United States Patent

Oda et al.

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[54] METHOD OF MANUFACTURE OF STEEL TURBINE BLADES

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[30] **Foreign Application Priority Data**

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[51] **Int. Cl.**.....**B22d 25/02,** C21d 7/14

[58] **Field of Search**.....148/142, 37, 38, 143, 2, 3, 148/12.3; 75/128

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[57] **ABSTRACT**

High toughness steel suitable for the manufacture of turbine blades is composed of defined quantities of Cr, Ni, Co, Mo, and iron, wherein the molybdenum may be replaced by tungsten. The steel composition also contains minor amounts of carbon, silicon and manganese. The composition of this steel is selected so that the quantity of δ Ferrite and the Ms point have predetermined values. The steel is subjected to heat treatment, cooling and aging.

8 Claims, 7 Drawing Figures

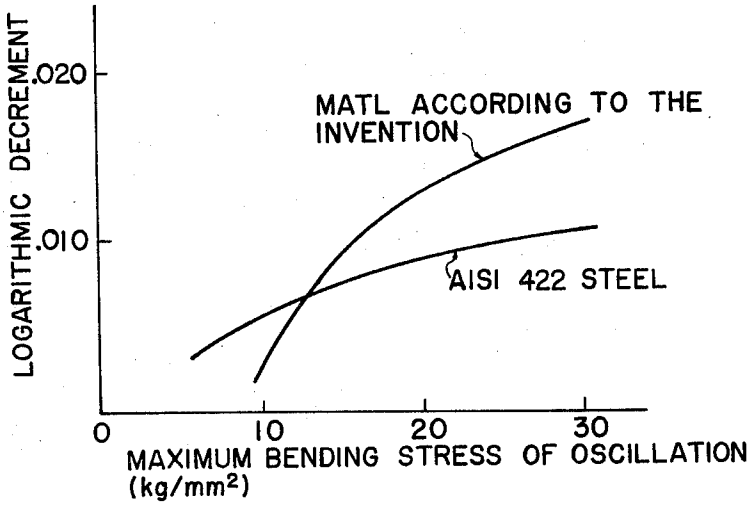


FIG. 1

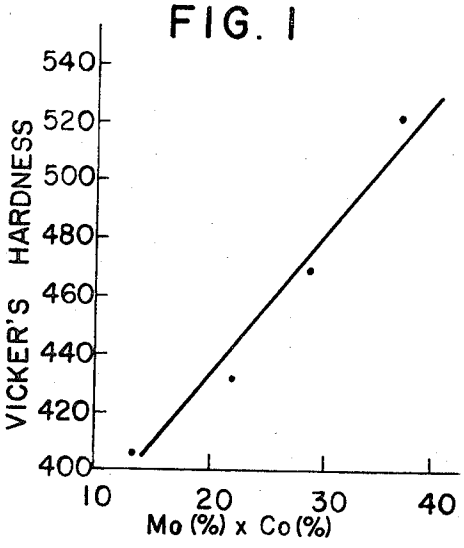


FIG. 2

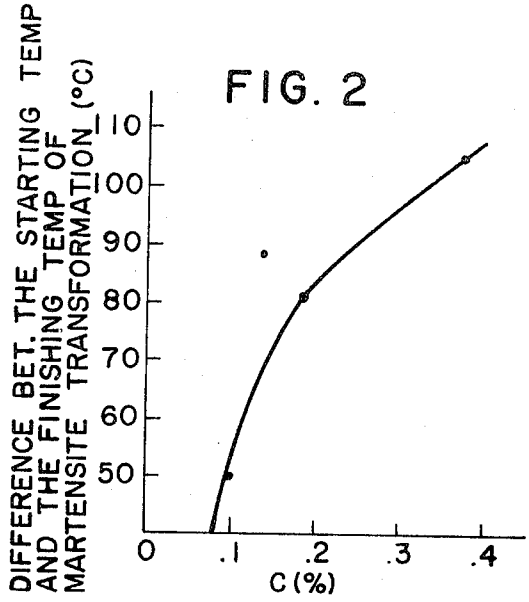


FIG. 4

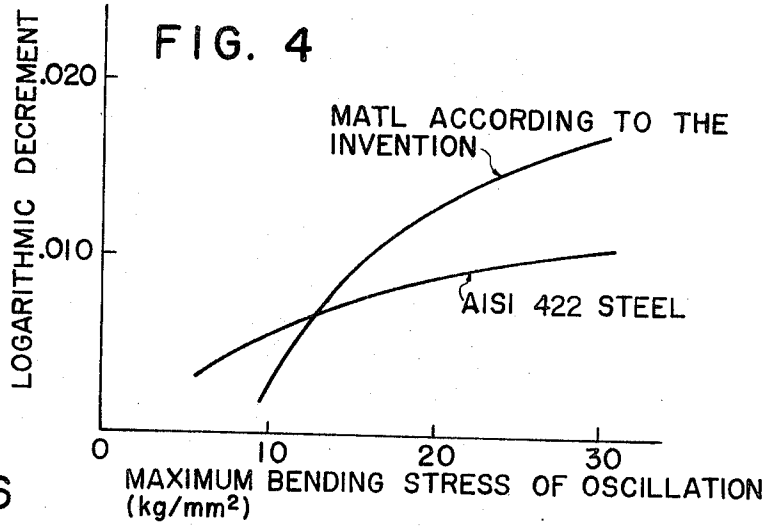
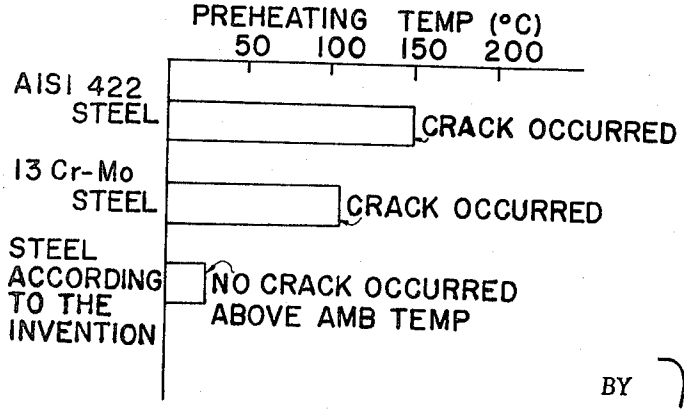


FIG. 6



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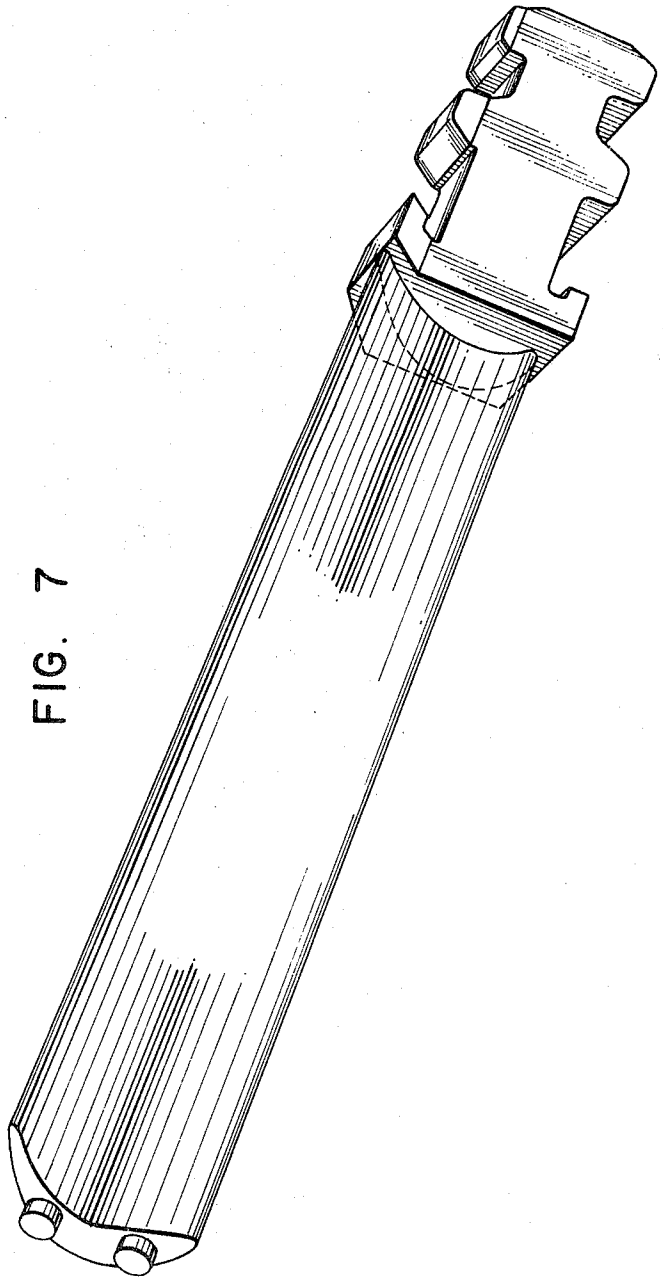


