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Effects of Heat Treatments on Steels for Bearing Applications

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AISI 52 100, 440C, REX20, and Crucible CRU80 steel samples were exposed to 16 different heat treatments to vary the levels of retained austenite. Rockwell C hardness measurements, optical microscopy, and compression testing were used to compare the properties of the different steels.

Keywords advanced steels, bearing applications, compression strength, heat treatments

1. Introduction

Historically, 52100 and 440C steels have been widely used for bearings in space systems for the last four decades. The AISI 52100 is a high-carbon chromium alloy steel developed specifically for the use of ball bearings. Its high resistance to wear and plastic deformation, without fracture, are what make this steel a high-quality choice for ball bearing applications (Ref 1). The 440C is a high-carbon martensitic stainless alloy that displays toughness and excellent corrosion resistance (Ref 2). 52100 is widely used in many space systems because of its higher strength and hardness compared to 440C, the latter is used where corrosion can be a concern.

Recently, hybrid bearings consisting of silicon nitride balls and steel raceways have shown improved fatigue properties. New class of bearing steels harder than 52100 is needed in hybrid bearing systems in order to take advantage of increased fatigue properties without reduction in the load bearing capacity. The load bearing capacity of the hybrid bearing systems is reduced compared to the all-steel bearing systems of the same size due to the higher modulus of the silicon nitride balls (Ref 3). These ball bearings will be providing a rolling surface for the shaft of the turbo pumps that move the liquid oxygen and liquid hydrogen to the shuttle's main engine (Ref 4, 5).

The REX20 or AISI M62 is a cobalt free, super high-speed tool steel that can only be made through a powder metallurgy process (Ref 3). REX20 and its vacuum processed version called VIM CRU20 have emerged as replacements for 52100 with substantially higher hardness, and hybrid bearing systems with silicon nitride balls and CRU20 raceway are under development for space applications (Ref 3). More recently, PM processed CRU80 steel was developed as a potential replacement of 440C, with increased hardness over 440C while maintaining similar corrosion resistance. The CRU80 is a new steel consisting of only four elements, and is still undergoing experimentation, but displays many favorable mechanical properties. REX20 and CRU80 gain their strength mainly from the martensite transformation of the matrix, but fine distribution of carbides also contribute to their strength. Carbides also give good wear resistance. All of these steels contain a large percentage of carbon, to have enough carbon in the steel matrix for strong martensite formation even after forming primary carbides at austentization temperatures. These high-carbon steels tend to possess more of the desired properties pertaining to applications of ball bearings (Ref 3).

In this study, the processing-structure-property relationships are studied in the new bearing steels (REX20 and CRU80) and are compared to the baseline 52100 and 440C steels. Even though the hardness values are widely used as a qualitative measure of the load capacity of bearings, it is shown that the compressive yield strength is a better indication of the load capacity, and that the amount of retained austenite affects the load capacity (Ref 3). For each steel, four different heat treatment schedules were developed to produce different microstructures with varying retained austenite contents to study the interrelationships of hardness, compressive yield strength, and the retained austenite.

2. Experimental Procedure

The as-received 52100, 440C, REX 20, and CRU 80 have the nominal compositions shown in Table 1.

The bars were cut in 0.635 cms (0.25-inch) thick discs. A total of 48 samples were received, 12 for each steel. Small baskets of 316 stainless steel wire mesh were used as a sample holder during heat treatments.

A schedule of 16 different heat-treatments were performed, 4 heat treatments per steel (Table 2). Heat-treatments consisted of preheating samples at 843 °C (1550 °F) using a Sybron Thermolyne 30400 furnace, and then austenitizing samples in a Keith furnace at temperatures of 843-1215 °C (1550-2220 °F); immediately followed by warm high-speed oil quenching at 48.9 °C (120 °F). Pre-heating was done to ramp the temperature of the samples prior to austenitizing and to prevent thermal shock. One heat treatment per steel was carried out

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Table 1 Chemical compositions of AISI 52100 (Ref 2), 440C (Ref 2), REX20 (Ref 6), CRU80 (Ref 7)

	Chemical % composition, wt.%								
Type of steel	C	Cr	Mn	Si	P	S	Mo	V	W
AISI 52100	0.98-1.10	1.30-1.60	0.25-.45	0.15-0.35	0.025 max	0.025 max	...	...	...
440C	0.95-1.20	16-18	1.0 max	1.0 max	0.04 max	0.03 max	0.75 max	...	...
CPM REX20	1.3	3.75	0.35	0.25	...	0.06	10.5	2	6.25
Crucible CRU80	2.35	14	...	...	...	...	1	9	...

