

June 18, 1968

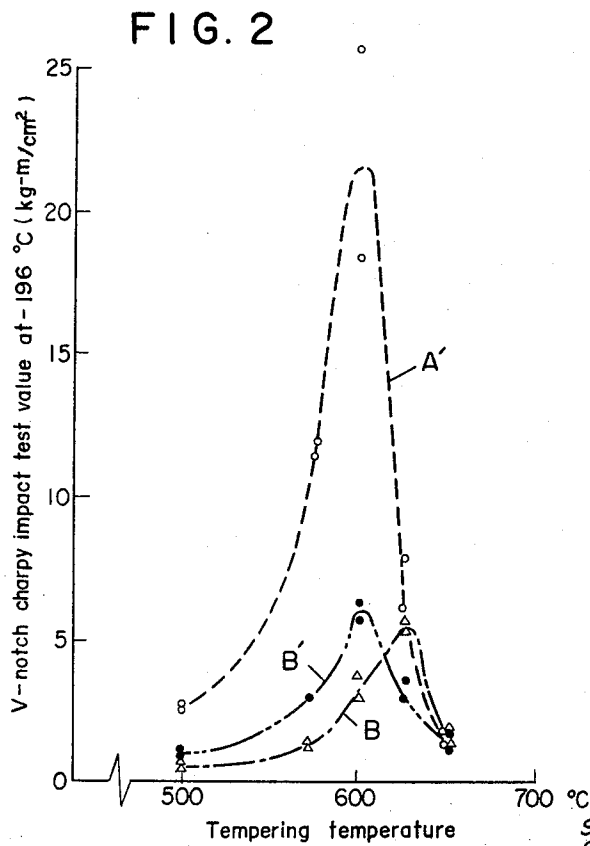
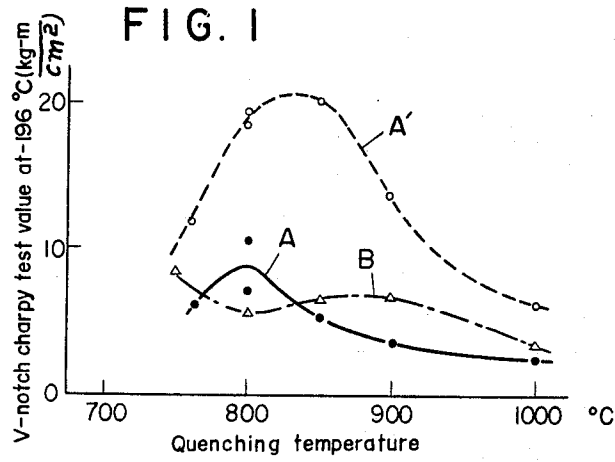
SHINICHI NAGASHIMA ET AL

