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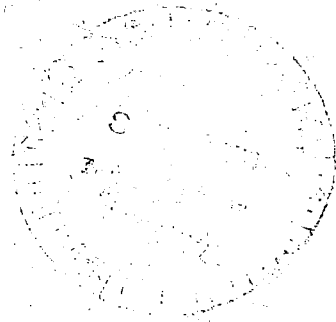
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Long-Term Hot-Hardness Characteristics of Five Through-Hardened Bearing Steels

Neil E. Anderson

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Long-Term Hot-Hardness Characteristics of Five Through-Hardened Bearing Steels

Neil E. Anderson

*Propulsion Laboratory, AVRADCOM Research and Technology Laboratories
Lewis Research Center
Cleveland, Ohio*

NASA

National Aeronautics
and Space Administration

**Scientific and Technical
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1978

SUMMARY

Long-term hot-hardness studies were performed with five vacuum-melted steels tempered to various room-temperature hardnesses: AISI 52100 and the tool steels AISI M-1, AISI M-50, Halmo, and WB-49. Hardness measurements were taken at both room temperature and the soak temperature at regular intervals until 1000 hours of soak time were accumulated. AISI 52100 was tested at temperatures to 478 K (400° F), and the tool steels were tested at temperatures to 700 K (800° F). None of the tool steels tempered (permanently lost hardness) during soaking. AISI 52100 that was initially hardened to R_c 62.5 or R_c 64.5 lost hardness during the first 500 hours of the 1000-hour soak tests at temperatures greater than 394 K (250° F), but it maintained its hardness during the final 500 hours of soaking. Similarly, AISI 52100 that was initially hardened to R_c 60.5 lost hardness during the first 500 hours of the 1000-hour soaking at temperatures greater than 422 K (300° F), but it maintained its hardness during the final 500 hours of soaking.

INTRODUCTION

The most commonly used rolling-element bearing material is AISI 52100. However, because of its potential loss of hardness at elevated temperatures, AISI 52100 has been limited to applications significantly below its tempering temperature of approximately 450 K (350° F). Because of this temperature limitation, high-speed tool steels such as AISI M-50 have been used as rolling-element bearing materials for applications above 394 K (250° F). However, operating time at temperature is just as important a parameter as temperature alone. Holloman and Jaffe (ref. 1) were the first to mathematically relate these two variables in their master tempering curves. From these curves, for any given temperature or time at temperature, the hardness of a material can be predicted.

The operating temperatures of gas turbine engines and their times between overhaul have both increased. Therefore, turbine engine rolling-element bearings are not only exposed to higher temperatures, but they are also exposed to these temperatures for longer times.

Although the short-term hot-hardness characteristics of heat-treated and tempered rolling-element steels have been investigated (refs. 2 and 3), their long-term hot-hardness characteristics are relatively unknown. Steel manufacturers produce master

tempering curves for their materials based on Holloman and Jaffe's master tempering curves. However, these curves are for as-quenched materials and do not take into account the stabilizing effect of tempering.

The research reported herein was conducted to determine the effects of long times at temperature on the room-temperature and hot hardness (1) of AISI 52100 at temperatures near its tempering temperature and (2) of several tool steels (M-50, M-1, Halmo, and WB-49) at temperatures below their tempering temperatures. These objectives were accomplished by soaking specimens of these materials at temperatures to 700 K (800^o F) for as long as 1000 hours. Hot-hardness measurements were made on a standard Rockwell hardness tester fitted with a low-oxygen-environment electric furnace.

TEST SPECIMENS

The materials used in this investigation were consumable vacuum-melted (CVM) AISI 52100, AISI M-1, AISI M-50, Halmo, and WB-49 - the same materials used in the short-term hot-hardness tests of reference 2. The chemical compositions of these materials are given in table I. Photomicrographs of the individual materials are shown in figure 1. All the tool steels show typically larger carbides than AISI 52100.

All specimens for each material, with the exception of AISI M-50, were made from one vacuum-melted ingot. Two different vacuum-melted ingots of AISI M-50 were used. The specimens were heat treated according to the schedules in table II.

APPARATUS AND PROCEDURE

Samples were prepared for hardness testing by sectioning bearing balls in half and then grinding two parallel flats to create the test surface. Both sectioning and grinding were done by hand with a copious supply of coolant to prevent overheating of the test specimens.

The specimens were encapsulated in glass tubes before they were soaked at the test temperatures. The glass tubes were evacuated and backfilled with an inert argon atmosphere to prevent oxidation or decarburization. At the conclusion of a soaking period the capsule was removed from the soaking oven and allowed to cool in room-temperature air (297 K (75^o F)). The specimens were then removed from the capsules for hardness testing.

The hardness of the material was measured at room temperature and at the soak temperature at the following time intervals: AISI 52100 - 0, 100, 250, 500, 750, and 1000 hours; and the tool steels - 0, 500, 700, 800, and 1000 hours. Hardness tests

were made on a Rockwell hardness tester using the R_C scale (150-kg load with a high-temperature diamond brale indenter). At least three hardness measurements were taken at each time-temperature condition. Hot-hardness tests were made with an electric resistance furnace attached to the Rockwell hardness tester (fig. 2). This furnace was not the same furnace used for the long-term soaking. A low oxygen environment, obtained by bleeding dry nitrogen gas through the furnace, was used to eliminate any possible effect of surface oxidation or decarburization during hot-hardness testing.

