Production Testing of a Chromium-Free Carburizing Grade Gear Steel

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DR. TOM CAMERON *is presently employed by J.M. Ney, Bloomfield, CT. At the time of the writing of this paper, he was on staff of AMAX Research and Development Center, Golden, CO, working on process development for wrought aluminum products. Prior to this assignment, he spent five years at AMAX's Ann Arbor, MI, center, working on alloy development of low alloy carburizing steels. This research was directed toward gearing applications and the relative roles of alloying and processing in gearing performance, and it led to the development of a combined overload-plus-fatigue test for carburized components that would determine the load at which cracking occurred in the case. Dr. Cameron earned his PhD from the University of Connecticut for research conducted on the Fe-B-C system.*

Fig. 1 – Power circulating gear test rig. Test gears are on the left.

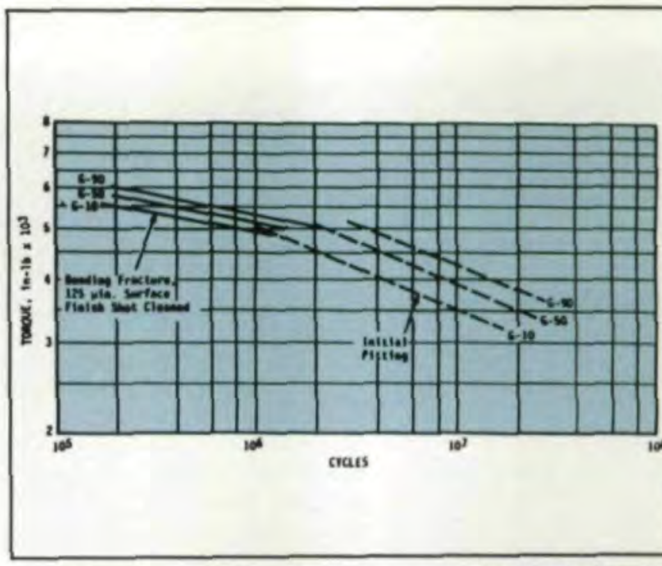

Fig. 2 – Torque vs. cycle life curves of the comparison data base developed by International Harvester from circulating gear tests.

Abstract:

The results of Bureau of Mines sponsored research under Contract #J0145009 to evaluate the manufacturing and engineering performance of a new chromium-free gear steel are reported. This material was developed under BOM Contract #J0113104. Since most chromium is imported from politically unstable regions of the world, alloys have been developed for contingency purposes. Gears were tested in a power circulating device to evaluate their strength (bending) and durability (pitting) characteristics for comparison with an existing data base. Selected samples were compared in terms of microstructure, cleanliness, grain size, x-ray retained austenite and x-ray residual stress. The new steel was shown to be comparable to 8620, the popular high-tonnage gear steel it was designed to replace.

Introduction

For many years chromium has been a popular alloy for heat treatable steels because of its contribution to hardenability more than offsets its costs. As a consequence, it is specified in such high-tonnage steel grades as the 5100, 4100 and 8600 series; and, as a result, about 15% of the annual U.S. consumption of chromium is used in constructional alloy steels.

Chromium is also a strategic alloy because it enhances corrosion and heat resistance of critical aircraft components. The United States imports most of its chromite ore and, unfortunately, much of this important material comes from politically unstable regions of the world. In fulfilling their responsibility to assure an adequate supply of strategic alloys, the Bureau of Mines has sponsored research to develop substitute material systems where feasible. In the first part (Phase I) of research with this aim, candidate substitute non-chromium bearing compositions were developed as potential replacements for 8620 and 4100 steels. The results of the alloy development phase were reported previously by Sharma and Keith.[1] This earlier work was accomplished utilizing a computer based alloy steel design system known as CHAT (Computer Harmonized Application Tailored).[2] The basic principle of the CHAT system is that steels will respond to heat treatment alike; i.e., develop the same microstructures if they have equivalent hardenabilities.

For carburizing grades, equivalent hardenability includes both case hardenability (D_{Ic}) and base hardenability (D_{Ib}). Other important considerations are carbon content and residual stress. Residual stress is thought to be controlled in part by martensite start (Ms) and martensite finish (Mf) temperatures; hence, a change in the alloy system should be kept minimal in order not to influence adversely residual stress. The aim is to calculate, by a computerized method, compositions which will have the same response to heat treatment, hardness and residual stress. A unique aspect of the system is that steels may be designed on a least-cost basis, since cost can be made an objective function. This system has been utilized successfully in developing steels for a number of specific applications and several of the SAE EX steel grades.

In the previous work reported in 1983, a five-year alloy cost projection was made. These costs were used as computer input with least-cost-without-chromium being a primary constraint. The cost projections turned out to be inaccurate; however, the relative costs are similar. Hence, the compositions developed still represent cost-attractive systems if chromium is not available. They are manganese-molybdenum (Mn-Mo) and manganese-molybdenum-nickel (Mn-Mo-Ni) systems. Of equal importance, this work has given another opportunity to confirm the concept that substitute steels having equivalent performance can be designed using fundamental metallurgical considerations.

In industry, however, performance concepts have not matured to the point where substitutes are readily accepted without back-up testing. In the real world, experience has not always justified theory. A great deal still remains to be learned (and unlearned) about alloy effects themselves, variations in nonmetallics, tramp elements, etc. Myths and illusions are not uncommon in the industrial community, and encumbent materials are highly favored. Substitute "ready" systems have to be validated with at least a limited amount of performance data before they will be accepted.

