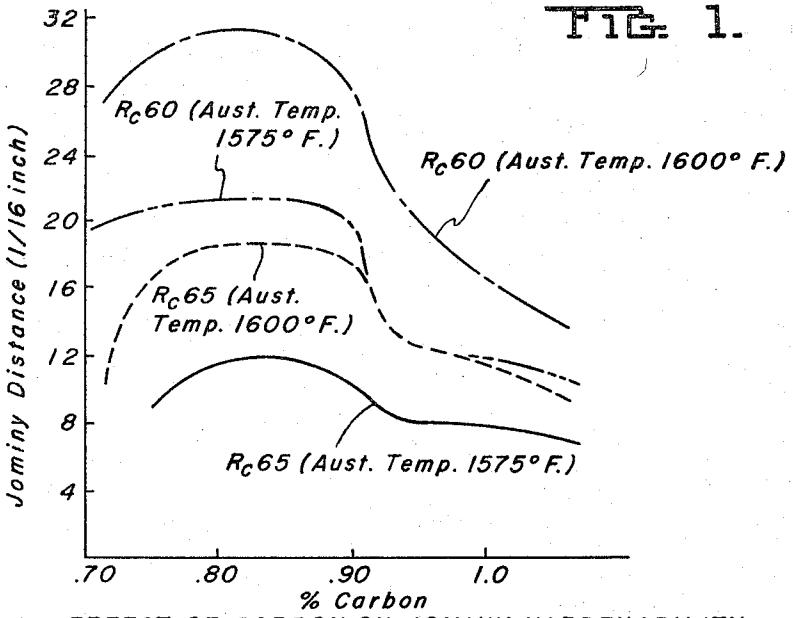
Feb. 28, 1967 A. M. AKSOY ETAL 3,306,734

LOW-ALLOY BEARING STEEL

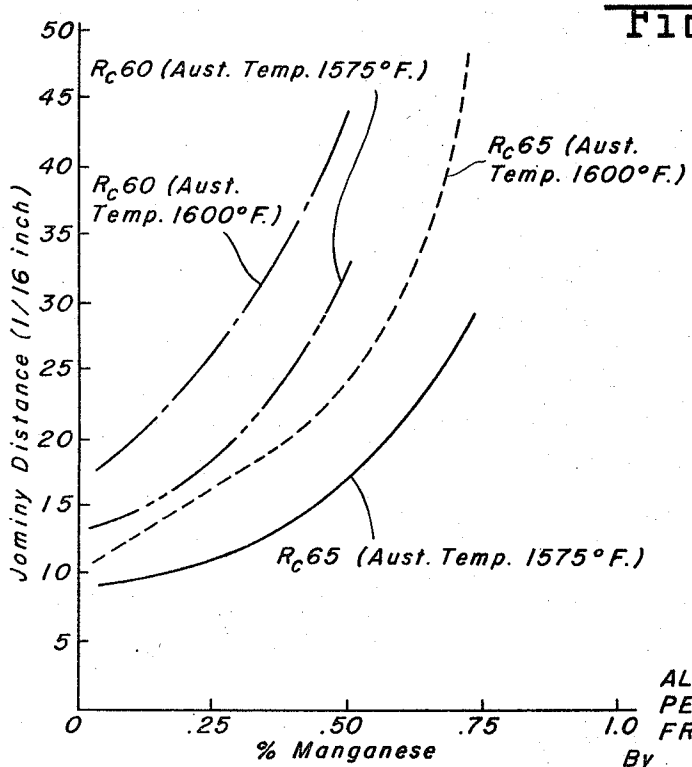
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FIG. 1.



EFFECT OF CARBON ON JOMINY HARDENABILITY

FIG. 2.



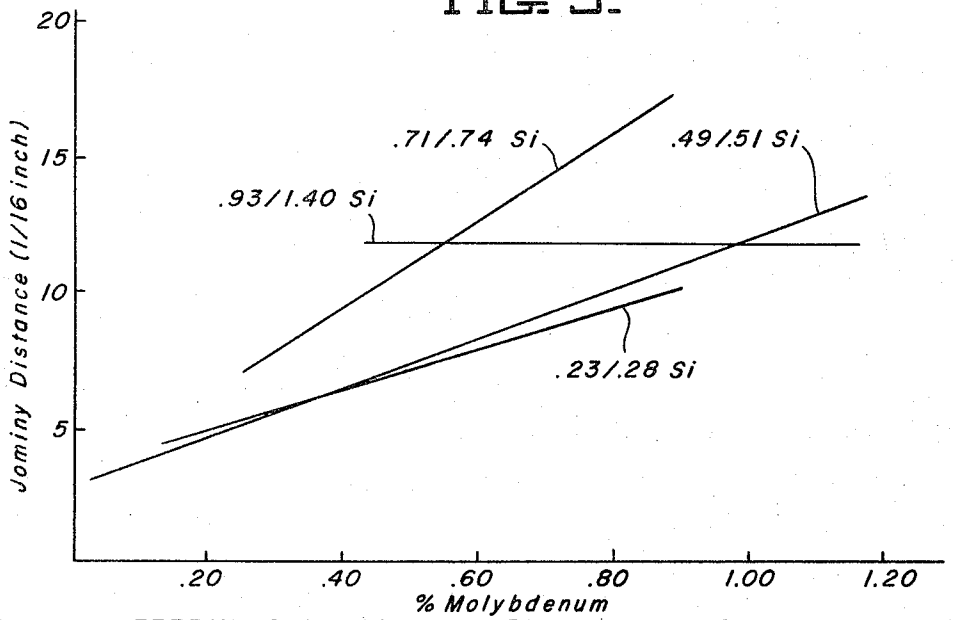
EFFECT OF MANGANESE ON JOMINY HARDENABILITY