3,388,988

LOW-TEMPERATURE TOUGH STEEL

Filed June 21, 1965

4 Sheets-Sheet 1



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4 Sheets-Sheet 2

FIG. 4

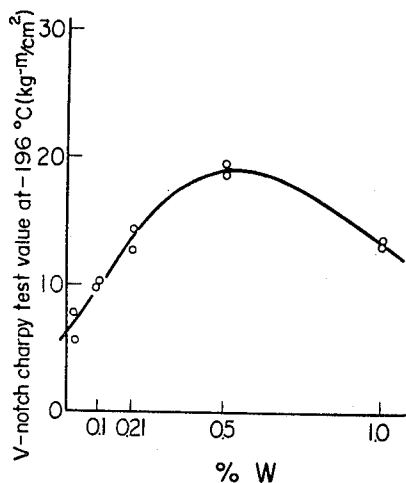


FIG. 3

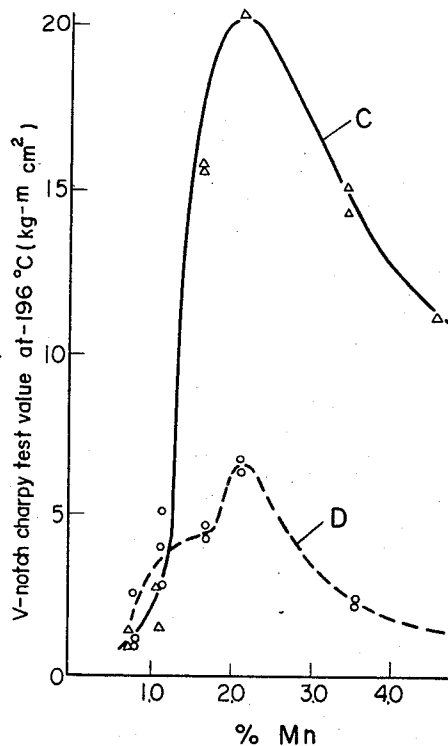
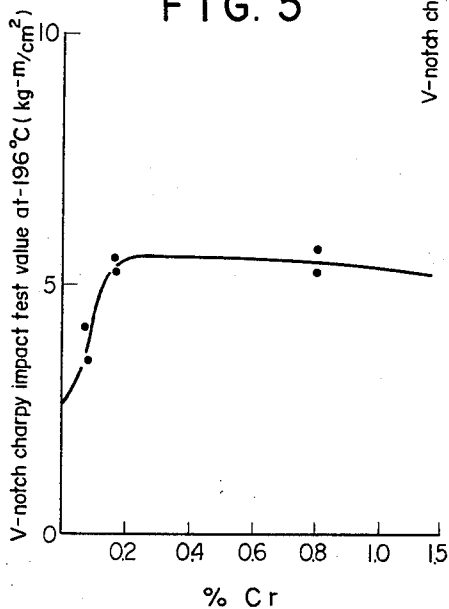


FIG. 5



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4 Sheets-Sheet 3

FIG. 6

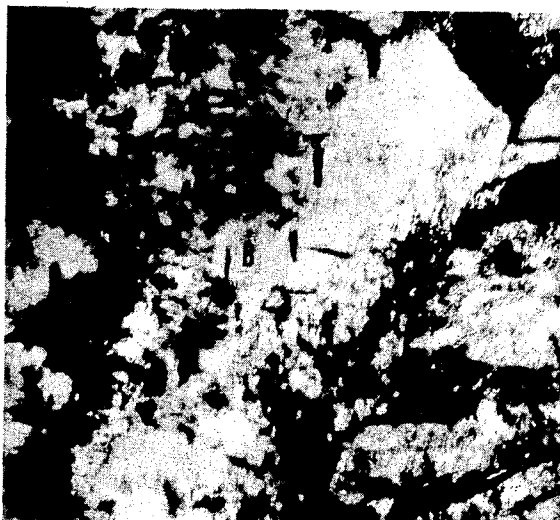


FIG. 7



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4 Sheets-Sheet 4

FIG. 8

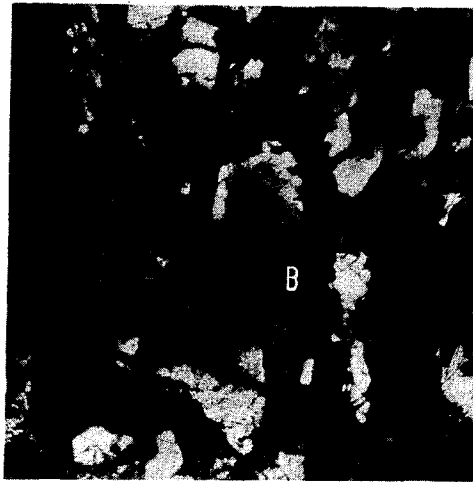


FIG. 9



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3,388,988

LOW-TEMPERATURE TOUGH STEEL

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39/35,392, 39/35,393

5 Claims. (Cl. 75-128)

ABSTRACT OF THE DISCLOSURE

A low-temperature tough steel consisting essentially of 0.01 to 0.15% by weight C, 0.05 to 0.40% by weight Si, 4.50 to 7.50% by weight Ni, 0.50 to 4.50% by weight Mn, 0.1 to 1.50% by weight Cr, 0.1 to 1.50% of a temper brittleness reducing material taken from the group consisting of W and a mixture of W and Mo, N less than 0.05% by weight, and a nitride forming element in an amount equivalent to less than 0.05% by weight acid-soluble Al, the balance being Fe and unavoidable impurities, said steel having as the base structure an austenite grain precipitated in a ferrite matrix.

This invention relates to economical alloy steel having a sufficient toughness and strength even at low temperatures and particularly to alloy steel having sufficient toughness and strength even at a boiling point of liquid nitrogen (-196°C.).