FIG. 7

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FIG. 3

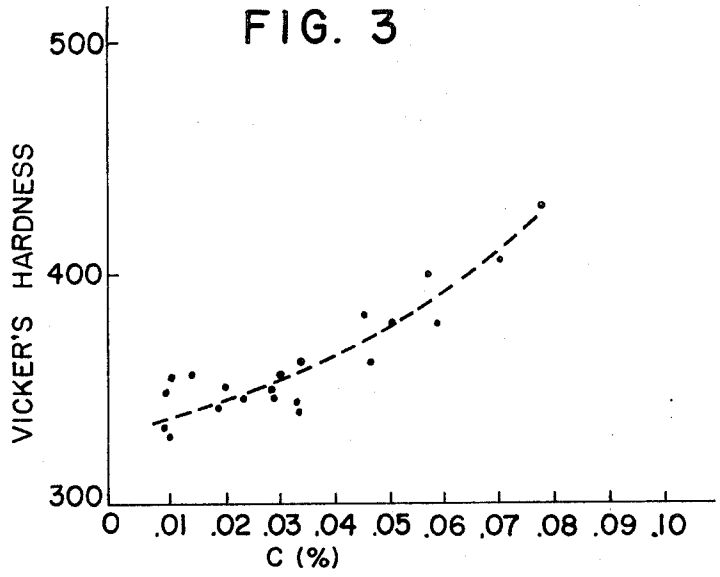
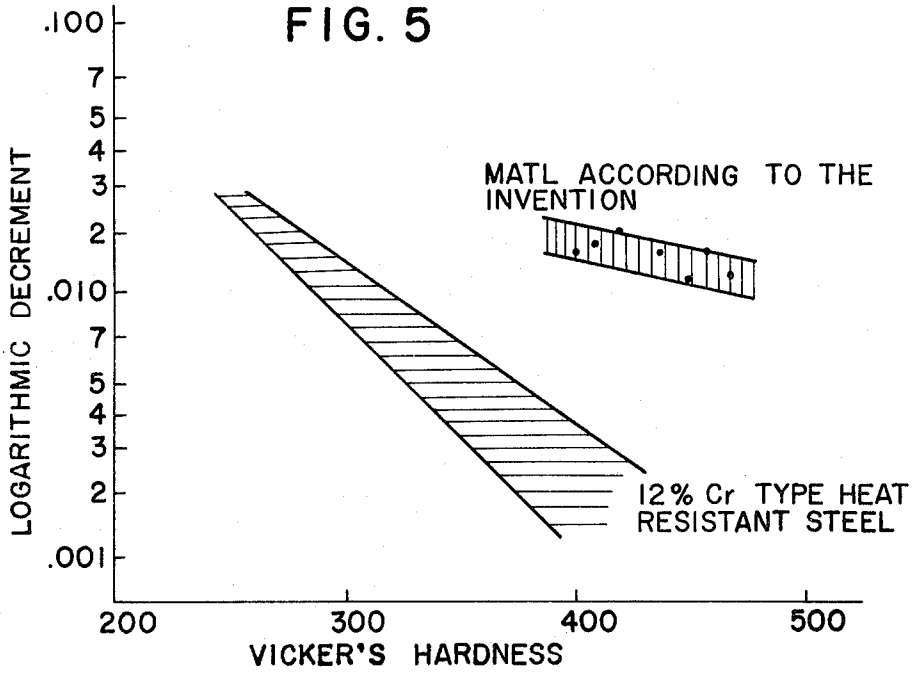


FIG. 5



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METHOD OF MANUFACTURE OF STEEL TURBINE BLADES

SUMMARY OF THE INVENTION

This invention generally relates to steels and is particularly directed to a high toughness steel suitable for the manufacture of steam turbine blades. The inventive steel composition is characterized by high strength, large damping capacity, good weldability and machinability.