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LOW-ALLOY BEARING STEEL

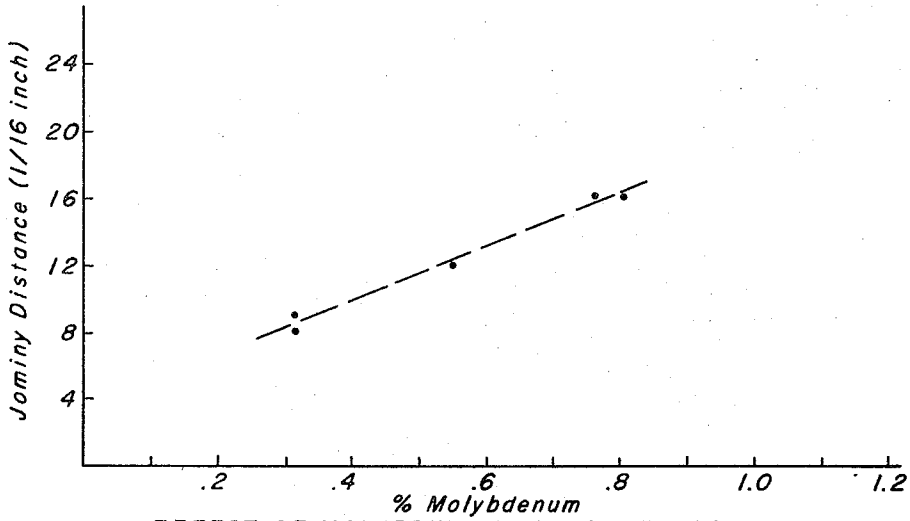
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FIG. 3.



EFFECT OF SILICON-MOLYBDENUM INTERACTION ON JOMINY HARDENABILITY

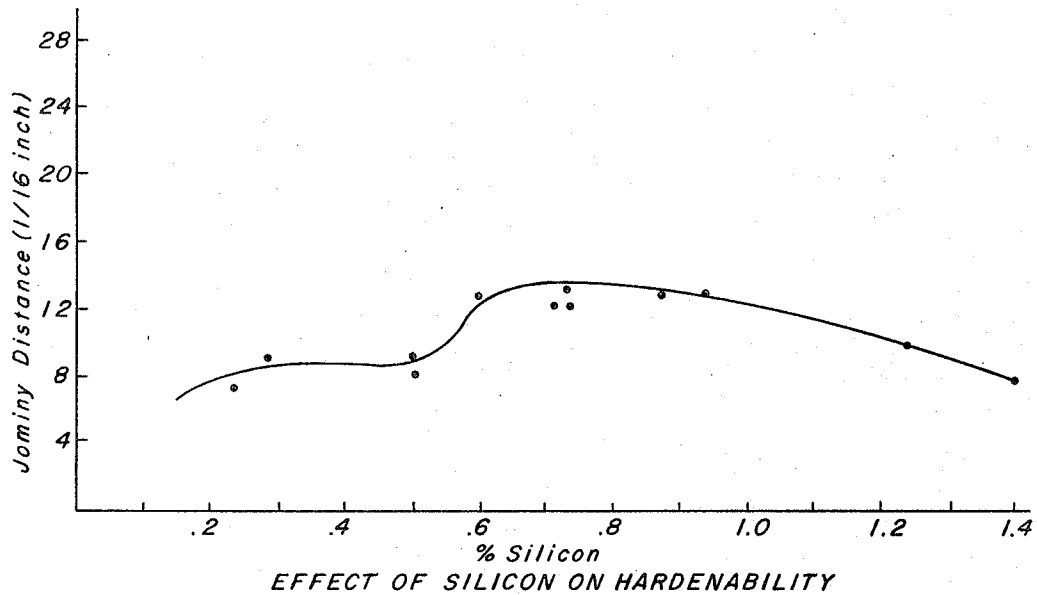
FIG. 4.



EFFECT OF MOLYBDENUM ON HARDENABILITY

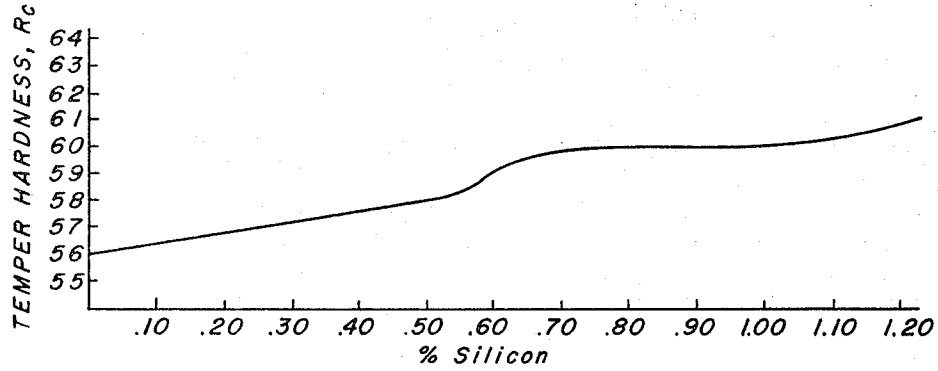
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FIG. 5.



EFFECT OF SILICON ON HARDENABILITY

FIG. 7.



EFFECT OF SILICON ON TEMPER HARDNESS (600°F.,-2 hrs.)

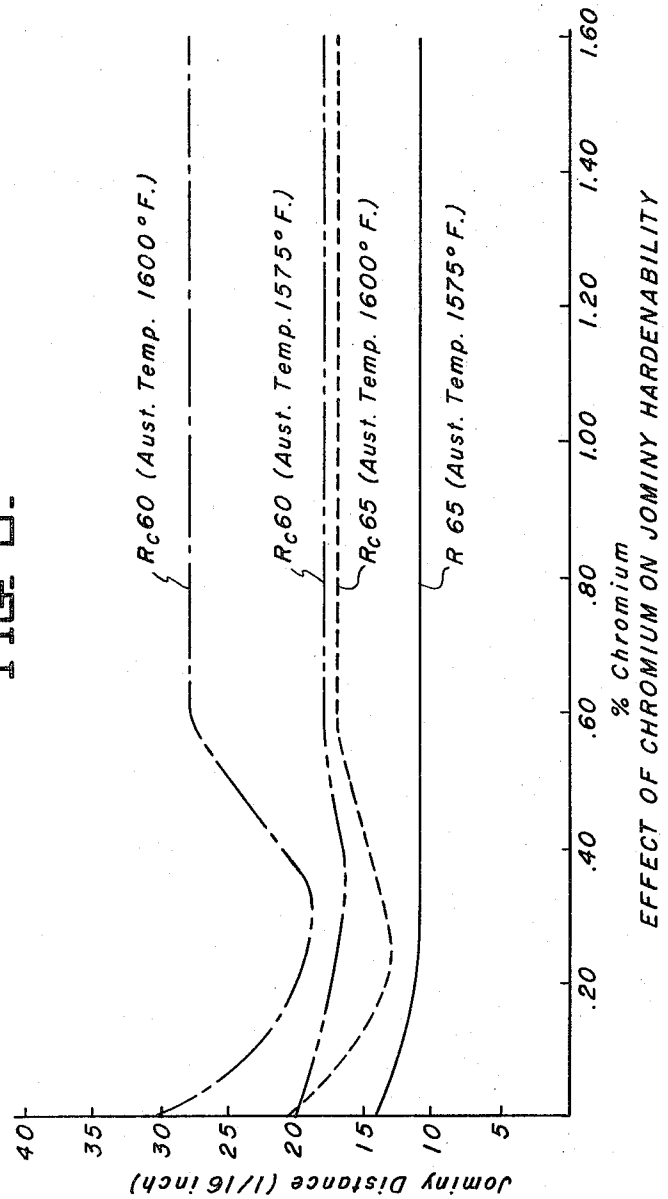
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LOW-ALLOY BEARING STEEL