The so-called 9%-Ni steel is already known as an economical commercial steel to take place of the 18-8 stainless steel. As properly heat-treated, this steel shows a toughness of about 8 to 11 kg.-m/cm.² in the V-notch Charpy impact value at -196°C. , the boiling point of liquid nitrogen, and has such considerable strengths as a tensile strength of 75 to 85 kg./mm.² and a yield strength of 60 to 65 kg./mm.² at room temperature. Although 9%-Ni steel has such toughness and strength as mentioned above but since such large amount as about 9% of Ni which is a costly alloying element for steel is used in this steel, the price of the steel is high. Specifically in a country poor in Ni resources, even if a steel material high in the Ni content would be produced, it will have only economically limited uses. Therefore, in order to reduce the price and structural weight, the development of more economical tough steels is required today.

An object of the present invention is to provide economically steel containing a reduced amount of expensive Ni and having a toughness and strength at low temperatures same as or higher than those of 9%-Ni steel in the A.S.T.M. Standard.

Another object of this invention is to provide steel having a toughness and strength at low temperatures same as or higher than those of 9%-Ni steel in the A.S.T.M. Standard by compensating the alloying elements that will be mentioned below, in particular, Mn, W (or Mo), Cr, for the reduction of expensive Ni.

A further object of this invention is to provide steel having a very high toughness and strength even at the boiling point of liquid nitrogen (-196°C.) by heat-treating the steel containing the above-stated alloying elements in response to the contained alloying elements and the amount of formed nitrides to form a stable structure at low temperatures.

Additional objects of this invention will become manifest by the following descriptions referring to the examples and the accompanying drawings in which:

FIG. 1 is a graph showing the relation of the austenitizing temperature and the V-notch Charpy impact test value at -196°C. , the boiling point of liquid nitrogen in the case where steels (A, A', and B) subjected to a diffusion treatment are air-cooled (A') or water-quenched (A and B), heated for 1 hour to 600°C. , and then water-cooled,

FIG. 2 is a graph showing the relation of the tempering temperature and the V-notch Charpy impact test value at -196°C. in the case where the steel shown in FIG. 1 are, after diffusion treatment, heated for 1 hour to 800°C. , air-cooled (A' and B') or water-quenched (B), and then tempered,

FIG. 3 is a graph showing the relation of the Mn content and the V-notch Charpy impact test value at -196°C. ,

FIG. 4 is a graph showing the relation of the W content and the V-notch Charpy impact test value at -196°C. ,

FIG. 5 is a graph showing the relation of the Cr content and the V-notch Charpy impact test value at -196°C.

According to the present invention, the steel of this invention has the following composition and structure. That is, the steel of this invention consists of (by weight percent) 0.01 to 0.15% C, 0.05 to 0.40% Si, 4.50 to 7.50% Ni, 0.50 to 4.50% Mn, 0.05 to 2.00% W (a part of W may be replaced with Mo) and/or 0.10 to 1.50% Cr (a part or whole of W may be replaced with Mo when W and Cr are present), less than 0.050% N, and Al in an amount sufficient to fix N or smaller than that (less than 0.05% as acid-soluble Al) in which Al may be replaced with one or more nitride forming elements in chemical equivalent of nitride, such as, Zr, Ti, Be, Nb, V, Hf, Ta and B, balance being Fe and unavoidable impurities.

The steel is, with or without applying the heat treatment as will be mentioned below, heated and quenched or air-cooled, and then tempered to form a ferrite structure in it and at the same time to precipitate a fine austenite a part of which may be, if necessary, transferred into martensite.

Thus, the fundamental metallurgical structure of the steel of this invention consists of, as mentioned above, a ferrite and precipitated austenite (or as partly martensite). More particularly, it has a ferrite structure in which an austenite stable even at the liquid nitrogen temperature (-196°C.) precipitates on an old martensite crystal grain boundary, old austenite crystal grain boundary or ferrite subgrain boundary by such proper heat-treating method as is described later in order to obtain such structure. Further, in case a fine dispersing precipitant composed mostly of a nitride is added for the purpose of improving the toughness by grain refining and of increasing the strength by a dispersion hardening mechanism, the abovementioned fundamental structure will become a structure in which a proper precipitant is dispersed in addition.