Table 2 Heat-treatment schedules for 52100, 440C, REX 20, and CRU 80

Alloy	Treatment	Pre-heat/time	Austenitization	Warm oil quenching (O.Q.)	Cryogenic quench	Tempering step. (T.S.)	# of T.S.
52100	1	...	1550 °F (843 °C)/30 min	120-130 °F (49-55 °C)	−120 °F (−49 °C)/1 HR	325 °F (163 °C)/2 HR	2
52100	2	...	1550 °F (843 °C)/30 min	O.Q.	...	325 °F (163 °C)/2 HR	2
52100	3	...	1650 °F (899 °C)/30 min	O.Q.	...	325 °F (163 °C)/2 HR	2
52100	4	...	1650 °F (899 °C)/30 min	O.Q.	...	275 °F (135 °C)/2 HR	2
440C	1	1550 °F (843 °C)/30 min	1950 °F (1065 °C)/15 min	120-130 °F (49-55 °C)	−120 °F (−49 °C)/1 HR	350 °F (177 °C)/2 HR	2
440C	2	1550 °F (843 °C)/30 min	1950 °F (1065 °C)/15 min	O.Q.	...	350 °F (177 °C)/2 HR	2
440C	3	1550 °F (843 °C)/30 min	2050 °F (1121 °C)/15 min	O.Q.	...	350 °F (177 °C)/2 HR	2
440C	4	1550 °F (843 °C)/30 min	2050 °F (1121 °C)/15 min	O.Q.	...	275 °F (135 °C)/2 HR	2
REX20	1	1550 °F (843 °C)/30 min	2175 °F (1190 °C)/15 min	120-130 °F (49-55 °C)	−120 °F (−49 °C)/1 HR	1000 °F (537 °C)/2 HR	3
REX20	2	1550 °F (843 °C)/30 min	2175 °F (1190 °C)/15 min	O.Q.	...	1000 °F (537 °C)/2 HR	3
REX20	3	1550 °F (843 °C)/30 min	2220 °F (1215 °C)/15 min	O.Q.	...	1000 °F (537 °C)/2 HR	3
REX20	4	1550 °F (843 °C)/30 min	2220 °F (1215 °C)/15 min	O.Q.	...	800 °F (427 °C)/2 HR	3
CRU80	1	1550 °F (843 °C)/30 min	2100 °F (1149 °C)/15 min	120-130 °F (49-55 °C)	−120 °F (−49 °C)/1 HR	975 °F (524 °C)/2 HR	3
CRU80	2	1550 °F (843 °C)/30 min	2100 °F (1149 °C)/15 min	O.Q.	...	975 °F (524 °C)/2 HR	3
CRU80	3	1550 °F (843 °C)/30 min	2175 °F (1190 °C)/15 min	O.Q.	...	975 °F (524 °C)/2 HR	3
CRU80	4	1550 °F (843 °C)/30 min	2175 °F (1190 °C)/15 min	O.Q.	...	500 °F (260 °C)/2 HR	3

with cryogenic quenching at −48.9 °C (−120 °F) immediately after oil quenching to increase the formation of martensite (Treatment 1). The cryogenic quench was prepared by submerging dry ice into ethanol. The final step was tempering, it was conducted at temperatures ranging from 135 to 537 °C (275-1000 °F). A Thermolyne Oven Series 9000 was used for tempering samples with low temperatures and the Barnsted/Thermolyne 30400 furnace was used to temper samples that had to reach high temperatures. 52100 and 440C steels were double tempered, which means that the samples were tempered and taken out of the oven, air cooled, and tempered again. REX 20 and CRU 80 were triple tempered.