The aim of the work reported herein was to "prove-up" the new steel compositions in terms of their production, processing and performance characteristics. Based on tonnage and the fact

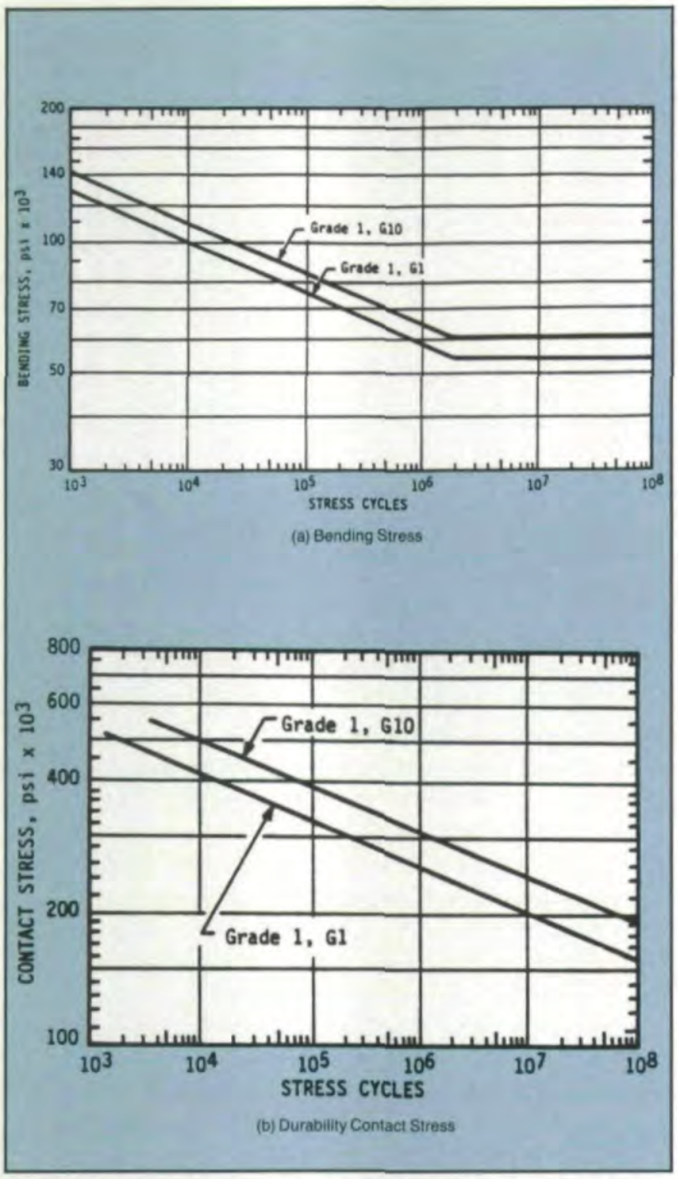

Fig. 3 – AGMA allowable stress curves for strength bending stress and durability contact stress.[5]

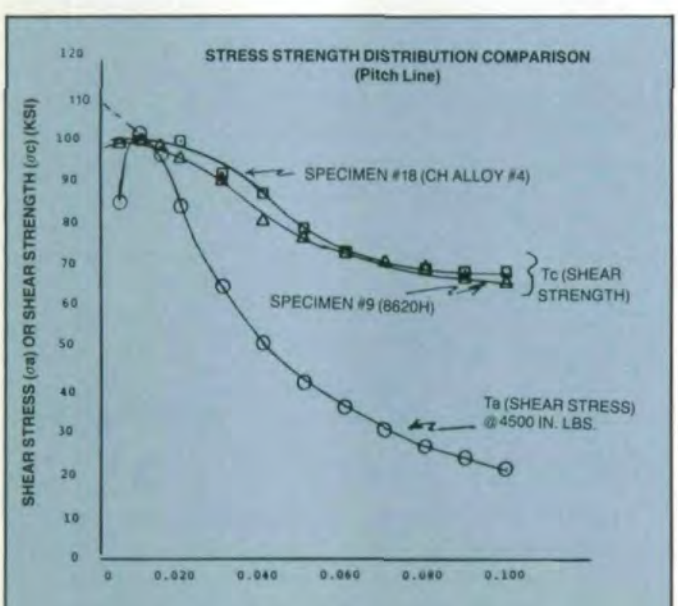

Fig. 4 – Gradient strength analysis.

that carburized applications are more complex, an 8600 equivalent from the Phase I work was chosen for evaluation. Based on cost, a Mn-Mo composition was selected to produce prototypes and specimens for tests. Its composition is shown in Table 1 in conjunction with the 8620 used as the control group. It was purposely produced with Mn to the high side since high-manganese steels have been an ongoing concern in the domestic industry. These types of steels are used, however, in high tonnages in Europe.

TABLE 1
CHEMICAL ANALYSIS (Wt%)

ELEMENT	EXPERIMENTAL ALLOY Cr free			CONTROL ALLOY 8620-H		
	SPECIFIED	HEAT ANALYSIS	SPECIMEN ANALYSIS	SPECIFIED	HEAT ANALYSIS	SPECIMEN ANALYSIS
Carbon	0.16/0.21	0.19	0.21	0.18/0.25	0.18	0.19
Manganese	1.00/1.30	1.29	1.27	0.70/0.90	0.73	0.73
Phosphorous	0.035 max	0.011	0.02	0.035 max	0.005	0.01
Sulphur	0.040 max	0.010	0.01	0.040 max	0.026	0.03
Silicon	0.15/0.35	0.26	0.25	0.15/0.30	0.22	0.22
Nickel	–	0.034	0.04	0.40/0.70	0.51	0.53
Chromium	–	0.055	0.06	0.40/0.60	0.49	0.45
Molybdenum	0.35/0.45	0.41	0.42	0.15/0.25	0.19	0.19
Aluminum		0.05	0.05			0.03

The strategy in this present endeavor was to produce prototype gears for evaluation using near-commerical procedures. Details concerning steel production, forging, machining and heat treat are given in a report by the Bureau of Mines authored by T. Cameron [3] and will not be repeated here. The material came from a 10 ton heat of steel. Gears were selected for evaluation, since they are critical components. They are sensitive to variations in steel quality, and gear performance data can be used as a basis for judgment concerning many other machine elements. Such properties as fatigue, both bending and contact, adhesive wear and surface finish are all incorporated into the design considerations for gears.