In recent years, steam turbines for power plants have been manufactured in ever increasing sizes and the general tendency is to make steam turbines of increased dimensions. In respect to industrial turbines, for compressor operations and the like, which are of relatively smaller sizes, it has recently been the tendency to increase the rotating speed of the turbines so as to raise the output power and efficiency values.

The increased demands on steam turbines place also ever increasing requirements on the turbine blades. In large-sized steam turbines and turbines rotating at high speeds, the blades are subjected to considerable centrifugal forces, particularly at the last stage of the low pressure portion of the cycle. For this reason, it has been found necessary to develop more resistant materials for the turbine blades so as to enable them to withstand for a long period of time, the various forces to which they are subjected. It has been found that desirable materials for the manufacture of turbine blades to be used in turbines of the kind referred to, should have high strength, satisfactory ductility, toughness, suitable corrosion resistance characteristics to wet steam and good weldability so that the usual rods or bars connecting adjacent blades for restricting their movements relative to each other can be readily welded to the blades to prevent or absorb resonant oscillations. It is of particular importance that the material has superior damping capacity. As is known, damping capacity is a measure of the rate at which a material dissipates energy of vibration, or in other words, a measure of the ability to damp out vibrations. Damping depends upon internal friction in the metal which is manifested at stresses well below those at which gross yielding occurs. Accordingly, a desirable material for the indicated purpose must have large internal friction values to obtain the desired damping capacities. In this connection, it should be observed that undesired resonant oscillation in the blades cannot be obviated merely by design.

Turbine blades have customarily been manufactured from heat resistant steels of the 12% Cr-type. Such steels have been considered to be suitable for turbine blades because of their relatively high strength, good corrosion resistance and large internal friction or damping capacities. However, such steels have the disadvantage that an increase in the strength or hardness values of the material, in turn, reduces the internal friction or damping value. Moreover, an increased content of carbon or the addition of hardening elements such as nickel, molybdenum and tungsten which are needed for imparting greater strength to the steel, in turn, significantly reduces the weldability characteristics. This, for example, applies to AISI 422 steels. For these reasons, the upper strength limit values for turbine blades made from the usual 12 percent chromium steels have been considered to be restricted to a maximum yield strength of 80 kg./mm.^{2}. However, blades to be used in turbines of large dimensions and operated at high speeds require yield strength values of 100–120 kg./mm.^{2} or even more. Prior to this invention, such materials have not been available and therefore the development of larger turbines and turbines operating at higher speeds has been significantly impeded.

Accordingly, it is a primary object of the present invention to provide a steel composition suitable for the manufacture of turbine blades of extremely high strength and large damping capacity and having a yield strength value sufficient to satisfy the requirements of large sized turbines and turbines operating at extremely high speeds.

Briefly, and in accordance with the invention, a steel composition superiorily meeting the above requirements comprises about between 8 to 14% of chromium, 3–10% of nickel, 4–10% of cobalt and 2–5% of molybdenum. The molybdenum content may be replaced by tungsten in a substitution ratio molybdenum to tungsten of 1:2. The balance of the composition is composed of iron. However, the composition contains also minor amounts of carbon, silicon and manganese which are incorporated in the steel composition together with the raw materials in minor amounts. In order to obtain the maximum benefits of the invention, certain upper limit values for the carbon, silicon and manganese contents are set. Thus, the carbon content should not exceed 0.06%, while the silicon content should not be above 0.6%. In respect to manganese, the upper limit value is 0.6%.

