A Perspective on the Performance of Carburized Gear Steels

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ABSTRACT

Recent research on carburized steels has demonstrated a correlation between the toughness properties of a carburized steel and the fatigue performance in combined load testing (high-cycle fatigue plus overload). The data presented suggest that, for applications where loads above the fatigue limit are encountered, both processing and alloying must be considered. Results from a number of investigations are reviewed to illustrate that high-cycle fatigue properties are controlled primarily by the processing, whereas toughness characteristics, such as resistance to random cyclic loading, are a result of the alloying.

CARBURIZING STEELS are generally used in heavy loading applications where premium performance characteristics are a necessity. In many instances, the situation is one where random cyclic loading conditions are encountered. An example is the gearing employed in various types of transportation equipment. In general, these applications can be characterized as consisting largely of a high-cycle fatigue component with intermittent higher loads resulting from such things as acceleration, gear shifting, resonant vibrations or other sudden changes in operating conditions. In this paper, this loading condition will be referred to as "combined loading" to emphasize the components involved, i.e., the high-cycle fatigue portion and the higher load conditions which will be referred to as "overloads."

From an engineering standpoint, combined loading situations are difficult to analyze. It is also very difficult to evaluate the relative contributions of the fatigue and overload portions of the loading spectrum. Even when these data are obtained, there is very little information available on the balance of properties required to sustain such combined loading. Similarly, there is a decided lack of understanding concerning the individual roles of alloying and processing in carburized steel performance. Specifically, the question is: How does one approach the fatigue and toughness requirements of a particular application?

In an effort to determine the nature and extent of the beneficial influence of molybdenum on carburized steel performance, this laboratory has conducted numerous investigations on the effect of various processing and alloying variables on fatigue and toughness related properties. It is very difficult to study many individual effects of these variables even in controlled laboratory situations because they are not easily isolated from one another. However, after extensive research along with confirming results from in-service performance, some general observations have been obtained on the relationship between processing and alloying and how this relationship influences performance.

One research program has been extremely helpful in providing insight into the relative effects of fatigue and overload on carburized steel performance. This program has focused on premature fatigue failure resulting from overload induced cracking. Other researchers have looked at the effect of similar loading situations. Work reported by Eagan and Shelton(1)* illustrated that overloading could decrease the subsequent high-cycle fatigue performance and that there were differences in the way various grades responded, with higher alloyed steels out-performing the lower alloy grades. Razim(2) reported results from an investigation of what was termed the "initial crack strength" of various grades of carburized steels. His results showed the crack strength (measured in terms of stress at cracking) was inversely related to surface carbon levels and directly

*Numbers in parentheses designate references at end of paper.

related to core hardenability. These earlier results are, to a large extent, consistent with recent results obtained by this laboratory on the performance of carburized steels under combined load testing. More recent data on this subject have been obtained under this program and a better understanding of the influence of alloying and processing has resulted.

BACKGROUND

The objective behind carburized steel research is to obtain laboratory test results that can be related to in-service performance. Our experience has shown that the impact properties of a carburized steel are a good relative indicator of performance in heavily loaded applications. However, a large portion of field failures from such applications have been diagnosed as fatigue type, and, indeed, it is quite clear that the failures have characteristics typical of fatigue crack propagation. Hence, fatigue properties have become more important than impact properties. Numerous examples of field performance, though, have been shown to be unrelated to laboratory fatigue test results. A recent example will be used to illustrate the point.

A gear set like the one shown in Figure 1 was machined from SAE 8620, carburized and tested in an Indianapolis type race car. While this design was sufficient for other engines, the engine used in this car had different performance characteristics, and the gear set failed prematurely. The substitution of a higher alloy grade, EX55, was enough to completely eliminate the gear set failures, and the gears were used successfully through several races. Though the failed gear sets were damaged too heavily for fractographic evaluation, there was nothing in the failure of the SAE 8620 gears to suggest that they had failed in a single impact type loading situation. Hence, the difference between the EX55 and SAE 8620 was ascribed to differences in the fatigue characteristics. Subsequent laboratory testing of these two steels, on the other hand, indicated that their high-cycle fatigue properties were not sufficiently different to account for the improved performance. Impact fracture testing on the other hand, showed a substantial advantage of the EX55 over the SAE 8620. Test results to be described in later sections will illustrate this point further.