The work reported herein had as a major objective validation of the equivalency of computer-designed Cr-free and 8620 steels. This objective was accomplished principally by comparing the strength (tooth bending fatigue) and durability (flank pitting fatigue) of gear specimens. The pinion gear specimen was a 6P, 18T, 20° PA system with 3.3" OD. Its mate was a 30T, 5.3" OD gear. Fig. 1 shows the gear set installed in a power circulating (PC) gear test rig. This gear set and test method was selected because of the availability of an existing data base.[4] This data base, shown in Fig. 2, was generated over a number of years in the laboratories of International Harvester Company and has been expanded with additional tests at the ASME Gear Research Institute. Another important source of gear performance data is the allowable stress curves published by AGMA[5] for design use. These curves for bending and contact are shown in Figs. 3a and 3b.

In addition to performance testing, several other comparisons were made. They included continous cooling transformation (CCT) characteristics, hardenabilities, gradient hardnesses, microstructures (case and core), grain size, grain flow direction, residual stress, distortion in heat treat, inclusion ratings, dimensional accuracy and surface finish.

Results

The Cr-free test gears and the control group of 8620 gears were processed as a group through the same equipment. The control group was used to calibrate the data base. This precaution was taken since gear performance is sensitive to small variations in metallurgy, surface finish and geometry.

Only the most pertinent of the above comparisons are reported here. The reader is referred to the official Bureau of Mines publication mentioned earlier for additional details.

Gradient Strength

Gradient strength, a critical design consideration, is important to prevent failure by subcase fatigue. This property was not evaluated in this study, since subcase fatigue will not occur if a sufficient gradient strength is provided. Gradient strength is comprised of a combination of case depth and core hardness. Previous studies [6-7] indicate that steels with hardenabilities similar to those used in this work, when properly carburized, develop adequate gradient strengths in heat treatment with this size gear. As a check, however, a strength/stress distribution analysis was conducted near the pitch line. The results of this analysis are shown in Fig. 4. The comparison was made for a load of 4600 lb-in. torque. As can be seen, both steels provide more than adequate gradient strength to prevent failure at the case/core fracture.

Metallurgical Considerations

The Jominy hardenability test and the CCT diagram determination are two different ways of evaluating the transformation sequence that occurs when cooling a piece of steel. The objective of Phase I of this program was to develop a composition that would have similar hardenability to 8620. The hardenability testing conducted in Phase I of this program was more extensive than that conducted in Phase II. Sharma and Keith conducted a number of Jominy hardenability tests to compare predicted hardenability with measured results. Their comparison indicated that a mid-range composition of the Cr-free steel has a very similar core hardenability profile to a mid-range composition of 8620, and that the case hardenability of the Cr-free steel was only slightly less than that of the 8620. The Cr-free steel composition employed in Phase II had an intentional high side Mn level, pushing the Jominy core hardenability curve to the high side of the SAE 8620H hardenability band. The results obtained were very similar to those expected.

A comparison of the CCT diagrams for 8620 and the Cr-free steels (Figs. 5 and 6) indicates that the transformation characteristics (at the core carbon level) are quite similar. The slight hardenability advantage of the Cr-free steel resulting from the high side Mn level and the fact that faster cooling rates were employed in analyzing the Cr-free steel are both likely reasons for the appearance of the martensite region in the CCT diagram at fast cooling rates. (See Fig. 6.) Because molybdenum has a strong retarding effect on the ferrite plus pearlite (F+P) reaction, the somewhat longer starting times for F + P in the Cr-free steel are probably a result of the increased molybdenum level. In general, the results from Phase I and Phase II indicate that both case and core hardenability of the Cr-free steel are equivalent to 8620.

Carburizing results performed on laboratory specimens indicated that even though the carbon profiles obtained on 8620 and Cr-free steels were similar, the hardness profiles were higher on the Cr-free steel. Retained austenite profiles indicated that this was not due to a difference in the amount of retained austenite between the steels. Since carbon content controls the hardness of the transformed martensite, the fact that the 8620 hardness values were lower near the surface suggests that the Cr in the 8620 may tie up some of the carbon near the surface as carbide. Sharma and Keith[1] observed in the case hardenability tests of Phase I that the surface carbon content after pack carburizing was lower in the Cr-free steel than the 8620. They concluded that, because of the elimination of the Cr, the Cr-free steel had

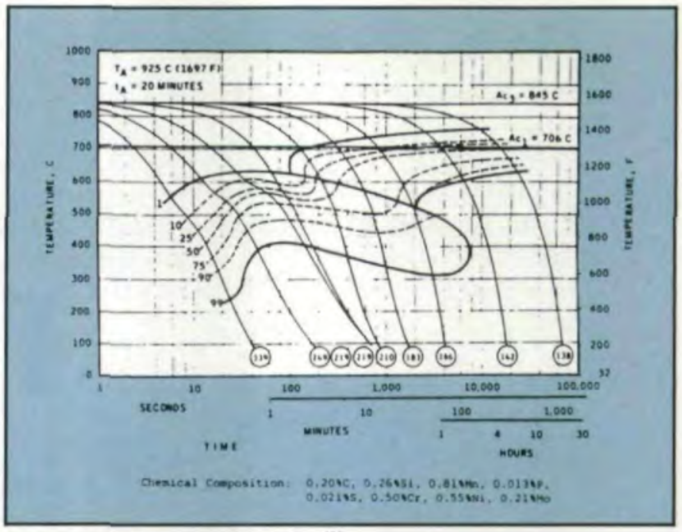

Fig. 5 – CCT diagram for 8620 steel.[3]