RESULTS AND DISCUSSION

Specimens of AISI M-50, AISI M-1, WB-49, and Halmo were soaked at temperatures of 366, 478, 539, 589, 644, and 700 K (200° , 400° , 510° , 600° , 700° , and 800° F) for 1000 hours. Room-temperature (297 K (75° F)) hardness and hardness at the soak temperature were measured at soak-time intervals of 0, 500, 700, 800, and 1000 hours. Similarly, specimens of AISI 52100 were soaked at temperatures of 366, 394, 422, 450, and 478 K (200° , 250° , 300° , 350° , and 400° F) for 1000 hours and tested at soak-time intervals of 0, 100, 250, 500, 750, and 1000 hours. These measurements were performed on specimens from each material group that were hardened to different initial room-temperature hardness values in order to determine what effect initial hardness may have on long-term hardness. Initial values of hot hardness (no soak time) were calculated from the equations presented in reference 2. The results of these measurements are presented in table III.

Tool Steels

An objective of this study was to determine whether soaking tool steels at temperatures below their tempering temperatures for long times would affect either their room-temperature hardnesses or their hardnesses at the soak temperature. The data of table III show no significant changes in room-temperature or hot hardness for AISI M-50, AISI M-1, WB-49, or Halmo for soak temperatures to 700 K (800° F) and soak times to 1000 hours. Since the variation in hardness over the 1000 hours was small, the data were not plotted.

Also, evident from these data is that initial hardness (or tempering temperature during heat treatment) did not affect the results. Since the lowest tempering temperature for any of these specimens was 797 K (975° F), loss of material hardness might not be anticipated until the soak temperature neared this value. The maximum test temperature of 700 K (800° F) was selected as an upper-limit operating temperature

for bearings and gears in the near future. Thus, the tool steels tested are capable of maintaining initial room-temperature hardness and hot hardness for 1000 hours when subjected to temperatures to 700 K (800° F).

AISI 52100

Specimens of AISI 52100 were tempered to three initial room-temperature hardnesses (R_c 60.5, R_c 62.5, and R_c 64.5). Figures 3 to 7 show the effect of time at each soak temperature for specimens at each of the three initial hardness values. At 366 K (200° F) (fig. 3), no significant changes occurred in either room-temperature or hot hardness during the 1000 hours of soak time. At temperatures greater than 366 K (200° F) (figs. 4 to 7), soak time at elevated temperatures affected both room-temperature and hot hardness in the following manner: After 100 hours (at a given test temperature) the room-temperature and hot hardnesses decreased to within $\pm 0.5 R_c$ for all specimens regardless of initial hardness. After 500 hours of soaking at each temperature the hardnesses of all three specimens converged to a common value. No further changes in hardness were observed to soak times of 1000 hours. The only exception to this trend was at 394 K (250° F) (fig. 4). In this case the final converged hardness values for the harder specimens were higher than that of the softest specimen. The hardness of the softest specimen was unaffected by time at temperature.

The common converged values of hardness at 100 and 500 hours of soak time at each test temperature are summarized in table IV. Since the data at 450 and 478 K (350° and 400° F) are nearly identical, the converged hardness values at 100 and 500 hours are the same.

The data in figures 3 to 7 have been replotted in figures 8 to 10 to show how soak temperature affects specimens of the same initial hardness. In figure 8 the data for the five test specimens that were initially hardened to a relatively low room-temperature hardness of R_c 60.5 \pm 0.5 are shown. In figure 9 the initial hardness was R_c 62.5 \pm 0.5, and in figure 10 the initial hardness was R_c 64.5 \pm 0.5.

Specimens with low initial hardness (fig. 8) are least affected by time at temperature. The final converged hardness value after 500 hours of soak time at a given soak temperature is a maximum of 2 R_c points below the initial hardness. The specimens with medium and high initial hardnesses (figs. 9 and 10) show larger changes in hardness, as much as 6 R_c points, with time at temperature. Although operation of a bearing at a hardness less than R_c 60 is not desirable, a commonly accepted lower limit is R_c 58 (ref. 4). Figure 7(b) shows that R_c 58 can be maintained for 100 hours at a temperature of 478 K (400° F), but sustained operation at this temperature will cause the

bearing hardness to decrease to R_c 56.5, at which point plastic flow of the bearing surface may occur and result in premature bearing failure (ref. 5).

SUMMARY OF RESULTS

Long-term hot-hardness studies were performed with five vacuum-melted steels (AISI 52100 and the tool steels AISI M-1, AISI M-50, Halmo, and WB-49) tempered to different initial room-temperature hardnesses. Specimens of AISI 52100 were soaked at temperatures to 478 K (400^o F), and the tool steels were soaked at temperatures to 700 K (800^o F). Hardness measurements were taken both at room temperature and at the soak temperature at regular intervals until 1000 hours of soak time were accumulated. The following results were obtained:

1. The tool steels examined did not permanently decrease in hardness (i. e., they did not temper) when exposed to temperatures to 700 K (800^o F) for as long as 1000 hours.

2. AISI 52100 did not temper when exposed to temperatures to 366 K (200^o F) for as long as 1000 hours.

3. The hot and room-temperature hardnesses of AISI 52100 steel with an initial hardness of R_c 62.5 or R_c 64.5 decreased during the first 500 hours of soak time at temperatures of 394 K (250^o F) or greater. No further decrease in hardness was observed after 500 hours.

4. The hot and room-temperature hardnesses of AISI 52100 steel with an initial hardness of R_c 60.5 decreased during the first 500 hours of soak time at temperatures of 422 K (300^o F) or greater. No further decrease in hardness was observed after 500 hours.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 26, 1978,
505-04.