After the heat-treatments, the samples were ground, polished, and etched in accord with standard metallographic procedures (Ref 8). An Olympus PME3 microscope was used for measuring the depth of decarburization, and for studying the microstructure. Rockwell C hardness measurements were also performed. Compression testing of 0.5 inches diameter specimens was performed in accordance with ASTM standard E 9-89a (Ref 9).

3. Results and Discussion

Optical microscopy, hardness measurements, and compression strength tests were performed on all of the test specimens. The results were as follows:

3.1 Decarburization

An effect of the heat treatments is the formation of a decarburized layer during austenitizing because the heat treatments were performed in an air furnace. The carbon allows the steel to be hardened by forming martensite on cooling. Strength of the martensite phase of the steel depends on the carbon content in the martensite. During heat treatments, the thermodynamic chemical potential of carbon in the ambient environment may not be the same as that of the carbon content in the steel. The result is the diffusion of carbon from the steel to the furnace atmosphere. The surface of the steel is then decarburized making it much softer because the different carbon carbides are not able to form because of the low carbon content (Ref 3, 5).

Measurements of the depth of the decarburized layers were taken from samples which undergone heat treatment (H.T) #3. Figure 1 shows the decarburized layers depth for 52100 and 440C, while Fig. 2 shows them for REX20 and CRU80. The REX20 had the largest decarburized layer and 440C had the smallest decarburized layer. The austentization temperature for REX20 was the highest and for 440C was the lowest. This heat treatment was performed in air and accounts for the depth of the decarburized layers. The numerical values of the decarburized depths for the test specimens are presented in Table 3.

The difference between the greatest depth, REX20, and the least depth, 440C, is 175 μm or 4.5 times greater.

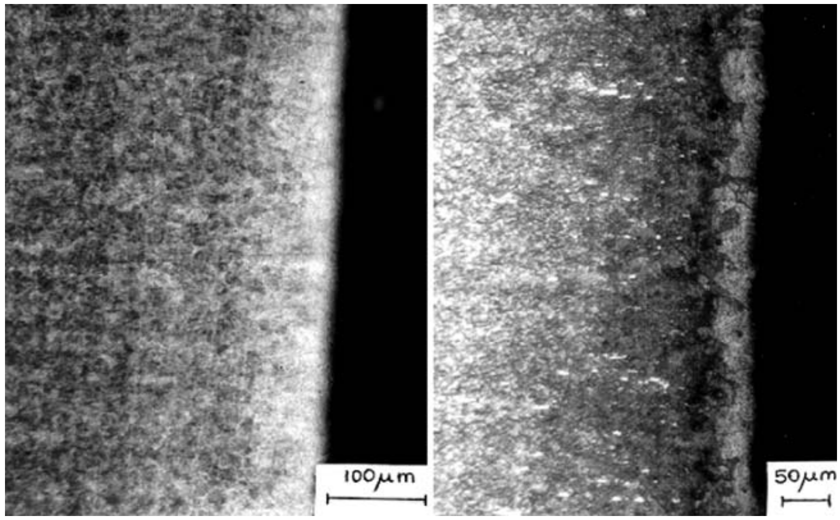

Fig. 1 Decarburized layer of 52100 (left) and 440C (right) at 200 × magnification under heat treatment 3. The decarburized layer is identified as the thin light region located 1/4 (right to left) of the photograph. 52100 had a depth of 75 μm (3 mil) and 440C had a depth of 50μm (2 mil)

