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy consisting of 20% to 60% nickel, 16% to 28% chromium, 4% to 20% molybdenum, from traces up to 3% manganese, from traces up to 2.5% silicon, from traces up to 3% titanium, less than 0.20% carbon, and the balance iron with not more than 1% of impurities, which has been quenched from a temperature between 1040° C. and 1260° C. and aged at a temperature between 750° C. and 950° C., the alloy being austenitic and having the relation among its alloying components that the chromium is greater than 27-0.2 (% Ni), and that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) + 1.6 (\% \text{ Ti}) + 1.2 (\% \text{ Si}) - 0.25 (\% \text{ Ni}) - 2] = 8\% \text{ to } 11\%$$

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11. A mechanical element which is to be subjected to a temperature of at least 650° C. and considerable stress in normal use consisting of a heat resistant alloy consisting of 52% to 60% nickel, 16% to 28% chromium, 8% to 20% molybdenum, from traces up to 3% manganese, less than 0.20% carbon, and less than 1% of impurities including iron, the alloy being precipitation hardened and having the relation among its alloying components that

$$\frac{1}{2} [\% \text{ Mo} + 0.8 (\% \text{ Cr}) + 0.75 (\% \text{ Mn}) - 0.25 (\% \text{ Ni}) - 1.5] = 8\% \text{ to } 11\%$$

and

$$\frac{1}{2} [\% \text{ Mo} - 0.8 (\% \text{ Cr}) - 0.75 (\% \text{ Mn}) + 0.25 (\% \text{ Ni}) + 13.5]$$

is greater than 6%.

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