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FIG. 6.



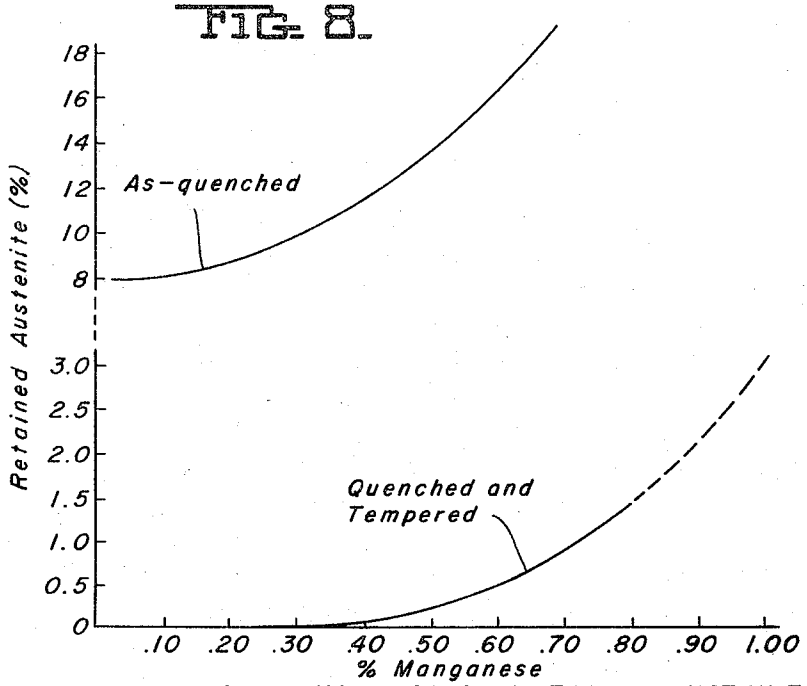
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LOW-ALLOY BEARING STEEL

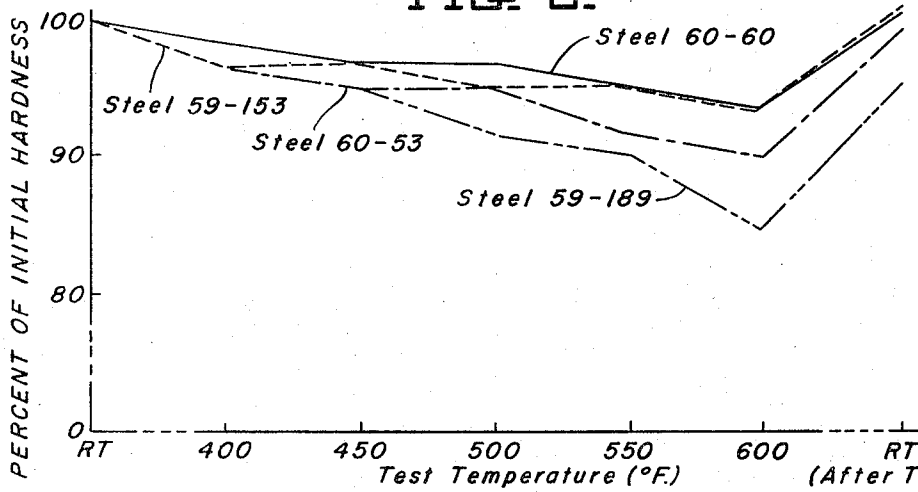
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FIG. 8.



EFFECT OF MANGANESE ON RETAINED AUSTENITE

FIG. 9.



HOT HARDNESS OF EXPERIMENTAL AND COMMERCIAL BEARING STEELS

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United States Patent Office

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3,306,734

LOW-ALLOY BEARING STEEL

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Filed May 28, 1963, Ser. No. 283,747
2 Claims. (Cl. 75—126)

This application is a continuation-in-part of our copending application, Serial No. 169,496, filed January 29, 1962, and now abandoned.

This invention relates to a low-alloy steel and particularly to such a steel exhibiting improved deep-hardening characteristics. More particularly, the invention relates to a deep-hardening bearing steel, which steel is suited for production by both air-melting and vacuum-melting processes.

In the field of bearing steels, the demand for improved properties at lower cost has been ever on the increase. However, this demand has been of added importance in connection with relatively larger-size bearings. In such bearings, the property of deep hardening is of special significance where maximum utility for special applications and long service life is desired. An initial step in the direction of satisfying the demand for deep-hardening properties in steels designed for larger bearings was the SAE 52100 steel. Primarily because of its limited deep-hardening properties, this steel soon gave way to a modified counterpart distinguished primarily by a relatively increased manganese content. The modification of the SAE 52100 steel, containing approximately 1.4 to 1.7 percent manganese as well as slightly higher silicon percentage, exhibits considerably better deep-hardening properties than the unmodified version, and through its widespread use among bearing manufacturers has become an accepted standard in the bearing art. However, in recent years, greater emphasis has been put upon the employment of large bearings for special applications in fields such as aircraft, missiles, and radar. Highly specialized applications where specific properties are called for often involve specialized processing techniques. This generalization holds true in the bearing-steel art, where the trend had definitely been in the direction of greater usage of vacuum-melted products. Attempts to vacuum-melt the modified SAE 52100 steel have not been entirely satisfactory. When vacuum-induction-melted, the high manganese content of the modified steel has often resulted in excessive quantities of non-metallic inclusions. When vacuum-arc-remelted, the high manganese content has been virtually prohibitive of obtaining close control of the final manganese content due to the volatility thereof.