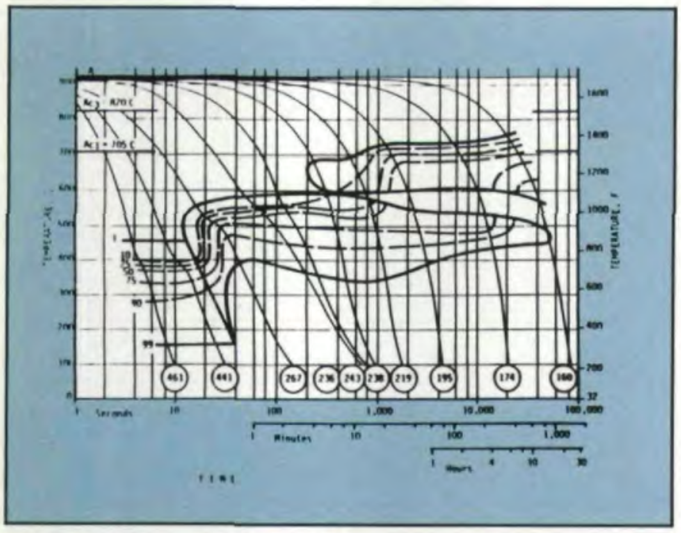

Fig. 6 – CCT diagram for Cr-free steel.

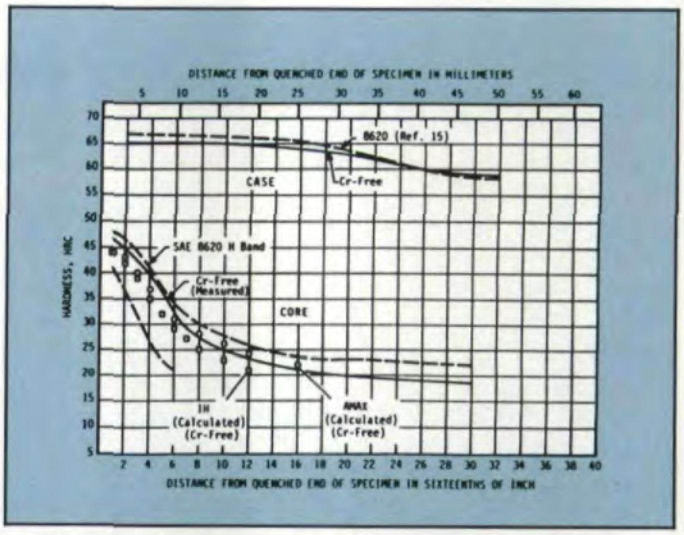

Fig. 7 – Case and core Jominy hardenability test results for Cr-free compared with published data and calculated predictions.

Fig. 8a – 8620 flank surface (unetched) showning IGO penetration (≈ 0.0007). Also shows a cluster of sulphide particles. (400X)

Fig. 8b – (Cr-Free) Flank surface (unetched showing IGO penetration (0.0007).

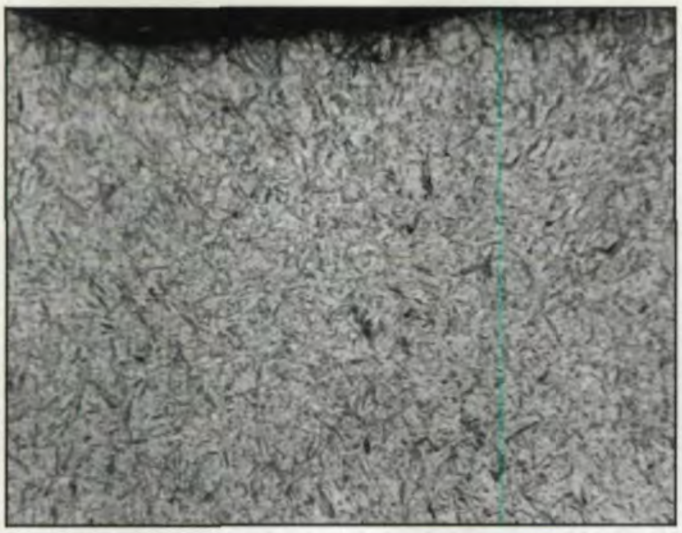

Fig. 9a – Etched 8620 root area surface. Strucure is martensite and austenite. (400X)

Fig. 9b – Cr-free root area surface. Structure is martensite and austenite. (400X)

Fig. 10a – 8620 flank in etched condition. Structure is a martensite austenite mix. (400X)

Fig. 10b – Cr-free flank (etched) to show martensite austenite structure. (400X) a reduced tendency to form carbides and would, therefore, tolerate a greater variation in furnace carbon potential than the 8620.

Hardenability comparisons are shown in Fig. 7. Only the hardenability of the Cr-free steel was measured. The comparison is made with published base (core) and case hardenability for 8620. The hardenabilities of the two steels are comparable in this program.

Microstructure, Grain Size and Cleanliness

These three items are critical to performance. Since in both bending and pitting fatigue, the fracture origins are at or very near the surface, it was critical that the Cr-free steel be capable of developing suitable properties near the surface.