The production of the steel of the present invention shall be described in the following. In the melting and producing step for producing the steel of the present invention, smelting can be easily carried out in such steel making furnace as a converter, open hearth-furnace, electric furnace or high frequency furnace. There is no problem in particular in this point. The molten steel containing the above mentioned alloying elements is smelted in the above mentioned furnace is cast and hot-rolled. In the casting and hot-rolling steps, too, no specific restriction is required. But, depending on the object such steps may be carried out by limiting the atmosphere of the heat-treatment. When the hot-rolled steel is heat-treated properly, the above described fundamental structure will be able to be obtained. However, this heat-treatment must be

regulated differently as explained below depending on the contents of N and Al. That is to say, in a steel which is normally smelted in a steel making furnace and N is not positively added, the amount of Al (which may be replaced by one or more other nitride forming elements such as, Zr, Ti, Be, Nb, V, Hf, Ta and B) required to fix N is added and the austenitizing followed by quenching (or air-cooling) and tempering treatments are carried out. However, the heating temperature in such case is preferably the austenitizing temperature corresponding to the components in it. If it becomes higher than the grain coarsening temperature, the toughness at low temperatures will tend to reduce. Further, the tempering temperature is preferably in the range of 525 to 650° C. in which the stable austenite precipitates in the properly tempered ferrite matrix. This is clear from the relation of toughness in the case of treating the steel having the composition as shown in Table 1 from the austenitizing temperature as shown in FIG. 1 and the relation of toughness in the case of quenching the steel to the temperature as shown in FIG. 2.

TABLE 1.—CHEMICAL COMPOSITION
(IN WEIGHT PERCENT)

	C	Si	Ni	Mn	W	Cr	Al	N
Specimen:								
A, A'.....	0.07	0.23	6.00	1.70	0.47	-----	0.015	0.0012
B, B'.....	0.07	0.20	6.00	1.70	-----	0.17	0.007	0.0015

Each of the above-mentioned steel A, A', B and B' in FIG. 1 and FIG. 2 is, diffusion-treated for 12 hours at 1,150° C., cooled, and then tempered. That is, in FIG. 1, after heating for 1 hour at the austenitizing temperature shown in the figure, steel A' is air-cooled and steels A and B are water-quenched, and steels A and A' are tempered at a temperature of 600° C. followed by water-quenching and steel B is tempered at a temperature of 625° C. followed by water-quenching. In FIG. 2, after diffusion treating as mentioned above, steels A', B and B' are heated for 1 hour to a temperature of 800° C., air-cooled for steel A' and B' or water-quenched for steel B, tempered from the temperature shown in the figure (heating period is 1 hour), and then water-quenched.

As clear from the both figures, it can be understood that while the toughness of steel, that is, the V-notch Charpy impact test value (kg.-m/cm.²) at -196° C. shows a considerably good value in the range of the austenitizing temperature, the impact value reduces as the temperature approaches the grain-coarsening temperature. Further, when the tempering temperature is lower than 525° C. and higher than 650° C., the V-notch Charpy impact test value tends to be reduced.

In the present invention, in case there is a possibility that more than 0.005% AlN will be formed in the steel as calculated from the N content (including the case that N is not positively added) and Al content in the steel, there will be carried out as required the following heat-treatment wherein the steel is hot-rolled, then subjected to a partial solid solution treatment at a temperature above the A₃ transformation point but below the crystal grain coarsening temperature, or heated to a proper temperature above the A₃ transformation point without solid solution treatment so that AlN may precipitate in finely dispersed manner and at the same time the austenite crystal grains may be made fine. It is then quenched or air-cooled so as to obtain a martensite or a mixed structure of a martensite and bainite. It is tempered in the temperature range of 525 to 650° C. so that a fine austenite may precipitate, and is quenched or air-cooled. Further, in case there is a possibility that an AlN content will be formed to be more than 0.005%, the object of the present invention will be able to be attained by the following treatment wherein the steel is hot-rolled, is subjected to a complete solid solution treatment of a temperature above 1,200° C., is quenched, is heated for a proper time at a

temperature around the A₃ transformation point so that AlN may precipitate, in finely dispersed manner, is cooled, is then heated at a temperature just above the A₃ transformation point so that the austenite grains may be made fine, is then quenched or air-cooled so as to obtain martensite or a mixed structure of a martensite and bainite, is then tempered at 525 to 650° C. so that a fine austenite may precipitate and is quenched or air-cooled.

These heat-treatments including (or not including) the solid solution heat-treatment should be selectively adopted in response to the amount of AlN in the steel and to an extent necessary for precipitating finely AlN in the steel. In the present invention, the steel made to contain the required elements in the above described ranges is heat-treated as stated above in response to the composition to regulate the fine structure so that the toughness and strength at low temperatures may be increased. That is to say, in the precipitated austenite, such alloying elements as Ni, Mn, N and C in the steel are enriched more than in the average composition of the alloy and it forms an austenite stabilizing condition at or below the room temperature, whereas, in the ferrite matrix, those elements are rather less than in the average composition and especially; the amounts of C and N solid-dissolved in the ferrite matrix are extremely small. The effects of both of such facts as described above serve to improve the low temperature toughness.