Therefore, a principal object of this invention is to provide a steel which has deep-hardening properties and is amenable to vacuum-meling processes.

Another object of the invention is to provide a bearing steel capable of deep hardening with but a relatively low alloy content.

A further object of the invention is to provide a bearing steel capable of deep hardening and having improved resistance to tempering.

A still further object of the invention, is to provide a bearing steel having improved hardenability and hot-hardness properties.

Yet another object of the invention is to provide a bearing having improved properties of hardenability and dimensional stability.

Other objects and advantages of the invention will be apparent from the following description wherein applicants' inventive principles have been set forth in detail and in the accompanying drawings which are graphically illustrative thereof.

The broad ranges of the compositional elements comprising the inventive steels are as follows:

	Percent
Carbon	0.75–0.92
Manganese	Less than 1.0
Silicon	0.60–0.90
Molybdenum	0.50–1.10
Chromium	Up to 2.0
Iron	Balance

For the obtention of certain properties necessary in specialized applications, the foregoing broad ranges are restricted to the following more limited ranges:

	Percent
Carbon	0.78–0.90
Manganese	0.20–0.60
Silicon	0.60–0.90
Molybdenum	0.55–1.00
Chromium	0.60–1.60
Iron	Balance

As is obvious to those skilled in the art and as is hereby expressly understood, the inventive steels are not to be construed as completely exclusive of such elements as are normally considered impurities, and such impurities may be present in the inventive steels in such amounts as to not significantly affect the desired properties thereof.

In the course of the investigation leading to the present invention, heats of various compositions were vacuum melted and cast as 50-pound ingots. These ingots were then heated to a temperature in the range 2000° F. to 2150° F. and forged to 1⅜ inch octagonal bars. The forged bars were then spheroidize-annealed by austenitizing at 1450° F., cooling to 1325° F., and holding at the latter temperature for a period of from four to sixteen hours. Jominy hardenability measurements were employed as the criterion for deep-hardening characteristics, the austenitizing temperatures employed being selected from the usual range employed with bearing-steel grades, i.e., about 1550° F. to 1600° F. The results of the Jominy tests were recorded in terms of 1/16 of an inch distance along the longitudinal axis of the test bar as measured from the water-quenched end thereof to terminal hardness readings of Rockwell "C" 65 and Rockwell "C" 60. Temper-hardness values of the tested steels were recorded for a tempering temperature of 600° F. and a period of two hours.

Table I presents Jominy hardenability and temper data for test steels wherein carbon is the only element substantially varied, the remainder of the steel composition being relatively constant.

TABLE I.—EFFECT OF CARBON ON JOMINY HARDENABILITY AND TEMPER HARDNESS

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.)				Temper Hardness, 600° F., 2 hr., R_c
						1,575° F.		1,600° F.		
						R_c 65	R_c 60	R_c 65	R_c 60	
61-99	.52	.31	.87	.60	1.23	[a]	1	[b]	6	56
61-100	.61	.31	.87	.60	1.23	[c]	13	[c]	18	57
61-101	.72	.31	.87	.60	1.22	[d]	20	[e] 10	[e] 27	59
61-65	.78	.30	.82	.59	.95	11	17	18	32	60.5
61-102	.83	.31	.87	.60	1.21			18	31	61
61-66	.84	.30	.82	.59	.95	10	16	17.5	30	61
61-87	.86	.24	.81	.61	1.03	11	18	18	28	60.5
61-67	.90	.30	.82	.59	.95	9	14	17	28	61.5
61-83	.90	.29	.87	.61	.73			18 / 18	28 / 28	61
61-68	.94	.30	.82	.59	.95	8	11.5	13	21	62
61-85	.98	.26	.81	.57	1.02	8	13	11 / 13	17 / 19	61
61-90	1.06	.26	.81	.57	1.02	7	10.5	9 / 10	13 / 14.5	62

[a] R_c 60 max. [b] R_c 61 max. [c] R_c 63 max. [d] R_c 64.5 max. [e] R_c 65.5 max.

The existence of a critical carbon range for the obtention of significantly improved deep-hardening characteristics is clearly indicated by the data of Table I, and is even more strikingly depicted in FIG. 1, wherein Jominy distance is plotted as a function of carbon content. Examination of FIG. 1 reveals a critical range common to each of the hardenability curves at approximately the same range of carbon. It will be noted that the hardenability of steels having carbon values in the critical regions of the respective curves is substantially superior to that of the compaartive SAE 52100 and modified SAE 52100 steels. The carbon range for the critical region of the curves is about 0.75 to 0.92 percent. In this regard, it will be noted that curve A intersects the Jominy distance ordinate equal to 9/16 of an inch at approximately these limits. Within this range of carbon, a further critical range of carbon manifests itself. This narrower and equally critical carbon range lies within the 0.78 to 0.90 percent region of the curves. In addition to the advantage of superior hardenability obtained through the discriminating use of a critical carbon range, FIG. 1 clearly depicts the advantageous synergistic effect of the higher solution temperature, i.e., 1600° F.

The role of manganese from the standpoint of the disadvantages attendant its use, e.g., the detrimental effect on the cleanliness of the resultant steels and the control difficulty due to excessive volatility, especially in vacuum-melting processes, has been discussed heretofore; but the beneficial aspects of the element have not been mentioned. In this connection, the test results set forth in Table II and depicted graphically in FIG. 2 very clearly show that Jominy hardenability properties are improved with increasing manganese content.