The ingredients of the inventive steel composition and their amounts are adjusted so that the quantity of δ ferrite, in percent, equals to the value a in the equation

$$a = -146 - 220\,(C+N) - 20\,Ni - 7Co - 6Mn + 6Si + 5\,Mo + 14Cr + 8W$$

is less than 0. In this equation, a, to wit, the δ ferrite value, represents this value at the austenitizing temperature, while the element symbols indicate the presence of 1 percent of the respective element, the actual value of a being determined by multiplying the actual percentage value of the respective element with the number preceding the respective element symbols. Thus, for example, if the total amount of carbon and nitrogen is 0.1 percent and the percentage value for the other elements is 0, the value for a would be determined by the equation

$$a = -146 - 220 \times 0.1 + 0 = -168$$

The equation also indicates that the a value is decreased by −20 if 1 percent of nickel is contained in the composition while the a value is increased by five for each percent of molybdenum. The a value thus has significance as an indication of the percentage of δ ferrite at the temperature of austenitizing.

A further characteristic of the inventive steel composition is that the components are adjusted so that the Ms point, in degree centigrade, (°C) is indicated by the value b in the equation

$$b = 554 - 474\,(C+N) - 17\,Ni - 15\,Co - 33Mn - 11Si - 21Mo - 17Cr - 11W$$

the b value is more than 100 and in the equation, the element symbols again indicate the presence of 1 percent of the respective elements, the actual value of b being determined by multiplying the actual percentage value of the respective element with the number preceding the respective element symbols. Thus, for example, if the amount of nickel in the composition is 1 percent and the value for the other elements is 0, the b value would be

$$b = 554 - 17 \times 1 = 554 - 17 = 537$$

As previously stated, the molybdenum content may at least partly be replaced by tungsten, at a substitution ratio of 1 to 2.

The steel composition is subjected to heat treatment, according to which the material is cooled in a suitable cooling medium such as, for example, water, oil or air from a temperature of 800° to 1000° C. The composition is then aged at a temperature of about between 400° to 550° C. for a period of 1 to 100 hours.

The inventive steel composition has excellent machinability characteristics, because the steel is relatively soft, the Vicker's hardness being 350 or less in the quenched state, while its work-hardenability is small. Since the subsequent aging is carried out in the relatively low temperature range of 400° to 550° C., the degree of oxidation and of deformation during the treatment is relatively insignificant. It follows that turbine blades made from the above steel material can be readily machined, if the machining is carried out in the quenched state of the steel and the aging is effected subsequent to the machining. Further, since the inventive steel has excellent forgability characteristics, the turbine blades may be manufactured by precision forging. This, of course, results in considerable savings in material.

The connecting members such as bars which are interconnecting adjacent blades may be readily welded to the blades because of the superior weldability characteristics of the steel composition.

The effect of the respective components and the reason for limiting their amounts in the composition to the indicated values will now be explained in reference to the accompanying drawings in which

FIG. 1 is a graph showing the effects of the molybdenum and cobalt contents on the Vicker's hardness of a steel composition suitable for turbine blades and embodying the concepts of the present invention, after aging at 500° C. for 20 hours.

FIG. 2 shows the relationship of the difference between the starting temperature and the finishing temperature of martensite transformation to the carbon content in the inventive steel composition.

FIG. 3 shows the effect of the carbon content on the hardness of the steel after quenching.

FIG. 4 represents the results of the damping capacity tests of the steel due to the internal friction prevailing in the material.

FIG. 5 is a graph showing the relationship of the material damping or internal friction, at the nominal stress of 25 kg./mm.^{2}, to hardness.

FIG. 6 indicates a comparison of the lowest preheating temperature necessary to avoid the generation of cracks in the steel according to the present invention, AISI 422 steel and 13 percent chromium molybdenum steel; and

FIG. 7 shows a turbine blade manufactured from the inventive steel composition.

Referring now to the quantity a, in percent, of δ ferrite, it will be appreciated that the existence of δ ferrite in the material lowers its strength, toughness and ductility. Accordingly, the value a is less than 0, to suppress the formation of δ ferrite. The Ms point b in degree centigrade (° C.) is restricted to above 100 for the reason that a desirable strength value cannot be obtained as the result of remaining austenite upon quenching, if the Ms point b is below 100.

The addition of chromium imparts the material with a suitable oxidation resistance, raises the aging hardenability and facilitates the attainment of desirable internal friction or damping capacity values. To obtain the required material damping values, a content of chromium in excess of 8 percent is necessary. For this reason, the lower limit value for chromium has been indicated as 8 percent. On the other hand, if the upper limit value for chromium of 14 percent is exceeded, then much larger amounts of nickel and cobalt would have to be added for adjusting the value a. This, in turn, would cause the value b to be reduced to below 100. Since this is undesirable, the upper chromium value has been indicated at 14 percent.