In the steel of the present invention, in the process of tempering the martensite structure or martensite-bainite mixed structure produced by quenching or air-cooling from the above-mentioned temperature, with the help of the effect of accelerating the diffusion by the presence of many dislocation groups therein, a fine austenite in which such alloying elements as N, C, Ni and Mn are enriched will precipitate in the martensite grain boundary, austenite grain boundary or ferrite subgrain boundary as mentioned above, therefore, the amounts of such elements in the ferrite matrix will reduce and, with the elimination and rearrangement of the dislocation within the martensite matrix, a ferrite matrix containing fine subgrain groups in which the amounts of C and N are very small will be formed. Thus, free N and C existing in solid-solution which are undesirable to the toughness of the steel will be fed from the ferrite matrix into the precipitated austenite. As a result, the precipitated austenite will be more stabilized. The austenite precipitated in the grain boundary will be in a state in which N, C, Ni and Mn are enriched as mentioned above and will be stable even at such low temperature as -196° C. but its fine dispersed state and stability will be determined by the tempering temperature and time corresponding to the alloy composition. The preferable temperature is 525 to 650° C. as mentioned above. In case a comparatively large amount of Mn is contained, the role of free N in the tempering process will be especially important to the stability of the precipitated austenite, and so the toughness and strength of the steel at low temperatures. Further, the nitride formed of such element chemically strongly combined with N as, for example, Al (or one or more other nitride-forming elements, such as, Zr, Ti, Be, Nb, V, Hf, Ta and B) will serve as a grain refining and dispersion hardening agent for the steel of the present invention. It is already widely known that the such precipitants are effective to refine the austenite grains and toughen the steel. However, the present invention includes also a heat-treating method of making the state of the formation and dispersion of a nitride as fine as possible. That is to say, there is carried out a treatment wherein large AlN formed at the time of freezing or hot-rolling an ingot is partly or completely solid-dissolved in an austenite and precipitate from an oversaturated state at a comparatively low temperature.

The reasons why the contents of the respective elements in the present invention are defined to be in the above mentioned ranges shall be described.

C is useful to improve the quenchability of the steel. That is to say, it is necessary to obtain a martensite structure or a mixed structure of martensite and bainite as quenched from the austenitizing temperature and will form the dislocations of a high density in the matrix. Further, C will diffuse and be absorbed into the austenite precipitated at the time of tempering and will increase the stability of the austenite at low temperatures. By taking these points into consideration, its lower limit is defined to be 0.01%. On the other hand, if the content of C increases, the amount of the solid-dissolved carbon in the ferrite matrix in the tempering process will increase and will impair the toughness. By taking this fact into consideration, the upper limit is defined to be 0.15%.

Si is an element which will improve the toughness of the steel and will increase the strength. It is also an element required for making steels. If it is less than 0.05%, the above mentioned object will not be attained. If it is added to be more than 0.4%, its toughness will tend to reduce. Therefore, Si is defined to be in this range.

Ni is an element useful for the toughness and strength of the steel. Especially it will serve to improve the toughness at the boiling point of liquid nitrogen. Further, with the help of the dislocation of a high density formed at the time of quenching or air-cooling, Ni will diffuse and be absorbed into the precipitated austenite comparatively quickly and will be able to stabilize the precipitated austenite at low temperatures. From these facts, it is necessary to add more than 4.5% Ni. If too much Ni is added, the cost of the steel will become high. Therefore, by taking these points into consideration, Ni is defined to be less than 7.50%.

Mn will improve the quenchability of the steel as well as will stabilize the fine austenite precipitated at tempering as in the case of N, C and Ni and increase the toughness and strength of the ferrite matrix. However, if the content of Mn in the steel is more than 4.5%, the toughness of the steel will be impaired. For example, in a simple series alloy steel of 0.05 to 0.1% C and 6% Ni containing 3.5% Mn, the temper brittleness at 500–600° C. is so severe as to reduce the toughness at low temperatures remarkably. FIG. 3 shows the relation of the Mn content and the V-notch Charpy impact test value at –196° C. in the case where the Mn content is varied about the steels having compositions shown in Table 2 and the steel is, after subjected to a diffusion treatment for 12 hours at 1,150° C., heated to 800° C. followed by water-quenching and then tempered to 600° C. followed by water-quenching.