TABLE II.—EFFECT OF MANGANESE ON JOMINY HARDENABILITY AND TEMPER HARDNESS

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.)				Temper Hardness, 600° F., 2 hr., R_c
						1,575° F.		1,600° F.		
						R_c 65	R_c 60	R_c 65	R_c 60	
61-86	.86	.03	.81	.61	1.03	9	13.5	11	17.5	60
61-87	.86	.24	.81	.61	1.03	11	18	18	28	60.5
61-83	.90	.29	.87	.61	.73			18 / 18	28 / 28	61
61-66	.84	.30	.82	.59	.95	10	16	17.5	30	61
61-67	.90	.30	.82	.59	.95	9	14	17	28	61.5
61-89	.84	.50	.81	.61	1.03	17	33	24	44	60
61-98	.85	.72	.82	.60	.95	28	[a]	48	[b]	59.5

[a] R_c 62 min. [b] R_c 64 min.

In attempting to improve deep-hardening characteristics, it became evident early in the course of the investigation leading to the present invention that efforts to isolate the effects of the individual elements silicon and molybdenum on Jominy hardenability were being thwarted by a masking synergistic reaction or cooperative relationship. Preliminary tests having pointed in this direction, a series of steels were melted containing various percentages of molybdenum at various levels of silicon content and subjected to Jominy hardenability tests. The results of these tests are given in Table III, data from which is plotted graphically in FIG. 3, wherein Jominy distance is plotted as a function of percentage molybdenum, with silicon as a parameter.

TABLE III.—EFFECT OF SILICON-MOLYBDENUM INTERACTION ON JOMINY HARDENABILITY AND TEMPER HARDNESS

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.)				Temper Hardness, 600° F., 2 hr., R_c
						1,575° F.		1,600° F.		
						R_c 65	R_c 60	R_c 65	R_c 60	
59-152	.89	.29	.28	.32	.53	6	7	6	7	56
59-154	.89	.30	.24	.77	1.02	11	14	13	15	58
60-57	.89	.28	.27	.32	1.06	6	8.5	6	9	57.5
60-59	.92	.28	.23	.80	.52	8	9.5	10	11	58
60-121	.90	.29	.51	.55	.33	8	10	8	10.5	58
61-5	.93	.14	.50	.54	.20	6	7	6.5	7.5	59
61-6	.92	.14	.50	.54	1.12	8	11	11	14.5	59
61-8	.91	.26	.50	.55	.77	9	11.5	9.5	13	58
61-11	.92	.22	.49	1.06	.76	13	16	18.5	22.5	58.5
59-153	.86	.27	.74	.77	.51	16	23	22	30	60
59-155	.88	.27	.73	.32	1.03	9	14	12	15	60
60-58	.90	.28	.72	.32	.51	8	11	9	12	60
60-60	.93	.28	.71	.81	1.04	16	24	18	30	61
61-122	.90	.29	.74	.55	.33	12	16.5	14	19	60
61-9	.90	.26	.93	.55	.78	13	19	15	23	60
61-12	.90	.21	.99	1.06	.76	12	16.5	20	25.5	61
60-123	.90	.29	1.23	.55	.33	10	15	14	20.5	61
60-124	.89	.29	1.40	.77	.33	12	16	15	23	62
61-83	.90	.29	.87	.61	.73	14	26	----	----	----
S-13344	.81	.36	.60	.60	.95	14	28	----	----	----

The effect of the silicon-molybdenum interaction on Jominy hardenability is depicted quite clearly. It is seen here, from FIG. 3, that Jominy hardenability improves with increasing molybdenum content for all but the highest silicon levels plotted, i.e., 0.93 to 1.40 percent silicon. Thus, it appears that a cooperative relationship between silicon and molybdenum is not observed above 0.90 percent silicon, and the disappearance of this advantageous synergistic relationship establishes the upper limit of the claimed silicon content of our steel.

The synergistic cooperation between molybdenum and silicon also becomes relatively ineffective when the silicon content is below about 0.60 percent, and this establishes the lower limit of the claimed silicon content of our steel.

For a given molybdenum value, it is noted that little or no improvement in Jominy hardenability occurs between the 0.23 to 0.28 percent and the 0.49 to 0.51 percent silicon levels. However, at the 0.71 to 0.74 percent silicon levels the same molybdenum content is attended by a substantial improvement in Jominy hardenability. A close analysis of FIG. 3 leads to the conclusion that significant improvement in Jominy hardenability begins at an intermediate level between the 0.49 to 0.51 percent and 0.71 to 0.74 percent silicon levels. In this connection it can be safely assumed that such intermediate silicon level would define a line passing approximately midway between the lines formed by the 0.49 to 0.51 percent and 0.71 to 0.74 percent silicon levels. The interpolated line will be observed to cross the Jominy 9/16" distance ordinate which represents the Jominy value, as aforesaid, for the prior art modified SAE 52100 bearing steel. As this intersection point has an abscissa of 0.50 percent molybdenum, it is apparent that molybdenum contents of 0.50 percent or higher will exhibit improved Jominy hardenability. However, this latter phenomenon will only be true where the silicon level is at least equal to that denoted by the interpolated line, i.e. about 0.60 percent. It will be noted that the line at the 0.93 to 1.40 percent silicon level is indicative of a constant Jominy hardenability. As the value of the Jominy hardenability indicated by this line is below that attained by combinations of molybdenum with silicon at the 0.71 to 0.74 percent level, it is obvious that the optimum combination of molybdenum and silicon has been passed, i.e., at the 0.90 percent silicon level, and no further improvement in Jominy hardenability can be obtained by combinations of molybdenum and silicon at the higher silicon levels. Hence, as improved deep-hardening properties can be obtained at lower molybdenum and silicon contents, it becomes economically unsound to employ increased alloying additions of said elements. It will be further noted from FIG. 3 that preferred Jominy distance values of at least 12/16 inch are obtained in the molybdenum range of 0.55 to about 1.00 percent, the outer limits of which range, it will be noted, intersect the lines designating the 0.49 to 0.51 percent and 0.71 to 0.74 percent silicon levels.

Since the former silicon range, i.e. 0.49 to 0.51 percent, is below the aforementioned minimum silicon level of 0.60 percent necessary to obtain an improved Jominy distance of at least 9/16 inch and since the latter silicon range, i.e., 0.71 to 0.74 percent, is above said minimum silicon level and provides an improved Jominy distance of at least 12/16 inch, the preferred silicon minimum is selected at about 0.60 percent. The preferred silicon range is, therefore, about 0.60 to 0.90 percent.