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TABLE I. - CHEMICAL COMPOSITION OF BEARING STEELS

Material	Alloying element, percent by weight (balance Fe)										
	C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni
AISI 52100	0.96	0.22	0.36	0.012	0.007	----	1.36	----	----	---	----
AISI M-1	.81	.32	.25	.007	.004	1.53	3.76	1.15	8.54	---	0.07
AISI M-50	.81	.14	.25	↓	.004	.01	3.97	1.07	4.29	---	.05
Halmo	.59	1.10	.31	↓	.005	----	4.79	.51	5.22	---	----
WB-49	1.07	.02	.30	↓	.006	6.8	4.4	2.0	3.9	5.2	.04

TABLE II. - TEST MATERIAL PROPERTIES AND HEAT TREATMENT

(a) SI units

Material	Heat-treatment identification	Heat treatment						
		Preheat	Austenitize	Quench	First temper	Subzero cooling	Second temper	Third temper
AISI 52100	A	-----	1116 to 1144 K for 30 min	325 K in oil	394 K for 60 min	-----	505 K	-----
	B	-----	↓	↓	↓	-----	450 K	-----
	C	-----				-----	433 K	-----
	D	-----				-----	394 K for 90 min	-----
	E	-----				-----		-----
AISI M-1	F	1061 K for 3½ min in salt	1478 K	322 K in oil ↓	867 K } for 120 min	-----	867 K } for 120 min	-----
	G	1061 K for 3½ min in salt	1478 K		812 K } min	-----	812 K } min	-----
AISI M-50: Group A	H	1061 K for 3½ min in salt ↓	1398 K ↓		812 K in salt; 339 K in air ↓	867 K } for 120 min	-----	867 K } for 120 min
	I			837 K } min		-----	837 K } min	-----
J	812 K } min			-----		812 K } min	825 K for 40 min	
Group B	K				(a)	194 to 172 K for 90 to 120 min	(a)	(a)
	L				↓	↓	↓	↓
	M				797 K for 120 min		797 K for 120 min	797 K for 120 min
	N							
Halmo	O							
	P		} 1422 K	322 K in oil	867 K } for 120 min	-----	867 K } for 120 min	-----
Q		837 K } min			-----	837 K } min	-----	
WB-49	R				812 K } min	-----	812 K } min	-----
	S	} 1089 K for 6 min in salt'	1492 K for 6 min in salt	936 K for 6 min in salt	825 K for 120 min	-----	825 K for 120 min	950 K } for 40 min
T								923 K } min
U								

^aTempered between 797 and 837 K for 120 min. Exact heat treatment unknown.

TABLE II. - Concluded.

(b) U. S. customary units

Material	Heat-treatment identification	Heat treatment									
		Preheat	Austenitize	Quench	First temper	Subzero temper	Second temper	Third temper			
AISI 52100	A	-----	1500° to 1600° F for 30 min	125° F in oil	250° F for 60 min	-----	450° F } for 60 min	-----			
	B	-----	↓	↓	↓	-----	350° F }	-----			
	C	-----				-----	320° F }	-----			
	D	-----				-----	250° F for 90 min	-----			
	E	-----				-----		-----			
AISI M-1	F	1450° F for 3½ min in salt	2200° F	120° F in oil	1100° F } for 120 min	-----	1100° F } for 120 min	-----			
	G	1450° F for 3½ min in salt	2200° F		1000° F }	-----	1000° F }	-----			
AISI M-50: Group A	H	1450° F for 3½ min in salt	2050° F		↓	1100° F } for 120 min	-----	1100° F } for 120 min	-----		
	I			1050° F }						1050° F }	1025° F for 40 min
	J										
Group B	K	↓	↓	1000° F in salt; 150° F in air	(a)	-110° to -150° F for 90 to 120 min	(a)	(a)			
	L				↓	975° F for 120 min	↓	975° F for 120 min	975° F for 120 min		
	M										
	N										
	O										
Halmo	P	↓	} 2100° F	120° F in oil	1100° F } for 120 min	-----	1100° F } for 120 min	-----			
	Q				1050° F }	-----	1050° F }	-----			
	R				1000° F }	-----	1000° F }	-----			
WB-49	S	} 1500° F for 6 min in salt	2225° for 6 min in salt	1225° F for 6 min in salt	1025 F for 120 min	-----	1025° F for 120 min	1250° F } for 40 min			
	T								1200° F }		
	U									1150° F }	

^aTempered between 975° and 1050° F for 120 min. Exact heat treatment unknown.

TABLE III. - ROOM-TEMPERATURE HARDNESS AND HOT HARDNESS OF TEST MATERIALS
DURING SOAK PROCESS TO 1000 HOURS CUMULATIVE SOAK TIME

(a) AISI M-50

Soak temperature		Heat-treatment identification	Time at soak temperature, hr									
			0	500	675	800	1000	0	500	675	800	1000
K	°F		Room-temperature hardness (R _C at 297 K (75° F))					Hot hardness (R _C at soak temperature)				
366	200	H	56.7	57.5	----	----	57.1	56.2	55.1	57.1	----	57.4
		I	60.1	60.3	----	----	60.3	59.6	59.0	----	59.5	
		J	61.6	61.9	----	----	62.2	61.1	60.9	----	61.4	
478	400	H	59.6	59.5	----	----	59.1	57.8	57.3	----	57.7	
		I	60.0	60.0	----	----	60.2	58.2	57.5	----	59.0	
		J	62.0	62.1	----	----	62.0	60.2	61.1	----	61.2	
539	510	H	58.4	58.5	----	----	58.3	55.7	56.6	----	55.6	
		M	62.3	62.7	----	----	62.3	59.6	59.7	----	60.2	
		O	62.5	62.8	----	----	62.3	59.8	60.5	----	61.0	
589	600	L	62.5	62.9	62.6	62.2	62.9	59.0	58.7	57.8	----	61.1
		O	62.3	----	61.3	61.9	62.1	58.8	----	----	----	61.2
644	700	K	58.0	57.8	57.8	56.8	57.6	53.5	----	----	----	55.1
		O	63.3	62.7	----	62.6	62.7	58.8	56.6	----	57.1	56.7
700	800	N	61.3	61.5	60.7	60.3	61.0	55.8	----	----	----	55.2
		O	63.4	62.5	----	62.7	----	57.9	55.3	----	57.2	----

(b) AISI M-1

366	200	F	61.8	62.2	----	----	62.4	61.3	60.5	61.7	----	61.3
478	400	F	61.6	61.5	----	----	61.8	61.1	60.8	----	60.5	61.0
539	510	F	62.3	62.8	----	----	62.6	59.6	60.0	----	60.4	61.0
		G	65.1	64.9	----	----	65.2	62.4	62.2	----	63.5	63.0
589	600	F	61.0	62.0	61.3	----	60.7	57.5	56.2	57.0	----	56.5
644	700	F	61.1	62.2	----	61.2	60.8	56.6	55.5	----	55.2	56.1
700	800	F	61.2	62.2	----	60.5	61.2	55.7	53.7	----	54.0	55.4

TABLE III. - Continued.