Near surface microstructures are compared in Figs. 8, 9, and 10. In addition to the conventional microstructure, which is intended to be a mix of martensite and austenite, surface intergranular oxidation (IGO) also plays an important role. Figs. 8a and 8b compare the two steels' conditions in the unetched condition. Both show normal penetration of IGO.

Figs. 9a, 9b, 10a and 10b compare their structures in the etched condition. Both are considered acceptable and normal. The 8620 control group seems to have had a slightly greater tendency to form transformation products in the IGO layer, although it is quite moderate. The core structures, not shown, were identical.

X-ray retained austenites were also compared. (Refer to Table 2.) Except for the value at 0.005", the results were almost identical.

TABLE 2

	X-RAY DIFFRACTION RETAINED AUSTENITE Cr-free Alloy	8620H
Surface	20%	22%
0.002	32%	35%
0.005	23%	36%
0.010	27%	27%

Cleanliness, of course, is a result of melting, pouring and rolling practice. Cleanliness was measured on both the raw material (ASTM and SAE methods) and qualitatively on finished parts as a part of the post mortem investigation. Both steels were very clean.

Both steels were made by a fine grain practice. The Cr-free steel contained 0.05 Al, the 8620, 0.03 Al. Grain size measured ASTM #9.5, as shown in Fig. 11. A heat etch method was used. In this method, a polished sample is heated to the test temperature (1700°) in a protective atmosphere. Boundary zones are accentuated (grooved) due to selective vaporization and diffusion.

Grain Flow

Rolled steel products, such as alloy steel bars for forging, have grain flow characteristics that are dependent on how they have been reduced to size. This grain flow is modified by the forging operation.

Figs. 12 and 13 compare the grain flow characteristics of two gears from the program. The 8620H was forged by axially compressing a 2" round cornered square cut to 3⅛" lengths. The

Fig. 11 – Typical prior austenite grain size (heat etch). (100X)

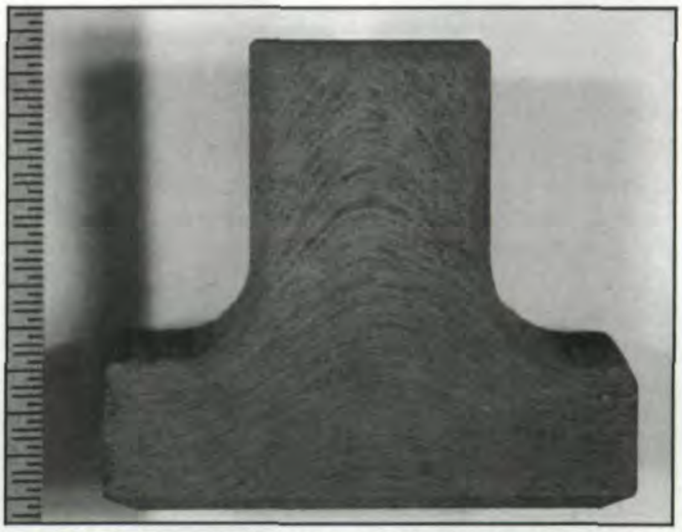

Fig. 12 – Grain flow – Specimen #25 – 8620H etchant: hot HCL. (2.8X)

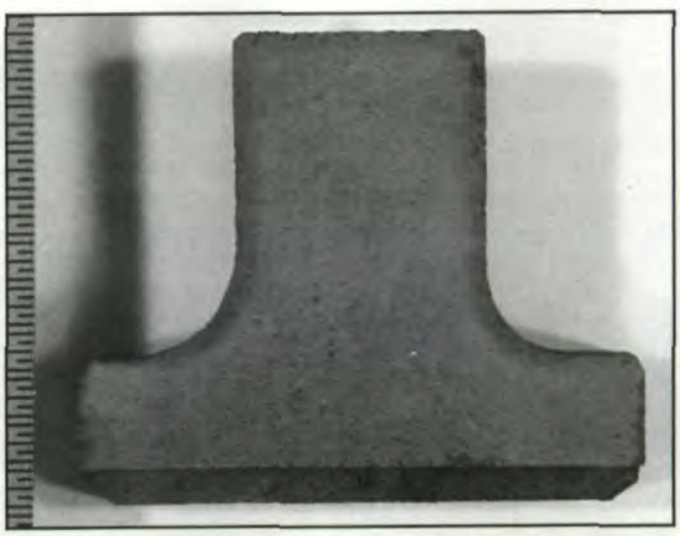

Fig. 13 – Grain flow – Specimen #18 – Cr-free alloy #4 etchant: hot HCL. (3.0X)

Cr-free was forged from a $2\frac{3}{8}$ " round cornered square cut to $2\frac{1}{4}$ " lengths. The compression direction could have been random, since it was nearly a cube. The views shown are from an axial cross section of a forging from each group to show longitudinal flow lines. The tooth load is applied perpendicular to the photograph. The 8620 shows typical flow lines. Although showing faint typical flow lines, Cr-free also shows significant end grains. The effect of this on performance is not known. It is not necessarily significant, as neither have flow lines which are optimum.

Effect of High Manganese

The maximum Mn level in the Cr-free steel is higher than that generally seen in low alloy steels. Most low alloy steels, except for those in the AISI-SAE 1300 series, have maximum Mn levels of 1.00% or less. Historically, high-side Mn levels have been associated with problems such as alloy segregation during ingot casting leading to banding, as well as intergranular oxide (IGO) formation during carburizing. The Mn level in the 10-ton heat used in this investigation was intentionally held to the high side of the suggested range so that questions such as these could be evaluated.