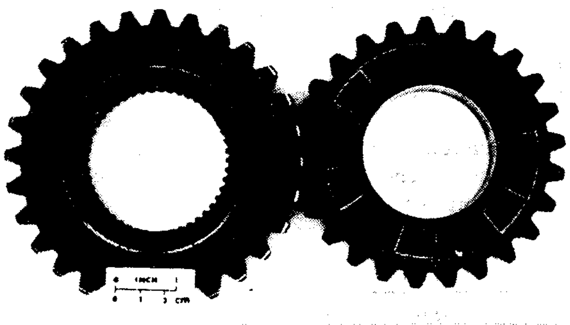


Fig. 1 - Racing Transmission Gear Set

This situation is typical of many that have been investigated. Hence, the approach which has been adopted is that in heavily loaded applications the impact fracture properties should be the indicator of the performance characteristics. However, because of the empirical nature of the correlation between impact properties and performance, there was a general reluctance to rely on the impact properties for material selection purposes. In addition, there was a suspicion that the laboratory fatigue test must somehow be deficient for its inability to reflect the differences in performance seen in service. A solution to this controversy has been suggested by the recent research done on combined loading of carburized steels. Details of the program and some of the initial data have been described in an earlier publication(3).

The combined loading test program was initiated based on evidence from numerous sources that "crack initiation" represented about 90% of the fatigue life of a carburized steel. The hypothesis was that loads above the fatigue limit resulted in premature crack initiation and that the properties governing crack initiation would be the ones controlling fatigue performance in combined loading situations.

Initial results showed that loads above the fatigue limit will result in cracking part way through the case and that premature fatigue failure can result. The stress required to form a crack in the carburized case was described as the "critical overload" (or OL_{cr}). The data also indicated that the load to form the cracks was related to the impact fracture stress (IFS) of the steel. This correlation between the IFS and case cracking at the OL_{cr} provided the key to the relationship between impact properties and fatigue performance. These initial results demonstrated that the OL_{cr} was sensitive to both alloying and loading rate or loading combination (i.e., fatigue plus overload). The research also showed that both OL_{cr} and IFS values increased with loading rate as does fracture toughness, suggesting that both OL_{cr} and IFS were related to the carburized fracture toughness of the steel. Subsequent work(4) has pointed out that a zone of intergranular fracture at the initiation site may be an indication that crack formation resulted from an overload.

More recent laboratory work on this combined loading program has focused on the effects of alloying and processing on the value of OL_{cr} in an effort to determine the extent to which the OL_{cr} stress and impact fracture stress are measurements of the same property. The data have continued to show a strong correlation between OL_{cr} and impact properties. However, these results have also been instrumental in providing a broader perspective on the relationship of alloying and processing to the high-cycle fatigue and toughness properties of carburized steels. Consequently, results from recent and previous investigations have been evaluated to estimate the relative importance of processing and alloying to the overall performance of carburized steels. The following examples of research data will be used to illustrate that processing variations (i.e., carburizing or subsequent processes like shot peening), in general, seem to have a dominant effect on the high-cycle fatigue performance but a negligible effect on the toughness. Alloying, on the other hand, will be shown to have very little, or what might be termed a second order, effect on fatigue properties and yet a dominant influence on the impact and overload characteristics. In essence, what these observations suggest is that the toughness of the carburized product will be largely determined by the alloy composition, while the fatigue properties will be controlled by the type of processing that is used.

PROCEDURE

Most of the fatigue, impact and combined load testing conducted by this laboratory has been performed using the specimen geometry shown in Figure 2. The design simulates a gear tooth, and the root section dimensions are very similar to those of the gears shown in Figure 1. Loading is accomplished in a cantilever fashion. Impact fracture testing is conducted with a Charpy impact tester in the manner of an Izod test. Combined loading tests and high-cycle fatigue tests are performed in a closed-loop servohydraulic test system under load control using a fixture similar to the one shown in Figure 3. Outer fiber stress values are obtained directly from measured load values using simple (elastic) bending moment relationships and a stress concentration factor representative of the notch root radius (1.56). The OL_{cr} value is obtained based on load-deflection measurements where the deflection is measured by clip gauge. Figure 4 illustrates a typical load-deflection curve obtained for a carburized steel in monotonic bending. The abrupt discontinuity between the linear and non-linear behavior has been correlated with