(c) Halmo

Soak temperature		Heat-treatment identification	Time at soak temperature, hr									
			0	500	675	800	1000	0	500	675	800	1000
K	°F		Room-temperature hardness (R _c at 297 K (75° F))					Hot hardness (R _c at soak temperature)				
366	200	P	61.5	62.1	----	----	62.1	61.0	62.1	61.1	----	61.6
478	400	P	62.4	62.1	----	----	62.8	60.6	60.2	----	61.2	61.8
539	510	P	62.2	62.1	----	----	62.7	59.5	60.8	----	60.1	59.6
		Q	61.2	61.1	----	----	61.1	58.5	58.8	----	58.6	58.8
589	600	R	56.6	57.0	----	55.4	56.7	53.1	51.5	----	51.6	51.5
644	700	R	56.3	57.4	----	56.5	55.1	51.8	51.1	----	48.8	51.1
700	800	R	55.7	56.7	----	55.8	56.0	50.2	48.6	----	48.3	48.4

(d) WB-49

539	510	U	64.9	64.6	----	----	65.1	62.2	62.2	----	62.5	62.0
		S	54.3	54.2	----	----	54.4	51.6	51.6	----	51.2	51.5
589	600	S	53.5	54.0	54.0	53.6	53.4	50.0	50.0	50.1	----	50.0
644	700	T	60.8	61.0	60.4	58.4	61.3	56.3	----	----	----	57.3
		T	58.7	58.5	----	58.2	57.7	54.2	51.7	----	53.3	54.6
700	800	T	58.0	58.3	57.5	57.3	57.9	52.5	----	----	----	51.9
		T	58.8	58.1	----	57.8	57.9	53.3	50.6	----	51.1	51.6

TABLE III. - Concluded.

(e) AISI 52100

Soak temperature		Heat treatment identification	Time at soak temperature, hr											
			0	100	250	500	750	1000	0	100	250	500	750	1000
K	°F		Room-temperature hardness (R _c at 297 K (75° F))						Hot hardness (R _c at soak temperature)					
366	200	A	60.5	----	----	60.2	----	61.5	59.7	----	59.7	59.8	60.3	60.7
		C	62.0	----	----	62.2	----	62.9	61.2	----	61.6	61.6	61.7	62.6
		D	64.2	----	----	64.4	----	63.8	63.4	----	63.1	62.8	63.0	63.0
394	250	B	60.2	61.4	60.2	61.0	60.2	61.3	58.8	60.6	59.8	60.5	60.7	60.8
		C	62.0	62.3	61.2	61.5	61.1	61.4	60.6	60.7	60.1	61.2	60.7	61.1
		D	64.3	63.2	61.9	61.4	61.4	61.3	63.0	62.1	61.4	60.9	61.2	60.9
422	300	A	60.5	60.1	59.6	59.5	59.1	59.7	60.1	59.4	58.7	58.7	58.8	59.2
		C	62.8	61.5	60.2	60.4	59.9	59.6	61.7	59.8	59.6	58.1	58.3	59.8
		E	65.0	61.4	60.6	59.9	59.7	60.0	63.1	59.6	58.6	58.6	59.4	58.5
450	350	A	60.7	59.9	59.4	58.4	58.7	59.1	58.2	57.5	57.2	56.6	57.3	57.2
		C	62.9	60.2	59.0	58.7	58.5	58.5	60.0	58.2	57.3	55.8	56.7	56.9
		D	65.4	60.0	58.7	58.4	57.7	58.5	62.3	58.1	57.0	56.1	57.0	56.7
478	400	A	61.2	----	*	59.5	----	59.4	57.6	59.0	56.7	57.0	58.1	57.6
		B	62.7	----	----	59.4	----	58.8	59.1	57.7	56.0	55.6	58.3	55.9
		E	65.0	----	----	58.7	----	57.0	61.4	57.5	57.2	56.5	57.4	56.3

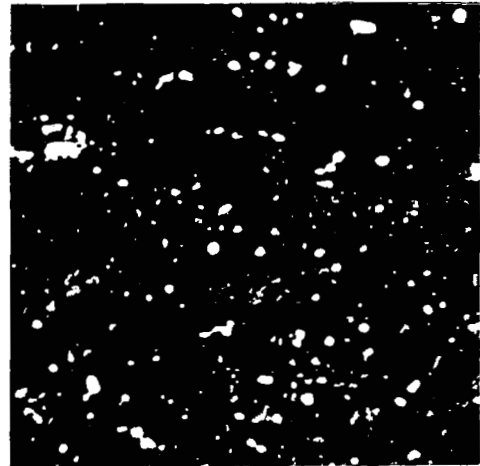
TABLE IV. - HARDNESS OF AISI 52100 STEEL INITIALLY HARDENED TO THREE HARDNESS VALUES (R_c 60.5, R_c 62.5, AND R_c 64.5) AFTER EXPOSURE TO INDICATED SOAK TEMPERATURES FOR 100 AND 500 HOURS