The extent of Mn segregation is a function of the size of the ingot and the cooling rate; i.e., smaller ingots with faster cooling rates will show less segregation than larger ingots. Although the heat size was small, the single ingot that was cast is roughly similar to what is used commercially. Hence, the cooling rates obtained during solidification were representative of those obtained in commercial ingot practice. Thus, to the extent that this investigation was able to duplicate a commercial practice, there was no indication that the Mn level of the Cr-free steel would produce excessive segregation.

Another concern associated with the Cr-free steel is the extent to which the high Mn level would increase the IGO formation during carburizing. IGO is an unavoidable product of most commercial carburizing processes (except vacuum carburizing) for alloys containing Cr, Mn and Si. Published research[9] indicates that these elements will be depleted from solution and will form oxides in the grain boundaries or in the matrix near the surface. The Si content of the steel grades used in most carburizing applications (approximately 0.25%) appears to be the major factor affecting the formation of IGO. The major detrimental aspect of IGO formation is a reduction of case hardenability due to alloy depletion. Although there has not been a definitive study on the relative contribution of Mn and Cr to IGO formation, the slight increase in Mn level can be expected to be offset by the total elimination of Cr in favor of increased Mo which does not oxidize under carburizing conditions.

A comparison of the micrographs in Figs. 8a and 8b suggests that the IGO formation in the Cr-free steel may even be slightly

Fig. 14 – View showing shape and toughness of root fillet. Specimen #3 – Cr-free alloy 20X.

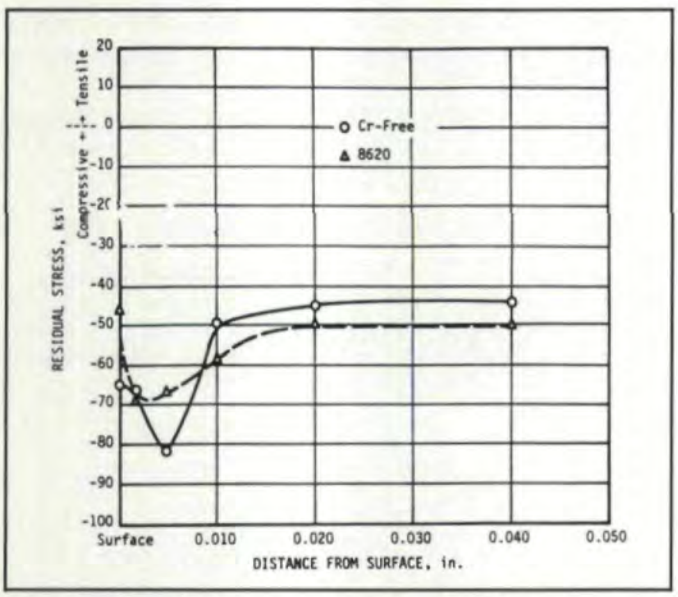

Fig. 15 – Typical residual stress profile shot cleaned like the data base gears.

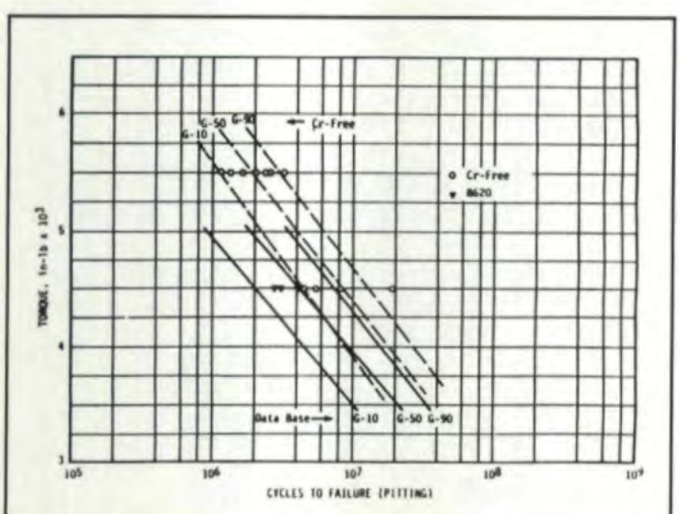

Fig. 16 – Comparison of durability test results of Cr-free and 8620 and data base. Cr-free Weibull distribution is shown along with similar results of the data base.

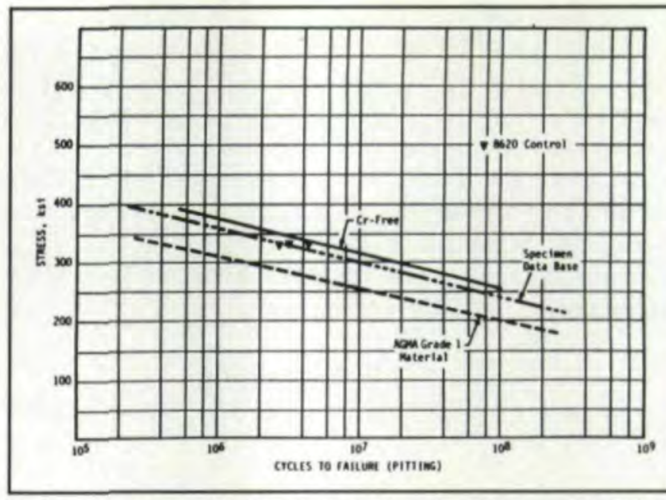

Fig. 17 – Comparison of G-10 Weibull point from durability tests with AGMA allowable stress specificaton for Grade 1 (Reg. 5).

less than that formed in the 8620. The fact that the Cr-free steel performed better than the data base in strength tests may be related to this factor (low IGO formation) also, but unless an analysis is conducted to evaluate relative IGO formation tendencies of the alloys used in the data base, this can only be presented as a possibility. Strength testing will be discussed subsequently.