TABLE 2.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

	C	Ni	Si	Mn	Mo	Al	N
Specimen:							
C.....	0.07	6.00	0.23	0.50– 4.50	0.20	0.01– 0.005	0.001– 0.002
D.....	0.09– 0.10	6.00	0.23	0.50– 4.50	-----	0.01– 0.005	0.001– 0.002

In FIG. 2, curve C corresponds to the result about the specimen C shown in Table 2 and curve D corresponds to the specimen D. From the figure it is clear that by adding about 2% by weight of Mn into specimen C that contains Mo, the steel is endowed with a very good toughness.

The above result obtained about specimen C is shown in the case adding Mo but the same is true in the case of adding the same amount of W. By our experiments, the V-notch Charpy impact test value at –196° C. of a specimen having the same composition as specimen C except that the Mo is replaced with 0.5% by weight of W is 18.1 to 19.5 kg.-m/cm.² in case where said specimen is heat-treated as in specimen C. From these results it may be concluded that the addition of a large amount of Mn becomes possible by the addition of a suitable amount of W or Mo.

However, if the content of Mn is high, (Fe, Mn)₃C will be present until high temperatures, which reduces the

grain boundary strength. As mentioned above, this fact will give a bad influence on the toughness of the ferrite matrix and will impair the stability of the austenite precipitated at tempering. For such reasons, the upper limit of Mn is defined to 4.5%. On the other hand, if the Mn content is less than 0.5%, the desired effect will not be obtainable.

W is an element useful for reducing the temper brittleness of the simple series alloy containing Ni, Mn, and C as mentioned above. Further, according to the observation with an electron microscope, W in the steel delays the recovery of the martensite, which results in refining the dispersed state of austenite precipitated in the grain boundary, accelerating the diffusion of Ni, Mn, C and N, and extending the optimum tempering temperature to higher temperatures. In order to obtain such results, the preferable range of W is 0.05 to 2.00% by weight.

In FIG. 4 is shown the result of the V-notch Charpy impact test at –196° C. in the case of varying the W content in the steel having the composition as shown in Table 3.

TABLE 3.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

C.....	0.08–0.11
Si.....	0.23
Ni.....	6.00
Mn.....	1.60–1.70
W.....	0.10–1.00
Al.....	0.015
N.....	0.002

The above steel is subjected to a diffusion treatment for 12 hours at 1,150° C., heated for 1 hour at 800° C., air-cooled, tempered for 1 hour at 600° C., and then water-quenched. From the result, it is clear that the toughness at low temperatures of the steel is extremely increased by the addition of W. W give the almost same effect as Mo but more economical steel can be obtained than the case of adding Mo. Further, a part of W may be replaced with Mo and in this case thus added Mo gives the effect same as W. Also, when Cr is added as will be mentioned below, the whole of W may be replaced with Mo.

Cr is an element to be added for extending the optimum tempering temperature to higher temperatures. That is, the martensite structure is formed by a quenching treatment, and by tempering the steel, it is converted into the ferrite structure the recovery of which has suitably proceeded, but in this case, the diffusion of Ni, Mn, C, N,

etc., must be accelerated by delaying suitably the recovery of martensite and making fine the dispersion of the austenite precipitated in the grain boundary. For obtaining thus effect, it is necessary to add 0.10–1.50% by weight of Cr. In FIG. 5 is shown the result of the V-notch Charpy impact test in the case of heating the steel having the chemical composition as shown in Table 4 to 800° C., water quenching, and then tempering it at 625° C.

TABLE 4.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

C.....	0.07
Ni.....	6.00
Si.....	0.20
Mn.....	1.70
Cr.....	0.50–1.50
Al.....	0.01–0.02
N.....	0.001–0.002

As clear from the result, the toughness of the steel at low temperatures can be extremely stabilized by the addition of Cr. However, if the content of Cr is higher than 1.5%, no remarkable results can be obtained.

In case N is present as a nitride as combined with Al (or one or more other nitride-forming elements, such as, Zr, Ti, Be, Nb, V, Hf, Ta and B), it will serve as a grain refining and dispersion hardening agent. Further, what is to be noted is that free N not fixed as a nitride will contribute to the stabilization of the precipitated austenite. This fact will perform an especially important role in the process of tempering an alloy containing a comparatively large amount of Mn. More than 0.001% N is contained in a normally smelted steel, but in order to attain the above mentioned object, less than 0.05% N is sufficient. Therefore, the range of addition of N is defined to be less than 0.05%.