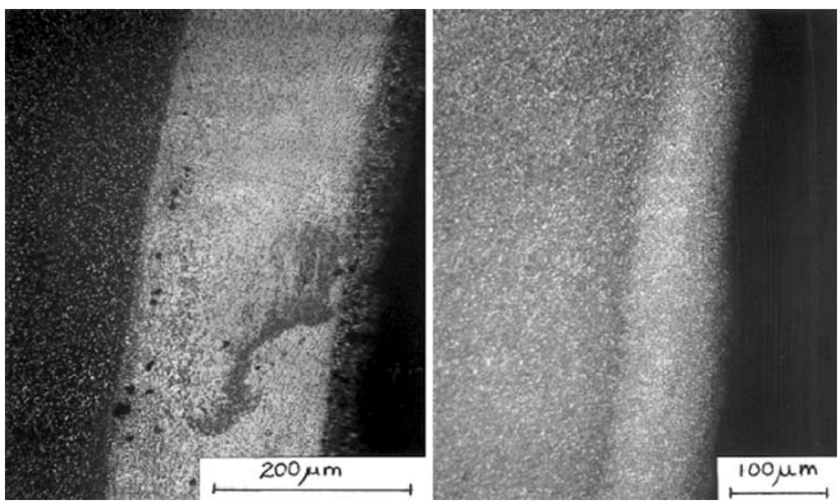

Fig. 2 Decarburized layer of REX20 (left) and CRU80 (right) at 200 × magnification under heat treatment 3. The decarburized layer is identified as the light region located 1/4 (right to left) of the photograph. REX had a depth of 225μm (9 mil) and CRU80 had a depth of 125μm (5 mil)

Table 3 Decarburization depths of test specimens

Sample	Decarburization depth (μm)
52100	75
440C	50
CRU 80	125
REX20	225

Steel 440C had a lower decarburized depth compared to that of 52100. It was expected to find a larger decarburized layer in CRU80 because it had the largest amount of carbon content. However, the results showed that REX20 had the largest decarburized depth. A possible reason for such a large decarburizated layer in REX20 may be explained by the alloying composition of the metal. REX20 showed to have significant amounts of alloying elements such as molybdenum, vanadium, and tungsten which might enhance the activity of carbon. Alternately the high content of chromium in CRU80 might explain the decrease of activity of carbon. The activity of carbon is decreased by the presence of chromium. In the case of high carbon contents and low-alloy chromium steels, carbides precipitate which contain chromium like (Fe, $Cr)_3C$) and (Cr, $Fe)_7C_3$). After tempering, the chromium content of the carbides increase and the amount of cementite decreases until at a minimum (Cr, $Fe)_7C_3$ remains as the only stable precipitate. Thus the activity and solubility of carbon are decreased in steels containing chromium (Ref 10).

3.2 Hardness

Hardness measurements were conducted on the specimens to compare their values with the standard industrial baseline hardness values. Hardness values were also taken after heat treatments to study the effect of varying the heat treatments and amount of retained austenite on the mechanical properties. Table 4 shows both the standard hardness values and the experimental hardness values.

It was observed that some of the experimental values resulting from heat treatments 2-4 of the 440C, REX20 and CRU 80 had slightly lower values than that of the standard hardness values. Overall, the hardness values of all steels under heat treatment #1 were within the standard hardness. For heat treatment #2, 440C and REX20 exhibited lower hardness values than the baseline hardness values. For heat treatment #3, only the 440C had hardness values that were less than the baseline hardness values. Heat treatment #4 produced a lower hardness values for REX20 and CRU80 when compared to the other heat treatments. In every heat treatment other than #4, REX20 attained the highest hardness of all the steels.

Table 4 Rockwell "C" hardness values comparison of the industrial baseline to the experimental average obtained in the research

Specimen	52100 (Ref 2)	440C (Ref 2)	REX20 (Ref 6)	CRU80 (Ref 7)
Industrial baseline values				
HRC range	60-66	58-65	66-68	61-63
Experimental averaged values				
H.T #	52100	440C	REX20	CRU80
1	64	59	66	64
2	62	57	65	61
3	64	51	66	62
4	63	54	62	59

3.3 Compression Testing

The results of the compression testing are shown in Table 5 and are compared to the hardness values. From the result of the compression testing, REX20 had the highest hardness and compressive yield strength and flow stress than all other alloys for the same heat treatment except for heat treatment #4. Although the results for the 52100 alloy were lower than the REX20 for most heat treatments, the hardness, compressive and flow stress values were still comparable. It is interesting to note from the 52100 alloy that different microstructures (different percent of retained austenite) can result in similar hardness numbers, yet have different yield strengths and load capacity. Thus, as pointed out in a previous study (Ref 3) traditional practice of using hardness values for estimating bearing load capacity is not valid.