Dimensioning and Heat Treat Distortion

All gears were processed in a similar manner. The manufacturers reported that the 8620 and the Cr-free materials were similar. Profile, lead checks and "over pin" changes were indistinguishable between the two sets. Both fillet radius and surface finish were basically the same and similar to the "data base" gears. A typical fillet profile is shown in Fig. 14. Surface roughness measured ≈ 125 rms.

Residual Stress

Residual stresses from processing; i.e., heat treat and post heat treat processes, such as cleaning and peening, are known to have major influence on fatigue performance, especially bending fatigue. Some influence is expected in contact fatigue, but less published data is available on this subject.

Variations in residual stress caused an unexpected and unwanted excursion in the test program. The data base is, as noted in Fig. 2, for shot *cleaned* gears. The root fillet compressive residual stress of cleaned gears usually varies from about 40Ksi to 70Ksi The first gear tested in bending (6200 lb-in) gave highly suspect results in that it lived well past the normal failure cycles for bending and then finally failed by pitting. This prompted an investigation of residual stresses. The FASTRESS method was used. Gears from this group were determined to contain a residual stress level of about 87Ksi. This level of residual stress is more in line with shot peened gears. The supplier had done an exceptional job of cleaning the gears. Because of this, it was deemed necessary to replace some of them. The replacement gears were processed through the same cleaning system as the data base gears. Levels more in line with what was expected were obtained. Comparison of results are shown in Table 3. These comparisons are for axial stress since this direction does not require removal of teeth and thus provided a quick answer to the problem.

Subsequently, the residual root stresses of gears from both

TABLE 3
X-Ray Residual Stress Analysis

Identification	Position:	A	B	C	D	Avg.
		Residual Stress,* ksi				
8620 Cleaned by Supplier		−92	−90	−84	−82	−87
8620 Cleaned Same as Data Base		−44	−40	−58	−34	−44
Cr-Free Cleaned as Data Base		−38	−28	−28	−40	−33.5

*Stress measurements were made at the midpoint of the gear tooth width in the root. They were made at four locations on each gear, 90 degrees apart in the root-axial direction.

groups were characterized in the circumferential direction. An in-depth profile analysis was conducted to determine if there were basic differences. This comparison is shown in Fig. 15. The circumferential direction coincides with the load stress direction and, thus, is a legitimate design consideration.

We elected to use the "over cleaned" gears in the durability (pitting) tests. This aspect will be discussed subsequently.

Power Circulating Gear Tests

Thirty-one gear sets were evaluated, six 8620 and 25 Cr-free. Twenty sets were tested in the durability (pitting) regime and eleven in the tooth strength (breakage) regime. (Refer to Fig. 2.) Tests were split between four load levels, two in each regime. Weibull statistics were used to analyze the data where applicable.

Durability

Figs. 16 and 17 show the torque-cycle results of PC tests conducted in the durability regime in comparison with existing information. The torque levels used were 4500 lb-in and 5500 lb-in. Fig. 16 compares the control group (3 tests) with the data base and the data base with the new Cr-free steel. The 10, 50 and 90% probability levels were determined by analyzing the data for each of the two loads using Weibull statistics.

There are two significant aspects to this data. One, the control group tends to validate the test specimens by falling within the existing data base band. As indicated earlier, these gears were from the "over peened" group. Since both groups — the control group and the test group — were exposed to the same cleaning, it is safe to make comparisons. Two, the Cr-free steel group shows slightly longer lives to pitting than the data base and the control group. In Fig. 17 the 10% probability SN curves of the data base and the Cr-free test group are compared with the G-10 curve for AGMA Grade 1 material. The control group data points are also shown. The AGMA recommended practice is slightly conservative to both the data base and the Cr-free data. This comparison again shows the Cr-free steel to be marginally better than the data base materials. Given the limitations of the analysis in terms of numbers of tests, etc., it is appropriate to conclude that the two groups perform comparably in terms of pitting fatigue.

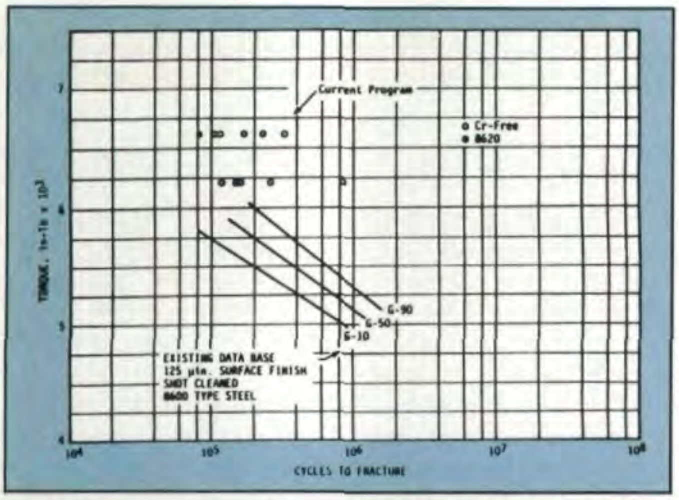

Fig. 18 – Comparison of strength test results of Cr-free and 8620 with data base. Cr-free results are shown with Weibull analysis results of the data base.