Al is not only added as a deoxidizing agent but is necessary to fix the required amount of N. Its amount is varied depending on the setting of the ratio of N to be fixed as AlN to free N. But, in case total N exceeds 0.025%, the maximum amount of addition of Al is 0.05% as acid-soluble. Al is to be used for the above-mentioned object. In place of or in addition to Al, there may be used one or more of Zr, Ti, Be, Nb, V, Hf, Ta and B.

Examples of the present invention are given in the following:

Example 1

A steel of the composition shown in Table 5 was hot-rolled, diffusion-treated for 12 hours at 1,150° C., heated at 800° C. for 1 hour, and cooled with water or air. The structure as air-cooled is a mixed structure of a martensite having a high dislocation density and a bainite. The steel was then tempered at each of the temperatures of 500 to 600° C. and 625° C. for 1 hour and was then water-cooled. When the specimen was further tempered at 600° C. for 1 hour, the structure contained a ferrite crystal (old martensite crystal) group having a fine sub-grain boundary within, fine austenite crystals precipitated in the old martensite crystal grain boundary, and an old austenite crystal grain boundary. The steel having such structure is very high in the strength and the toughness at low temperatures. The mechanical properties of this steel are shown in Table 6. For comparison, those of the conventional 9%-Ni steel of the A.S.T.M. Standard are shown. This 9%-Ni steel was heat-treated exactly the same as in the example of the present invention.

TABLE 5.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

Constituent	C	Si	Mn	Ni	Mo	Al	N
Tested steels:							
Steel of the present invention	0.11	0.28	1.55	6.00	0.22	0.014	0.001
9%-Ni steel of A.S.T.M. Standard (Conventional steel)	0.10	0.25	0.80	9.00		0.010	0.001

TABLE 6.—2 MM. THICK V-NOTCH CHARPY IMPACT TEST VALUE (KG.-M/CM.²)

Tested steels	Tempering temperature, ° C.					
	500	600	625			
	Measuring temperature, ° C.					
	-145	-196	-145	-196	-145	-196
Steel A of the present invention	3.0	2.00	30.50	8.5	11.5	3.50
Steel B of the present invention	5.0	2.50	27.50	13.5	12.0	6.50
9%-Ni steel of A.S.T.M. Standard (conventional steel)	4.25	15.19	10.7			5.32

NOTE.—Of the steels of the present invention in Table 6, after diffusion treating for 12 hours at 1,150° C., A was heated at 800° C. for 1 hour, water-cooled, tempered at each temperature, and then cooled and B was heated at 800° C. for 1 hour, air-cooled, tempered at each temperature, and then cooled.

As mentioned above, though the optimum temperature for the steel of this invention is 600° C., the mechanical properties of the steel of the present invention are higher than those of the 9%-Ni steel. Especially it is a great feature of the present invention that, even by the tempering treatment at higher temperatures, reduction of the toughness is not so serious. Further, the air-cooling from the austenite temperature will give properties better than by the water-cooling, irrespective of the subsequent tempering temperature. As a result, it is shown that the steel of the present invention is a practically excellent steel.

Example 2

The steels having the compositions shown in Table 7 were processed. After diffusion treatment for 12 hours at 1,150° C., steel (A) of this invention was heated for 1 hour at temperatures of 760° C. and 800° C. followed by quenching and steel (B) of this invention was heated for 1 hour at a temperature of 800° C. followed by quenching.

TABLE 7.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

	C	Si	Mn	Ni	Al	N	Cr
Steel (A) of the present invention	0.06	0.214	1.64	5.93	0.007	0.0015	0.178
Steel (B) of the present invention	0.06	0.234	1.70	5.89	0.017	0.0013	0.810

These steels were then tempered for 1 hour at the temperatures of 600° C. and 625° C. respectively and measured about the 2 mm. V-notch Charpy impact test value at -196° C. The results are shown in Table 8.

TABLE 8.—2 MM. V-NOTCH CHARPY IMPACT TEST VALUE AT -196° C. (KG.-M/CM.²)

Tested steels	Quenching condition, ° C./hr.			
	760	800		
	Tempering condition, ° C.			
	600	625	600	625
Steel (A) of the present invention	6.6	8.4	3.5	5.5
Steel (B) of the present invention			3.0	5.5

The impact value of the steel quenched from the temperature of 800° C. and tempered from the temperature of 625° C. is about 1 kg.-m/cm.² higher than that of the steel containing 0.09% C., 6.0% Ni, and 1.70% Mn as shown by curve (D) in FIG. 3. Also, by reducing the austenitizing temperature to a point just above the A₃ point, the impact value may be considerably improved.