Soak temperature		Time at soak temperature, hr			
K	°F	100	500 to 1000	100	500 to 1000
		Room-temperature hardness (R _c at 297 K (75° F))		Hot hardness (R _c at soak temperature)	
366	200	(a)	(a)	(a)	(a)
394	250	^b 63.2	^b 61.5	^b 62.1	^b 61.2
422	300	61.0	60.0	60.0	58.8
450 - 478	350 - 400	60.0	58.7	58.0	56.5

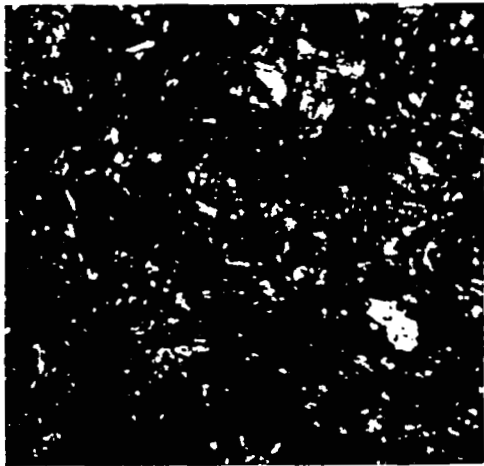
^aNo change from initial values.^bMaximum value attainable; if initial hardness is below this value, time at this temperature will have no effect.



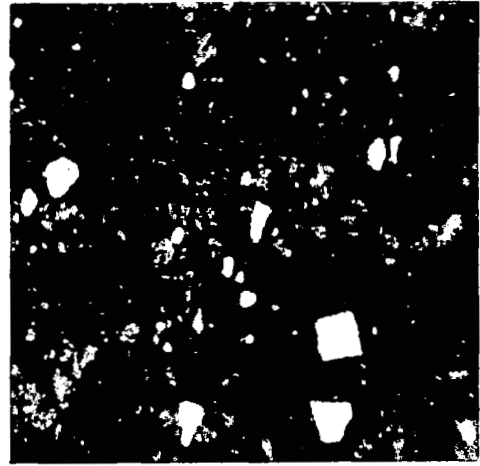
(a) AISI 52100.



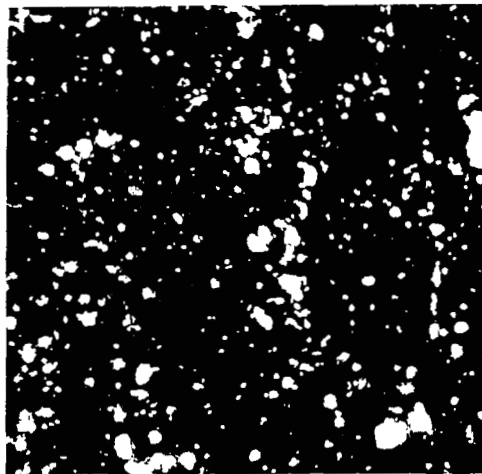
(b) AISI M-1.



(c) AISI M-50 (Groups A and B).



(d) Halmo.



(e) WB-49.

0.00254 cm
(0.001 in.)

Figure 1. - Photomicrographs of materials. Etchant, 2 percent nital.

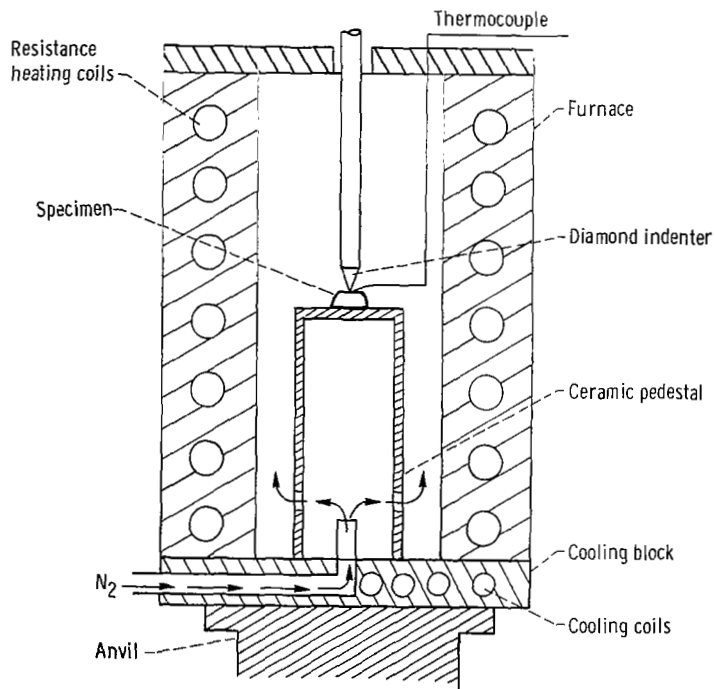


Figure 2. - Cross section of hot-hardness tester.