Table 5 Compression data for the different steels

Steel	Heat treatment	Hardness (HRC)	Compressive YS Mpa (Ksi)	Maximum stress Mpa (ksi) (Flow stress at 5% strain)
52100	1	64	2890 (419)	3620 (525)
52100	2	62	...	...
52100	3	64	2553 (370)	3475 (504)
52100	4	63	2574 (373)	3688 (535)
440C	1	59	2265 (329)	3153 (457)
440C	2	57	...	...
440C	3	51	731 (106)	1380 (200)
440C	4	54	659 (96)	1471 (213)
REX20	1	66	3445 (500)	4103 (595)
REX20	2	65	...	...
REX20	3	66	3075 (446)	4337 (629)
REX20	4	62	1360 (197)	2373 (344)
CRU80	1	64	2319 (336)	3113 (452)
CRU80	2	61	...	...
CRU80	3	62	2413 (350)	3310 (480)
CRU80	4	59	1818 (264)	2650 (384)

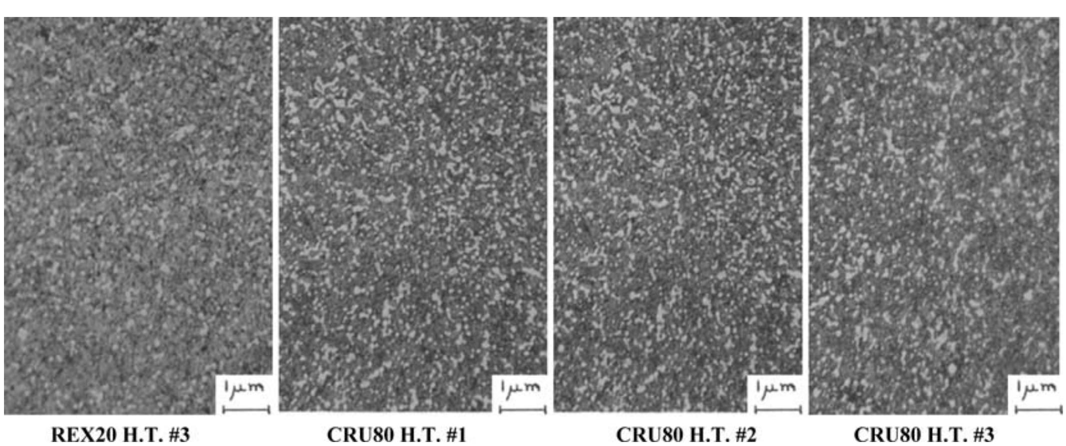

Fig. 3 Optical microstructures of Rex 20 and CRU 80

3.4 Microstructure

The microstructure, Fig. 3, of CRU80 in heat treatments 1 to 3 is compared to each other and to that of REX20 (heat treatments). It is noted that the microstructures at a magnification of 1000× are similar.

Chiefly the austenitization temperature was raised to dissolve more carbon into solution. The carbon stabilizes the retained austenite. The properties were supposed to be correlated to microstructure. Unfortunately optical microscopy did not reveal clear differences between the different heat treatments in an alloy system or between different alloys under the same heat treatment, Fig. 3. Accordingly a correlation between microstructure, hardness and compression testing values was not obtained.

4. Conclusions

Within the limitations of this experiment it was concluded:

1. That the heat treatments performed had significant effects on the mechanical properties of the steels. The REX20 had the highest decarburization layer under the same environment as the other steels. 440C showed to have a thinnest amount of decarburization layer.
2. For hardness measurements, the REX20 had overall the highest hardness values while 440C had the lowest hardness values. Heat treatment #1 had generally the highest hardness values while heat treatment #4 had the lowest hardness values.
3. This study confirms previous studies that the traditional practice of using hardness values alone for estimating bearing load capacity in steels is not valid. Compression tests should be used.
4. A correlation between microstructure hardness and compressive strength values was not obtained in this study.

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