As further evidence of the criticality of the lower limit of silicon content at about 0.60 percent, attention is invited to Tables IV and V and their corresponding graphs, FIGURES 4 and 5. When it was sought to plot Jominy hardenability against silicon content for steel of constant molybdenum content of about 0.55 percent to demonstrate the remarkable increase in hardenability that occurs when the silicon content is raised past 0.60 percent, it became apparent that resort to data for steel of other molybdenum content would be required, with a correction being applied dependent upon the difference in molybdenum content from the 0.55 percent level. Accordingly, Table IV, showing the effect upon Jominy hardenability of different molybdenum contents for a constant silicon content of about 0.70 to 0.75 percent, was compiled.

TABLE IV.—EFFECT OF MOLYBDENUM ON HARDENABILITY

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.) 1,575° F., R_c 65
59-155	.88	.27	.73	.32	1.03	9
60-58	.90	.28	.72	.32	.51	8
60-122	.90	.29	.74	.55	.33	12
59-153	.86	.27	.74	.77	.51	16
60-60	.93	.28	.71	.81	1.04	16

From this, it can be seen that chromium had no effect upon the observed 1575° F. R_c 65 Jominy distance. The values of said Jominy distance are plotted in FIG. 4 as ordinates, with corresponding molybdenum contents plotted as abscissae. FIG. 4 affords a correction factor to enable construction of a plot, FIG. 5, of Jominy distance versus silicon content, despite variation in the molybdenum contents of the steels used.

TABLE V.—EFFECT OF SILICON ON HARDENABILITY

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.) 1,575° F., R_c 65	
						Uncorrected	Corrected
59-154	.89	.30	.24	.77	1.02	11	7
59-152	.89	.29	.28	.32	.53	6	9
61-8	.91	.26	.50	.55	.77	9	9
60-121	.90	.29	.51	.55	.33	8	8
S-13344	.81	.36	.60	.60	.95	14	13
59-155	.88	.27	.73	.32	1.03	9	12
60-58	.90	.28	.72	.32	.51	8	13
60-122	.90	.29	.74	.55	.33	12	12
61-83	.90	.29	.87	.61	.73	14	13
61-9	.90	.26	.93	.55	.78	13	13
60-123	.90	.29	1.23	.55	.33	10	10
60-124	.89	.29	1.40	.77	.33	12	8

The corrected values are plotted in FIG. 5 as ordinates, with corresponding silicon contents as abscissae. The remarkable increase in hardenability at about 0.60 percent silicon content appears clearly in FIG. 5.

The effect of chromium on Jominy hardenability was next studied and the test results thereon are contained in Table VI.

TABLE VI.—EFFECT OF CHROMIUM ON JOMINY HARDENABILITY AND TEMPER HARDNESS

Steel	C	Mn	Si	Mo	Cr	Jominy Hardenability (1/16 in.)				Temper Hardness, 600° F., 2 hr., R_c
						1,575° F.		1,600° F.		
						R_c 65	R_c 60	R_c 65	R_c 60	
61-82	.90	.29	.87	.61	None	15	21	23	39	60
								27	39	
61-145	.89	.32	.85	.63	.01	13	18.5	15	22	60
61-142	.90	.31	.77	.62	.25	11	17	13	19	60
60-122	.90	.29	.74	.55	.33	12	16.5	14	19	60
61-143	.88	.31	.78	.61	.50	11	17.5	16	25	60
61-83	.90	.29	.87	.61	.73	14	26	18	28	61
								18	28	
61-144	.89	.31	.80	.61	1.57	9	17	16	28	60
61-9	.90	.26	.93	.55	.77	13	19	15	23	60
61-67	.90	.30	.82	.59	.95	9	14	17	28	61.5
61-87	.86	.24	.81	.61	1.03	11	18	18	28	60.5
61-84	.90	.28	.87	.61	1.37	10	19	18	33	61
								18	32	

While the data given in Table VI is indicative of good to excellent Jominy hardenability in test steels having chromium contents up to about two percent, plots of this data in FIG. 6 show a preferred chromium range of about 0.60 to 1.60 percent, particularly with respect to steels austenitized at 1600° F. The data of Table VI also indicates that chromium has substantially no effect on temper hardness.

While adequate Jominy hardenability was considered a prerequisite in the course of the present quest for a bearing steel having good deep hardening characteristics, another essential quality sought was that of good resistance to tempering. To determine the latter property, steels of various compositions were hardened from 1600° F. and subjected to a 600° F. temper for a period of two hours and thereupon air-cooled and tested for Rockwell "C" hardness. Analysis of all the data compiled indicated clearly the significant role that silicon plays in the obtention of this property. As a "benchmark" or standard against which to compare the resistance to tempering of the tested steels, a temper hardness value of Rockwell "C" 59 obtained in the case of the modified SAE 52100 standard bearing steel, said steel having been hardened from 1600° F., was taken. It will be noted from Table VII, wherein the results of this study are set forth, that those steels having less than 0.60 percent silicon have a lower temper hardness than Rockwell "C" 59, whereas those steels having 0.60 percent or more silicon have a temper hardness as good as, or better than, that of the standard bearing steel.

TABLE VII.—EFFECT OF SILICON ON TEMPER HARDNESS

Steel	C	Mn	Si	Mo	Cr	Temper Hardness 600° F., 2 hr., R_c
61-7	.91	.26	Trace	.55	.79	56
61-8	.91	.26	.50	.55	.77	58
61-9	.90	.26	.93	.55	.78	60
60-121	.90	.29	.51	.55	.33	58
60-122	.90	.29	.74	.55	.33	60
60-123	.90	.29	1.23	.55	.33	61
59-153	.86	.27	.74	.77	.51	60
60-124	.89	.29	1.40	.77	.33	62

This fact is more strikingly revealed in FIG. 7 wherein steels 61–7, 61–8, 61–9, 60–121, 60–122 and 60–123 are plotted in terms of temper hardness vs. percent silicon. A comparison of the results of steels 61–8 and 60–121 reveals clearly that temper hardness is independent of chromium content, since the temper hardness of these steels is only Rockwell "C" 58 despite the fact that the compositions of these steels are practically identical except for the chromium levels. Steels 60–122 and 59–153 are shown in Table VII for the purpose of showing the effect of molybdenum on temper hardness. Here it is seen that despite an increase of 0.22 percent molybdenum, the temper hardness is substantially unaffected. Steels 60–123 and 60–124 are set forth in Table VII to show that some further beneficial effect with respect to temper hardness is possible at the higher silicon levels.