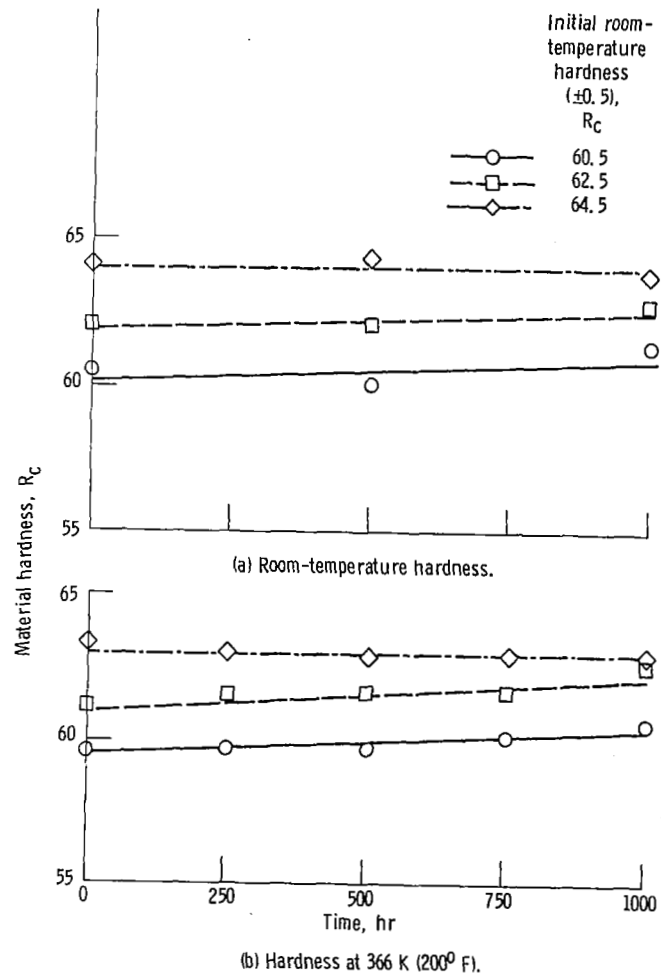


Figure 3. - Effect of time at a soak temperature of 366 K (200° F) on hardness of AISI 52100 steel tempered to three initial room-temperature hardnesses.

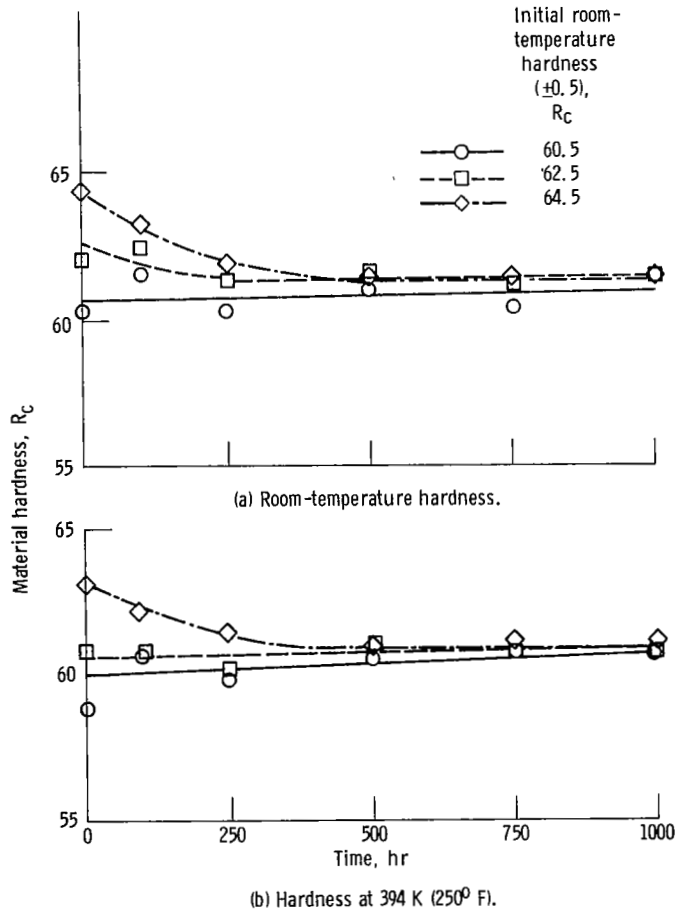


Figure 4. - Effect of time at a soak temperature of 394 K (250° F) on hardness of AISI 52100 steel tempered to three initial room-temperature hardnesses.

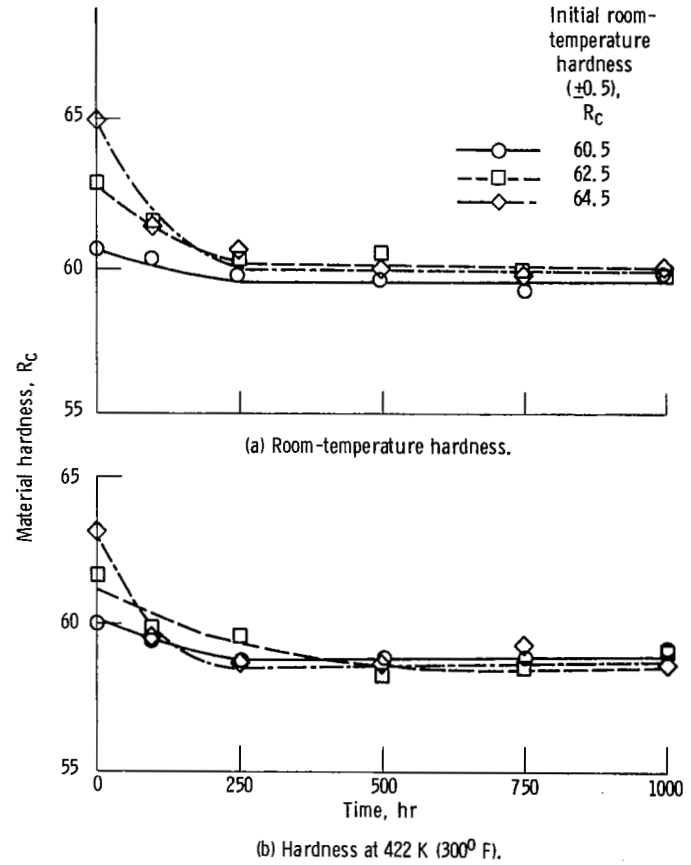


Figure 5. - Effect of time at a soak temperature of 422 K (300° F) on hardness of AISI 52100 steel tempered to three initial room-temperature hardnesses.