The nickel is added for the purpose of increasing the toughness and for the proper adjustment of the a value. To obtain desirable toughness, at least 3 percent of nickel is required, while the upper limit value of 10 percent is determined in consideration of the variation of the value b. The addition of cobalt imparts the material with desirable aging hardenability characteristics, due to the interaction of cobalt with molybdenum and/or tungsten, and, moreover facilitates adjustment of a proper a value.

To gain the required strength value of the inventive steel composition, at least 4 percent of cobalt has to be added. The upper limit value of 10 percent for the cobalt is established for the reason that additions in excess of 10 percent exert a harmful influence on several mechanical or physical characteristics of the steel. Thus, for example, larger amounts of cobalt would cause a tendency of embrittlement during aging and also a decrease of the b value of the material.

Molybdenum is added for causing precipitation hardening, since molybdenum interacts with the cobalt as stated above. As a result, the material is imparted with the required and desired strength values. In order to make sure that the required values in this respect are obtained, at least 2 percent of molybdenum have to be contained in the steel composition. The upper limit value is restricted to 5 percent because greater amounts of molybdenum reduce the ductility and toughness characteristics while raising the strength values. Precipitation hardenability by molybdenum and cobalt increases in linear manner with an increase of the product of the respective added quantity, as shown in FIG. 1. As previously stated, however, the effects of molybdenum can also be obtained by tungsten, provided the substitution ratio of molybdenum to tungsten is 1 to 2. Accordingly, the entire amount or a portion or the molybdenum may be replaced by tungsten.

Carbon, as indicated in FIG. 2, extends the difference between the starting temperature and the finishing temperature of martensite transformation and makes it easy to retain the austenite. On the other hand, carbon raises the hardness after quenching and thus has an undesired influence upon the machinability, as indicated in FIG. 3. Accordingly, the amount of carbon should be relatively small and should not exceed 0.06 percent. The addition of manganese and silicon as alloying elements is not desirable for the reason that their elements lower the ductility and toughness. However, both elements should be added in small amounts for deoxidizing purposes to remove undesired harmful excess oxygen, particularly if the material is melted in the open atmosphere. Experiments have indicated that the best results are obtained if the silicon and manganese contents do not exceed 0.6 percent.

It will be appreciated, that in addition to the above components, other alloying elements may be added. Thus, for example, boron, aluminum, calcium, vanadium, columbium, zirconium, titanium and the like may be added singly or in mixture for various purposes such as, for example, for purposes of deoxidation, denitrification and refining of the crystal grains. Such further additions are permissible to the extent that they are useful for the increase of the ductility and toughness values but care should be taken not to add such further elements in amounts which would exert an undesirable influence on the damping capacity of the steel composition.

In the following, the mechanical properties of the steels in accordance with the invention are described. Table 1 indicates the chemical compositions of the materials tested. Test specimen G of Table 1, was made according to the following procedure: 2 tons of an alloy of the inventive composition G were melted in a basic high frequency vacuum furnace with a 2 ton capacity, were cast in a metal mold and then forged to a square size of 40 × 53 mm. The other test specimens, A, B, C, D, E and F were each manufactured into square sizes of 40 × 40 dimension by forging an ingot, 30 kg. of which were melted in air in a basic high frequency furnace with a 30 kg. capacity, and subsequent casting in a metal mold.

TABLE 1

Material No.	Chemical composition, percent												
	C	Si	Mn	P	S	Cr	Ni	Co	Mo	W	B*	a	b
A	0.03	0.36	0.35	0.014	0.010	12.23	5.96	7.02	3.13			−134	114
B	0.01	0.09	0.15	0.013	0.011	12.01	6.21	6.76	3.08			−136	135
C	0.01	0.04	0.14	0.012	0.010	12.00	6.12	7.13	2.02			−143	158
D	0.03	0.06	0.10	0.015	0.018	12.51	5.81	4.48	4.53			−102	106
E	0.03	0.07	0.08	0.014	0.017	12.30	5.92	6.79	3.93			−126	110
F	0.02	0.05	0.31	0.012	0.013	11.43	4.22	7.43		4.23		−94	184
G	0.03	0.32	0.19	0.014	0.010	12.08	5.57	6.86	2.71		0.003	−128	139

*B is the quantity of addition.