Another important factor which was the subject of further investigation was the amount of retained austenite. Where conditions are not substantially critical, as much as three percent retained austenite may be permitted in bearing steels, as, for example, in the case of the modified SAE 52100 bearing steel. In more critical applications, as, for example, in the case of larger bearings where dimensional changes are more prone to cause cracking, even as little as one percent retained austenite is detrimental. In recent literature, it has been calculated that the transformation of one percent austenite to martensite during use of a hardened SAE 52100 bearing will result in a linear size change of approximately 150 microinches per inch. As indicated heretofore, many critical applications cannot tolerate instability of such magnitude. In investigating the percentage of retained austenite, measurements were made by X-ray diffraction techniques on test steels of varying composition in order to determine the effect, if any, of the individual elements thereon. Early studies pointed to manganese as having a measurable effect on the percentage of retained austenite in the experimental steels. Table VIII lists a series of four steels having substantially similar compositions except for varying manganese and

FIG. 8 depicts a plot of this data in terms of retained austenite vs. percent manganese.

52100 and modified SAE 52100 bearing steels as indicated by the results given in Table IX.

TABLE IX.—DIMENSIONAL STABILITY OF EXPERIMENTAL AND COMMERCIAL BEARING STEELS

Steel	C	Mn	Si	Cr	Mo	Heat Treatment [a]	Exposure Temp. (° F.)	Length Change (10^{-6} in./in.) after—			
								50 hr.	100 hr.	200 hr.	400 hr.
59–153	.86	.27	.74	.51	.77	1	400	2.5	1.3	−2.5	−1.3
							450	−2.5	−3.8	−6.3	−6.3
							500	−8.8	−16.3	−26.3	−42.5
						2	400	5.0	7.5	8.8	6.3
							450	5.0	2.5	21.3	10.0
							500	33.8	−12.5	−30.0	−52.5
60–60	.93	.28	.71	1.04	.81	1	400	3.8	−7.5	10.0	0
							450	−2.5	1.3	15.0	−15.0
							500	−3.8	−8.8	−18.8	−36.3
						2	400	2.5	0	5.0	−5.0
							450	−2.5	0	−1.3	−7.5
							500	−8.8	−15.0	−30.0	−51.0
59–189 (SAE 52100)	1.02	.39	None	1.43	.02	3	400	−6.3	−26.3	−52.3	−95.0
							450	−132.5	−211.3	−211.3	−275.0
							500	−336.3	−363.8	−395.0	−425.0
60–53 (Modified SAE 52100)	.94	1.47	.74	1.54	Trace	4	400	33.8	56.3	91.3	103.8
							450	93.8	107.5	110.0	113.8
							500	55.0	50.0	35.0	+5.0

[a] Heat-Treatments:
1—1,600° F., 45 min. Air Cooled + 575° F. 4 hr. Air Cooled.
2—1,600° F., 45 min. Oil Quenched + 575° F. 4 hr. Air Cooled.
3—1,575° F., 20 min. Oil Quenched + 450° F. 4 hr. Air Cooled.
4—1,500° F., 40 min. Oil Quenched + 500° F. 4 hr. Air Cooled.

TABLE VIII.—EFFECT OF MANGANESE ON RETAINED AUSTENITE

Steel	C	Mn	Si	Mo	Cr	Retained Austenite (percent)	
						OQ [1]	OQ&T [2]
61–86	.86	.03	.81	.61	1.03	8	0
61–87	.86	.24	.81	.61	1.03	9	0
61–89	.84	.50	.81	.61	1.03	16	1
61–98	.85	.72	.82	.60	.95	18	1

[1] Oil quenched after austenitizing at 1,600° F. for 45 minutes.
[2] Oil quenched after austenitizing at 1,600 °F. for 45 minutes and tempered at 550° F. for 4 hours.

FIG. 8 shows retained austenite as a function of manganese content for test steels in both the as-quenched condition (upper curve) and the quenched-and-tempered condition (lower curve). It will be appreciated that, by the very nature of the X-ray diffraction techniques employed in making retained-austenite measurements, for very small percentages, i.e., less than one percent, precise measurements are obscured by the normal margin of error. Hence, the point represented by steel 61–89 in the quenched-and-tempered condition was omitted in FIG. 8 and the lower curve was drawn so as to conform with this measurement and well as the general form of the as-quenched curve.

In determining the limits of manganese in the experimental steels, it was, of course, obvious from a comparison of FIGS. 2 and 8 that a balance had to be reached between the detrimental effects of low Jominy hardenability at the minimum and increased retained austenite at the maximum, a preferred manganese range being 0.20 to 0.60 percent wherein low values of retained austenite and relatively good deep-hardening characteristics are obtained. In applications where dimensional stability is a paramount factor, an instability of 25 microinches per inch after 1,000 hours of exposure at operating temperature is the maximum which can be tolerated. This is equivalent to a transformation of about 0.2 percent retained austenite or an equivalent amount of tempering. Hence, it can be seen from FIG. 8 that a maximum of about 0.45 percent manganese is critical in this respect.

The improved dimensional stability of the inventive steels contrasts sharply with that of the prior art SAE

Here, it is seen that steels 59–153 and 60–60, typical of bearing steels of the invention, have significantly superior dimensional stability than the bearing steels of the prior art. For example, at an exposure temperature of 400° F. the largest length change in the inventive steels was an expansion of 10.0×10^{-6} in./in. (steel 60–60), as compared with the prior-art steels, wherein an expansion of 103.8×10^{-6} in./in. (steel 60–53) was observed. At an exposure temperature of 450° F., the superiority of the inventive steels still prevails, as note the length-change comparison between an expansion of 21.3×10^{-6} in./in. (steel 59–153) as against a contraction of 175.0×10^{-6} in./in. (steel 59–189). Even at an exposure temperature of 500° F., the superiority of the invention is obvious, as indicated by contrasting a contraction of 52.5×10^{-6} in./in. (steel 59–153) with a contraction of 425.0×10^{-6} in./in. (steel 59–189). It is significant to note that even when the tabulated data is considered in a light most favorable to the prior-art bearing steels, the superiority of the inventive steels is obvious. For example, the largest length changes attributed to the inventive alloys at the exposure temperatures of 400° F., 450° F., and 500° F. were 10.0×10^{-6} in./in., 21.3×10^{-6} in./in., and -52.5×10^{-6} in./in.; respectively These values compare with the prior-art steels as follows: At exposure temperatures of 400° F., 450° F., and 500° F., the smallest length changes observed were -95.0×10^{-6} in./in., 113.8×10^{-6} in./in., and 55.0×10^{-6} in./in. In addition to the superiority of the inventive steels over the prior-art steels, it will be further noted from Table IX that as between the inventive steels themselves, the higher-chrominum steel, i.e., steel 60–60, exhibits a somewhat better dimensional stability than the lower-chrominum steel, i.e., steel 59–153.