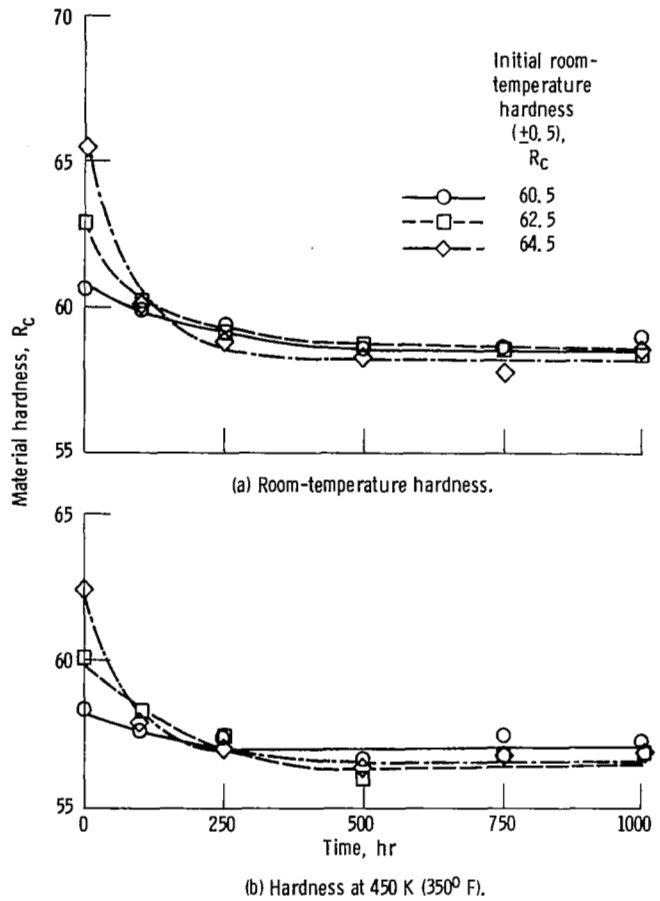


Figure 6. - Effect of time at a soak temperature of 450 K (350° F) on hardness of AISI 52100 steel tempered to three initial room-temperature hardnesses.

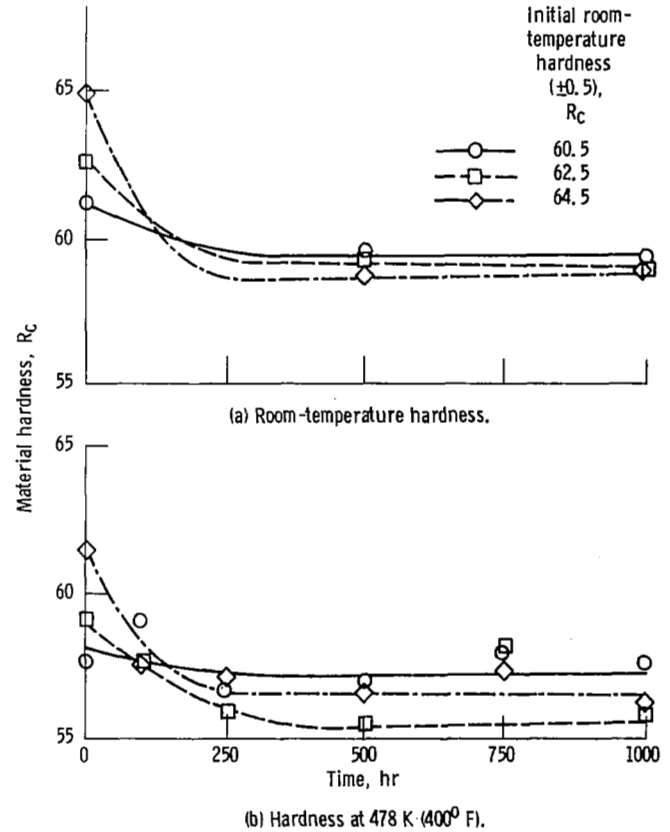


Figure 7. - Effect of time at a soak temperature of 478 K (400° F) on hardness of AISI 52100 steel tempered to three initial room-temperature hardnesses.

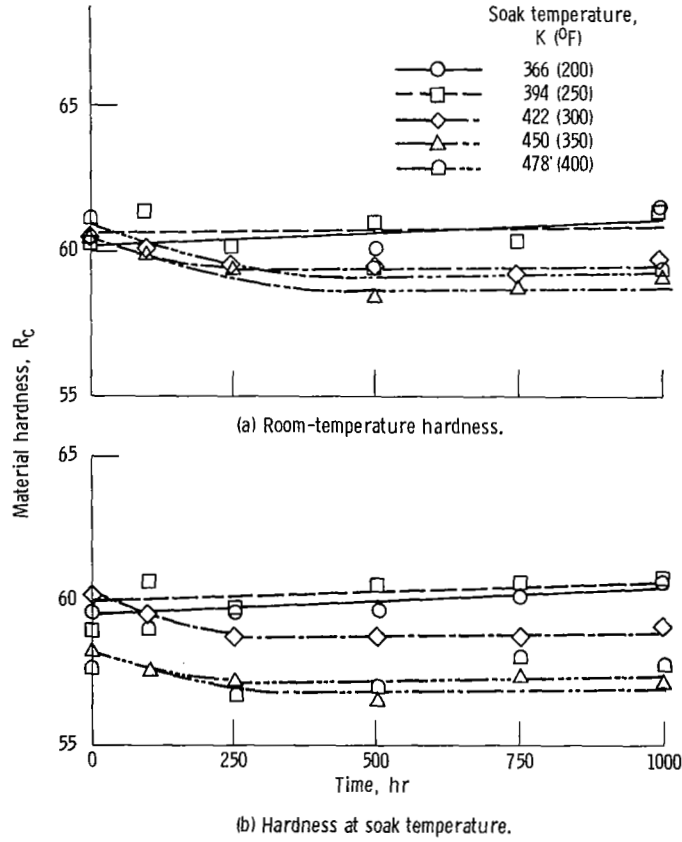


Figure 8. - Effect of soak temperature and time on hardness of AISI 52100 steel tempered to an initial room-temperature hardness of R_c 60.5