Table 2 indicates the mechanical properties of the materials listed in Table 1 under various heat treatment conditions. The table clearly indicates that the steels according to the present invention have a rather low hardness after being cooled from the austenitizing temperatures but are also characterized by high strength values as well as by superior ductility and toughness characteristics obtained by the age hardening treatment.

FIG. 4 indicates the results of the damping capacity or internal friction tests of the material A–5 in Table 2 in the shape of a tuning fork.

FIG. 5 shows the relationship of the internal friction or damping capacity to hardness of the steels in accordance with the invention at a nominal oscillating stress of 25 kg./mm.^{2}. The dots in the figure correspond to the value for the specimens A–2, A–5, B–5, C–2, E–2 and G–2 in Table 2, respectively. It is clear from the figure that the steels, in accordance with the present invention exhibit a relatively large internal friction or damping capacity even at a high hardness level, to wit, at a high strength value.

FIG. 6 is a diagram indicating the results of weld crack tests performed with a 13 percent chromium-molybdenum steel (Japanese Industrial Standard SUS 37B), with AISI 422 steel, both of which are each commonly used as turbine blade manufacturing material, and with the turbine blade steel composition according to the present invention. The AISI 422 steel has a yield strength value of 80 kg./mm.^{2} while the 13 percent chromium-molybdenum steel has a yield strength value of only 50 kg./mm.^{2}. While the two prior art steels satisfy the respective standard, it will be noted that in the steel of the present invention, corresponding to sample specimens A–4 in Table 2, no cracks were generated even in the absence of preheating and that the material has excellent weldability characteristics. By contrast, the prior art AISI 422 and 13 percent chromium-molybdenum steels have to be preheated above 100° C.

FIG. 7 represents a turbine blade made of the inventive steel composition.

FIG. 8 represents the changes in the dimension of the blades made from the material G in Table 1 during aging, which was aged for 6 hrs. at 500° C.

What is claimed is:

1. The method of manufacture of high strength and high toughness steel turbine blades, which comprises forming a turbine blade from a steel essentially consisting of

	between about	8–14% of Cr,
	between about	3–10% of Ni,
	between about	4–10% of Co,
	between about	2–5% of Mo,
	not more than	0.06% of C,
	not more than	0.6% of Si,
and	not more than	0.6% of Mn,
	the balance being Fe,	

and, being further characterized by a quantity of δ Ferrite, in percent, which is equal to the value a in the equation,

$$a = -146 - 220\,(C+N) - 20\,Ni - 7\,Co - 6\,Mn + 6\,Si + 5\,Mo + 14\,Cr + 8\,W = \text{less than zero,}$$

wherein a is the δ ferrite value at the austenitizing temperature and the element symbols indicate the presence of 1 percent of the respective element, the value of a being determined by multiplying the actual percentage value of the respective element with the number preceding the respective element symbol and also being characterized by a Ms point in °C. which is equal to the value of b in the equation

$$b = 554 = 474\,(C+N) - 17\,Ni - 15\,Co - 33\,Mn - 115: -21\,Mo - 17\,Cr - 11\,W = \text{more than } 100,$$

wherein the element symbols indicate the presence of 1 percent of the respective element, the value of b being determined by multiplying the actual percentage value of the respective element with the number preceding the respective element symbol; cooling said steel in a medium selected from the group consisting of water, oil and air from a temperature of from about 800° to about 1,000° C.; and aging said steel at a temperature of from about 400° to about 550° C. for a period of from about 1 to about 100 hours.

2. The method of manufacturing turbine blades as claimed in claim 1, wherein at least a portion of its Mo content is substituted for W at a substitution rate Mo:W of 1:2.

3. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.23%
Ni:	5.96%
Co:	7.02%
Mo:	3.13%
C:	0.03%
Si:	0.36%
Mn:	0.35%

4. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.01%
Ni:	6.21%

Material No.	Specimen No.	Heat treatment	0.2% offset yield strength (kg./m.^{2})	Tensile strength	Elongation	Reduction of area	Impact value	Vicker's hardness
A	1	950° C.×1 hr. OQ	83.7	108.2	15.5	53.3	8.3	333
	①2	950° C. plus 450° C.×7 hr	123.7	135.2	16.0	58.7	5.9	405
	3	950° C. plus 450° C.×23 hr	140.8	152.2	15.7	55.9	3.4	490
	4	950° C. plus 500° C.×1 hr	107.1	120.7	20.6	61.4	8.1	365
	⑥5	950° C. plus 500° C.×9 hr	126.1	137.5	16.6	58.3	5.7	435
	6	950° C. plus 550° C.×4 hr	128.1	138.5	18.1	57.7	2.4	425
B	1	950° C.×1 hr. OQ	90.9	106.0	13.9	36.9	8.7	322
	2	950° C. plus 450° C.×10 hr	119.4	132.9	19.6	56.9	5.0	420
	3	950° C. plus 450° C.×36 hr	133.8	145.5	15.1	52.7	3.5	457
	4	950° C. plus 500° C×2 hr	107.3	120.5	19.4	59.0	6.5	386
	⑥5	950° C. plus 500° C.×10 hr	119.3	133.2	18.4	57.1	5.4	416
	6	950° C. plus 550° C.×3 hr	117.2	123.3	18.5	59.5	5.1	401
C	1	950° C.×1 hr. OQ	90.0	106.0	13.9	36.9	8.7	322
	⑦2	950° C. plus 450° C.×17 hr	118.3	130.6	18.8	56.7	4.5	417
	⑤3	950° C. plus 450° C.×100 hr	132.9	141.5	16.6	54.6	3.5	460
	4	950° C. plus 500° C.×6 hr	115.9	121.7	20.0	59.6	5.6	397
	5	950° C. plus 500° C.×50 hr	128.5	135.0	16.4	55.0	4.3	434
D	1	950° C.×1 hr. OQ plus 500° C.×10 hr	119.5	132.3	17.2	51.4	2.1	426
	2	950° C. plus 500° C.×60 hr	143.7	154.6	13.2	46.2	1.0	500
	3	950° C. plus 500° C.×100 hr	154.7	171.1	16.0	41.4	1.9	513
E	1	850° C.×1 hr. OQ plus 500° C.×10 hr	108.5	140.0	19.2	53.8	4.3	449
	④2	850° C. plus 500° C.×20 hr	128.4	142.7	20.0	53.2	4.3	455
	3	850° C. plus 550° C.×10 hr	141.0	154.4	18.0	49.0	3.6	473
F	1	1,000° C.×1 hr. OQ	89.2	114.2	18.0	59.9	7.2	
	2	1,000° C. plus 500° C.×100 hr	124.8	134.6	18.8	53.0	2.1	
G	1	950° C.×2 hr. OQ	93.0	115.9	17.2	51.0	16.9	360
	②2	950° C. plus 500° C.×1 hr	105.5	125.9	23.6	67.5	13.8	407
	3	950° C. plus 500° C.×6 hr	120.7	135.3	20.4	67.1	8.0	429
	4	950° C. plus 500° C.×16 hr	135.5	144.6	18.0	63.8	5.8	447

Co:	6.76%
Mo:	3.08%
C:	0.01%
Si:	0.09%
Mn:	0.15%

5. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.00%
Ni:	6.12%
Co:	7.13%
Mo:	2.02%
C:	0.01%
Si:	0.04%
Mn:	0.14%

6. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.51%
Ni:	5.81%
Co:	4.48%
Mo:	4.53%
C:	0.03%

Si:	0.06%
Mn:	0.10%

7. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.30%
Ni:	5.92%
Co:	6.79%
Mo:	3.93%
C:	0.03%
Si:	0.07%
Mn:	0.08%.

8. The method of manufacturing a turbine blade of high strength steel as claimed in claim 1, wherein said steel contains the following elements in percentage by weight substantially in the following amounts:

Cr:	12.08%
Ni:	5.57%
Co:	6.86%
Mo:	2.71%
C:	0.03%
Si:	0.32%
Mn:	0.19%.

* * * * *