By way of further investigative efforts, the inventive and prior-art steels of Table IX were subjected to hot-hardness tests. These tests were conducted by measuring the hardness of the steels at room temperature, heating the steels to a maximum temperature of 600° F. while measuring the hardness of such steels at various elevated temperatures as the maximum temperature was approached, and cooling the steels to room temperature where the hardness was again measured. Results of these tests are tabulated in Table X.

TABLE X.—HOT HARDNESS OF EXPERIMENTAL AND COMMERCIAL BEARING STEELS

Steel	Initial Hardness (R_c)	Percent of Initial Hardness at—					Recovery Hardness (R_c)
		400° F.	450° F.	500° F.	550° F.	600° F.	
59–153	60	96.7	96.7	95.0	95.0	93.3	60
60–60	60	98.3	96.7	96.7	95.0	93.3	60
59–189 (SAE 52100)	59	96.6	94.9	91.5	89.8	84.1	56
60–53 (Modified SAE 52100)	59	96.6	94.9	94.9	91.5	89.8	58

In order to present a meaningful visual representation of this data, a plot of percent of initial hardness vs. test temperature was prepared and is shown in FIG. 9. As suggested, the ordinate points were obtained by dividing the elevated-temperature hardness by the room-temperature hardness and multiplying by 100.

FIG. 9 clearly shows that the hot hardnesses of the inventive steels are substantially greater than those of the prior-art bearing steels, which fact becomes increasingly obvious as the maximum test temperature of 600° F. is approached. It will be further noted from FIG. 9 that the recovery hardnesses of the experimental steels were also superior to those of the prior-art steels, as indicated by the points of intersection of the curves with the right-hand ordinate of FIG. 9. Recourse to Table X together with some elementary calculations reveals a 100 percent recovery in the case of each of the experimental steels, while only a 98.3 percent recovery in the case of the modified SAE 52100 steel and an even lower 94.9 percent recovery in the case of the original 52100 steel.

The foregoing bearing steels of both the invention and the prior art were subjected to further testing to determine comparative hardness retention, i.e., the ability to retain initial hardness after exposure for varied periods of time at elevated temperatures. The results of such testing are set forth in Table XI.

TABLE XI.—HARDNESS RETENTION OF EXPERIMENTAL AND COMMERCIAL BEARING STEELS

Steel	Heat Treatment[a]	Exposure Temp. (° F.)	Initial Hardness (R_c)	Hardness Loss (R_c pts.) After—			
				50 hr.	100 hr.	200 hr.	400 hr.
59–153	1	400	60	1	1	1	1
		450	60	1	1	1	1
		500	60	0	1	1	0
	2	400	60	0	0	0	0
		450	60	0	0	0	0
		500	60	0	0	0	0
60–60	1	400	59	1	1	0	0
		450	59	0	0	0	0
		500	57	1	1	1	1
	2	400	61	1	0	0	0
		450	61	1	1	1	0
		500	61	1	1	1	0
59–189 (SAE 52100)	3	400	60	1	1	1	2
		450	60	2	1	1	1
		500	60	3	3	3	3
60–53 (Modified SAE 52100)	4	400	60	1	1	1	1
		450	59	0	1	0	0
		500	60	1	1	1	1

[a] Heat Treatments:
1—1,600° F., 45 min., air-cooled +575° F., 4 hr., air-cooled.
2—1,600° F., 45 min., oil-quenched +575° F., 4 hr., air-cooled.
3—1,575° F., 20 min., oil-quenched +450° F., 4 hr., air-cooled.
4—1,500° F., 40 min., oil-quenched +500° F., 4 hr., air-cooled.

Hardness loss, i.e., the difference between the initial hardness value and the hardness value measured after a period of exposure at elevated temperature, constitutes a relatively good basis for comparison of hardness retention among the tested steels. Hence, on this basis, it can be seen from Table XI that regardless of the heat treatment employed, the steels of the invention exhibit hardness retention superior to that of SAE 52100 steel. With respect to the modified SAE 52100 steel, it is seen that an oil quench is used in the heat treatment; inventive steel 59–153 exhibits superior hardness retention at all exposure temperatures, and inventive steel 60–60 exhibits superior hardness retention at exposure temperatures of 400° F. and 500° F. Air cooling the inventive steel 60–60 results in a hardness rention superior to that of modified SAE 52100 steel, even at an exposure temperature of 450° F.

While the invention has been described and disclosed in connection with various specific embodiments thereof, it is understood that no limitations or restrictions are intended thereby and that said embodiments are merely indicative of the best mode of practicing applicants' invention, the embodiments thereof in which an exclusive property of privilege is claimed being defined as follows in the appended claims.

We claim:

1. An ingot of bearing steel having good hardenability, resistance to tempering, hot-hardness retention, and dimensional stability, said steel consisting essentially of 0.78 to 0.90 percent carbon, 0.60 to 0.90 percent silicon, 0.20 to 0.60 percent manganese, 0.55 to 1.00 percent molybdenum, 0.60 to 1.60 percent chromium, balance iron.

2. An ingot as defined in claim **1**, characterized in that said steel exhibits (1) a Rockwell "C" 65 Jominy distance of about 16 sixteenths of an inch when a 1⅜-in. octagonal bar thereof is water-quenched from 1575° F., (2) a temper hardness of at least Rockwell "C" 60 after being exposed for 2 hours to a temperature of 600° F., (3) retention of over 90 percent of its as-quenched hardness when heated to 600° F., and (4) a length change of about 10 microinches per inch or less when exposed to a temperature of 400° F. for a period of 200 hours.

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