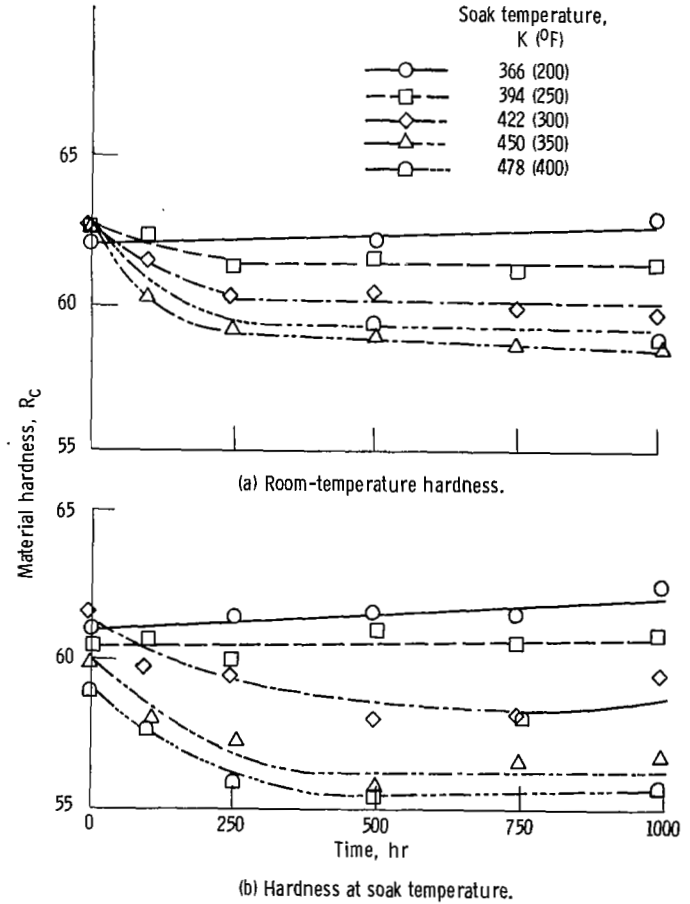


Figure 9. - Effect of soak temperature and time on hardness of AISI 52100 steel tempered to an initial room-temperature hardness of R_c 62.5.

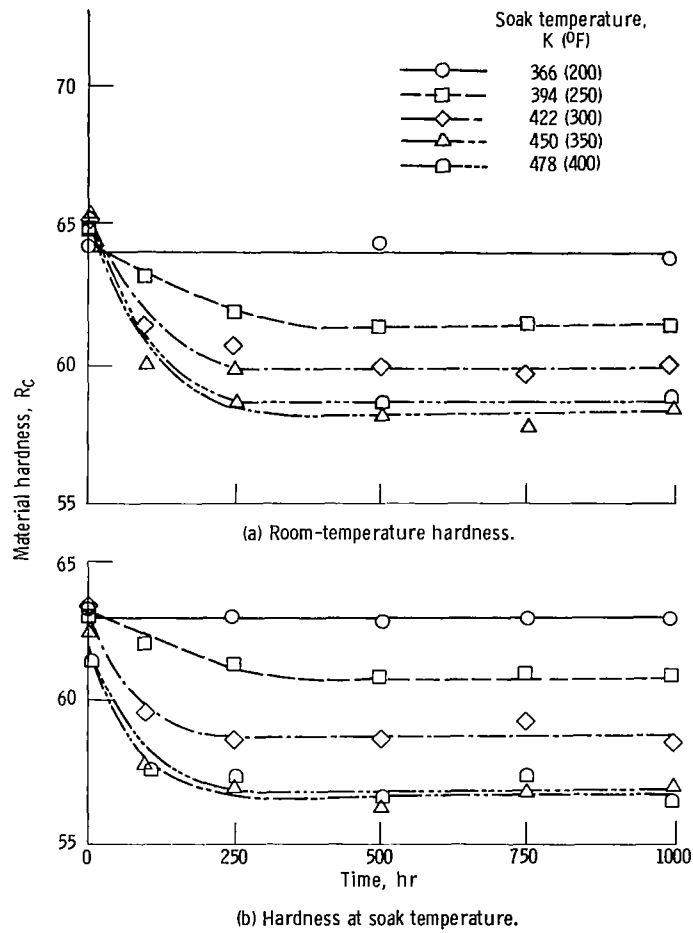


Figure 10. - Effect of soak temperature and time on hardness of AISI 52100 steel tempered to an initial room-temperature hardness of Rc 64.5.

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16. Abstract Long-term hot-hardness studies were performed with five vacuum-melted bearing steels tempered to various room-temperature hardnesses: AISI 52100 and the tool steels AISI M-1, AISI M-50, Halmo, and WB-49. Hardness measurements were taken on AISI 52100 at room temperature and at elevated temperatures after soaking it at temperatures to 478 K (400° F) for as long as 1000 hours. Hardness measurements were also taken on the tool steels after soaking them at temperatures to 700 K (800° F) for as long as 1000 hours. None of the tool steel tempered during soaking. AISI 52100 did not temper when soaked at 366 K (200° F) for 1000 hours. AISI 52100 that was initially hardened to R_c 62.5 or R_c 64.5 lost hardness during the first 500 hours of the 1000-hour soak tests at temperatures greater than 394 K (250° F), but it maintained its hardness during the final 500 hours of soaking. Similarly, AISI 52100 that was initially hardened to R_c 60.5 lost hardness during the first 500 hours of the 1000-hour soaking at temperatures greater than 422 K (300° F), but it maintained its hardness during the final 500 hours of soaking.					
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