Thus, by adding a suitable amount of Cr, the impact value of the steel may be increased.

Example 3

The steel having the composition shown in Table 9 was smelted in a 1 ton electric furnace and rolled into a plate of 25 mm. in thickness.

TABLE 9.—CHEMICAL COMPOSITION (IN WEIGHT PERCENT)

	C	Si	Mn	Ni	Cr	Mo	Al ¹	N ¹
Steel of the present invention	0.08	0.11	1.10	5.99	0.95	0.41	0.032	0.0110
9%-Ni Steel of A.S.T.M. Standard	0.07	0.21	0.53	9.10				

¹ Acid-soluble Al and N.

The steel plate was subjected to a normalization treatment for 1 hour at 900° C., quenched, and then tempered. The quenching treatment was carried out by heating the steel for 1 hour at 800° C. and then water-quenching, and the tempering treatment was carried out by heating for 1 hour at 600° C., 625° C. and 650° C. respectively and cooling with water. For comparison, 9%-Ni steel of the A.S.T.M. Standard was, without applying the normalization treatment, quenched, and tempered.

These steels were tested about the tensile strength at normal temperature and the 2 mm. V-notch Charpy impact test at -196° C. The results are shown in Table 10.

TABLE 10.—2 MM. V-NOTCH CHARPY IMPACT TEST VALUE AT -196° C. (KG.-M/CM.²)

	Thick- ness (mm.)	Normal- ization	Tempering (° C./hr.)	Tensile strength (kg./mm. ²)	Yield point (kg./mm. ²)	2 mm. V- notch Charpy impact test value at -196° C. (kg.-m/cm. ²)
Steel of the present invention.....	25	(1)	600	83.2	75.6	8.5-11.0
	25	(1)	625	81.4	72.0	14.0-15.5
	25	(1)	650	88.4	68.8	11.0-12.0
	25	(2)	625	84.3	68.3	8.8-9.4
	12	(1)	625	-----	-----	25.8-28.4
9%-Ni steel of A.S.T.M. Stand- ard (conventional steel)-----	20	(2)	570	74.0	69.2	³ 9.9
	16	(2)	570	73.4	68.7	³ 11.9

¹ Applied.² None.³ Result at -190° C.

From the above results, it is clear that the optimum tempering temperature of the steel of the present invention of this kind is 625° C. The mechanical properties of the steel of the present invention are same as or better than those of 9%-Ni steel of the A.S.T.M. Standard. Also, by applying the normalization treatment, the steel can be endowed with better impact characteristics.

The structures of the steels in the case of tempering the steel from the temperature of 625° C. in the above example, contained a ferrite crystal (old martensite crystal) group having a fine subgrain boundary in it and a fine austenite crystal precipitated in the old martensite crystal boundary.

Thus, from Table 10 it has been confirmed that the steel having such a structure has a high strength as well as an extremely high toughness at low temperatures.

What we claim is:

1. A low-temperature tough steel consisting essentially of 0.01 to 0.15% by weight C, 0.05 to 0.40% by weight Si, 4.50 to 7.50% by weight Ni, 0.50 to 4.50% by weight Mn, 0.1 to 1.50% by weight Cr, 0.05 to 2.00% by weight W, N less than 0.05% by weight, and acid-soluble Al less than 0.05% by weight, the balance being Fe and unavoidable impurities.

2. A low-temperature tough steel consisting essentially of 0.01 to 0.15% by weight C, 0.05 to 0.40% by weight Si, 4.50 to 7.50% by weight Ni, 0.50 to 4.50% by weight Mn, 0.1 to 1.50% by weight Cr, 0.1 to 1.50% of a temper brittleness reducing material taken from the group consisting of W and a mixture of W and Mo, N less than

0.05% by weight, and a nitride forming element in an amount equivalent to less than 0.05% by weight acid-soluble Al, the balance being Fe and unavoidable impurities, said steel having as the base structure an austenite grain precipitated in a ferrite matrix.

3. A low-temperature tough steel as claimed in claim 2 in which said temper brittleness reducing material is a mixture of W and Mo.

4. A low-temperature tough steel as claimed in claim 2 wherein said nitride forming element is an element selected from the group consisting of Al, Zr, Ti, Be, Nb, V, Hf, Ta and B.

5. A low-temperature tough steel as claimed in claim 2, further including a precipitated martensite grain.

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