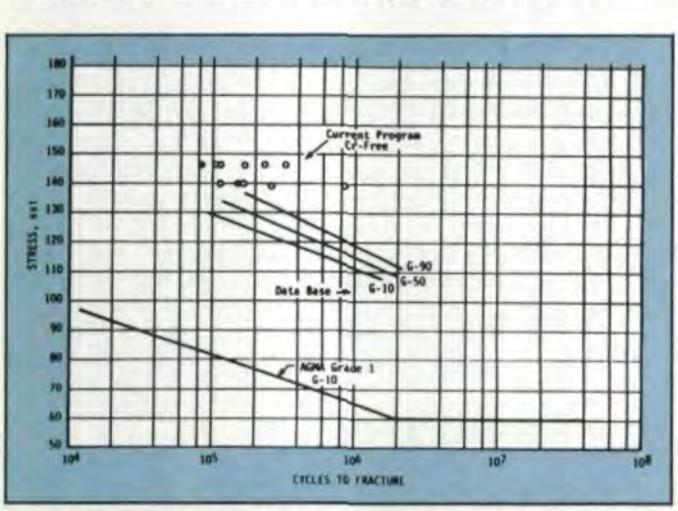

Fig. 19 – Comparison of results from strength tests with data base and the allowable stress specification for AGMA Grade 1.

Tooth Strength

The data generated for comparing bending fatigue is shown in Figs. 18 and 19. The two load levels were 6200 lb-in (139,500 psi) and 6600 lb-in (148500 psi). These load levels are quite close together for this type testing; however, it was necessary to go as high as 6200 lb-in to assure tooth fracture instead of pitting, and the 6600 lb-in is near the upper limit of the test machine being used. Even so, gearing and shaft failures were experienced during this phase of the program.

Fig. 18 shows all data points, including the control group, in comparison with the G-10, 50 and 90 curves for the data base. In one of the tests at 6200 lb-in, the test was terminated due to pitting after 805,000 cycles; i.e., fracture did not occur. There is not quite enough data to perform a legitimate statistical analysis; however, two conclusions can be made. One, the control group samples ran to the low side of the Cr-free group, but to the high side of the data base; and two, the Cr-free group appears to be able to carry higher torques at the same cycles compared to the data base.

Fig. 19 shows this same data, but in terms of stress plotted along with the AGMA allowable stress curves. In this comparison the AGMA design curves appear very conservative. This may be due to many factors, including metallurgical quality, size effects, etc. It is apparent, though, that with good control, gears can be designed and used at significantly higher loads than those indicated.

Summary

1. The Cr-free steel had equivalent (marginally better) durability characteristics compared to the data base.

2. The Cr-free steel exhibited significantly higher strength (tooth bending fatigue) than the data base steel.

A number of factors may be involved, the two most likely being metallurgical quality and residual stress. Since the data base represents a large number of gear sets, it probably included gears with a wider variety of cleanliness, microstructure and residual stress conditions. The Cr-free steel had good structure, was fairly clean and contained residual stress to the high side of that expected for cleaned gears. Thus, this small group may represent high-side performance for these type steels.

3. The hardenability response was pretty much as predicted and, thus, microstructures were satisfactory. This tends to validate the concept of developing substitute steels based on equivalent hardenability. Some reservations are in order as mentioned earlier.

4. Processing characteristics, from steel melting to rolling to forging to machining to heat treating for the Cr-free steel, were similar to other alloy steels of the 8620 type.

5. It was not necessary to modify the green size from that customarily employed in order to accommodate the Cr-free steel movement in heat treatment.

6. Grain flow was different in the Cr-free gears as compared to the control group and the data base gears. This difference is not thought to be of great significance, however, more work is required to validate this assumption.

Conclusion

The purpose of this investigation was to provide a performance comparison between the proposed Cr-free steel composition and the current AISI-SAE 8620 steel grade. None of the comparative tests indicated a compromise in properties as a result of the substitution of Cr-free steel for 8620. On the contrary, there were several points in favor of the substitution. Phase II of this research has built upon the results obtained in Phase I by evaluating the Mn-Mo Cr-free 8620 steel substitute proposed in Phase I in a scaled up application. This Cr-free steel composition was cast as a 10-ton heat and evaluated in a carburized gearing test program along with an 8620 steel control group of gears. The control group was used to calibrate an existing data base with which the new steel was compared. A variety of production, performance and metallurgical aspects of the Cr-free steel were compared with the characteristics of 8620 in an effort to determine whether the Cr-free steel could be recommended as a suitable alternate composition for 8620 in the event of an interruption of the domestic chromium supply. The major conclusions obtained from this program can be summarized as follows:

1. The performance of the Cr-free steel in a carburized gearing test program was at least equivalent to or slightly better than the performance obtained in a similarly processed 8620 control group. In addition, the Cr-free steel performance in the gearing test fell to the high side of an existing data base obtained from steels of similar hardenability. These test results indicated that the Cr-free steel would perform at least as well as 8620.

2. The various processing characteristics that were evaluated indicated that the Cr-free steel could easily be substituted for 8620 steel in existing application with little or no processing changes. For instance, in the production of the gears in this investigation, no significant differences were observed between the Cr-free and 8620 steels in forging, machining or heat treatment.

3. Detailed metallurgical evaluation of the Cr-free and 8620 steels indicated that transformation characteristics, microstructures and fracture morphologies were similar, that no segregation problems were encountered with the higher Mn level of the Cr-free steel and that both steels had similar core and case hardenability.

4. The overall performance of the Cr-free steel is sufficiently similar to that of 8620 that direct substitution of the Cr-free steel for 8620 can be made in gearing applications with no loss in performance characteristics and with little or no change in processing parameters. In other general structural applications, it is expected that the Cr-free steel will process and perform in a similar manner to 8620 steel.

This work has significantly added to the knowledge base required to make successful substitutions in critical applications. It further proved the metallurgical design system for substitution and encourages its use for peaceful purposes, such as cost control.

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