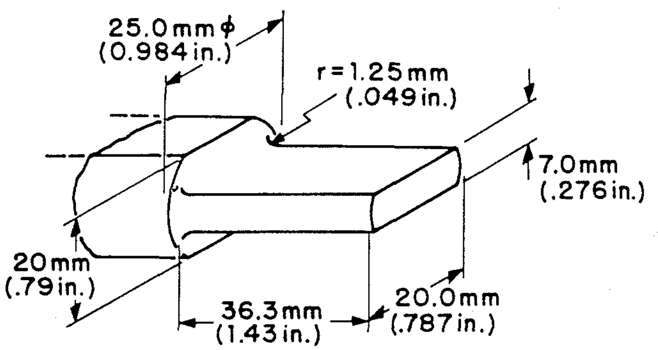


Fig. 2 - Test Specimen Geometry for Impact, Fatigue and Combined Load Tests

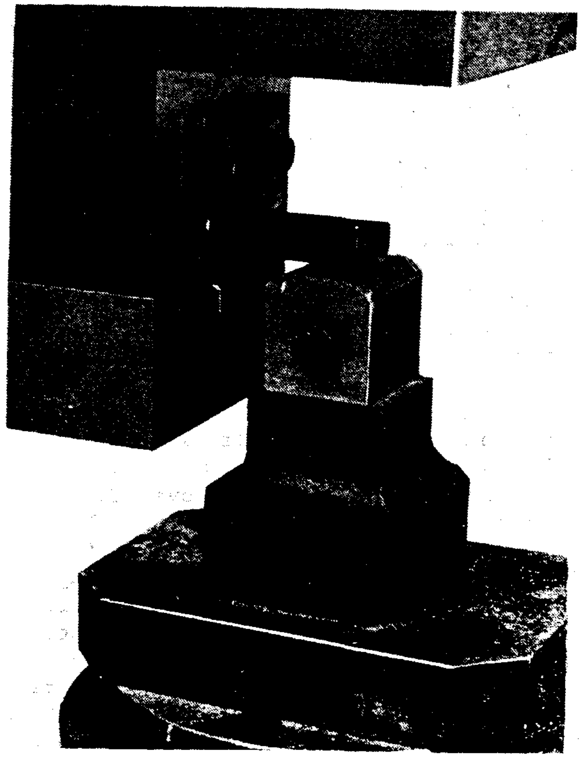


Fig. 3 - Fixture for Fatigue and Combined Loading Tests

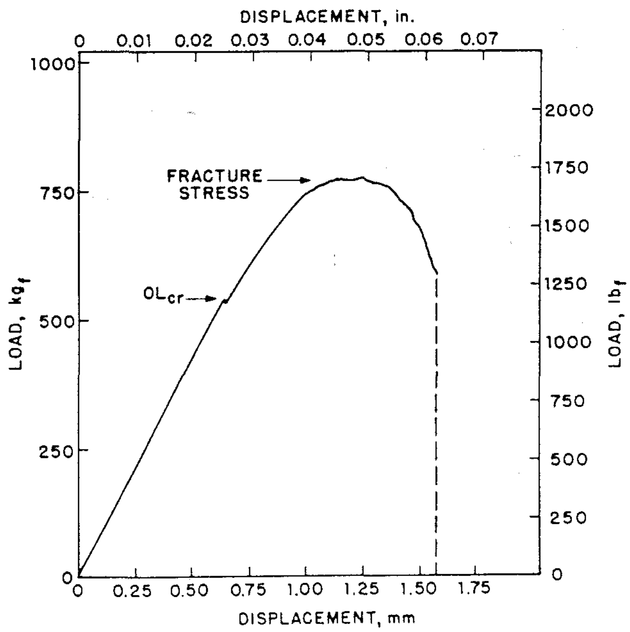
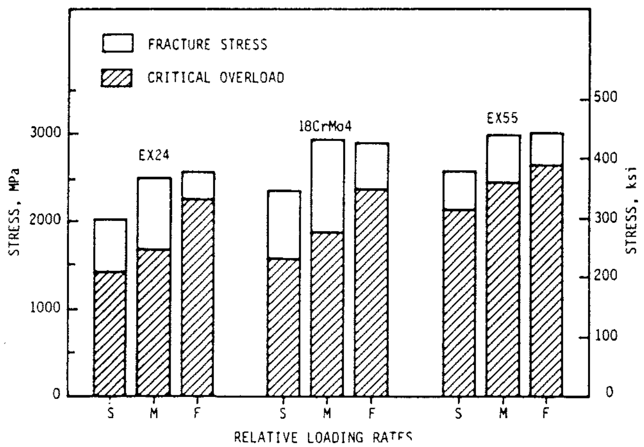


Fig. 4 - Load versus Displacement for Monotonic Bending

crack formation and has been designated the OL_{cr}. A similar approach has been used in impact and combined loading tests to determine OL_{cr} values.

Because the concept of the OL_{cr} has been instrumental in development of the relationship showing the influence of processing and alloying on performance, it is useful to review briefly some of the recent test observations. One of the initial investigations focused on loading rate sensitivity of OL_{cr} and fracture. The results illustrated in Figure 5 show fracture stress and OL_{cr} values obtained at different loading rates (load converted to stress) in monotonic bending. Both the OL_{cr} and the fracture stress are heavily dependent on the loading rate under which they are measured. The value of stress obtained is proportional to the loading rate. These results also illustrate the influence of alloying on the IFS and OL_{cr} values obtained. The higher alloyed EX55 has higher values of OL_{cr} and IFS at all loading rates than the lower alloy EX24 or 18CrMo4.

The combined load testing program employs the computer-controlled testing regime illustrated in Figure 6. Intermittent and linearly increasing overload "spikes" are programmed to occur after every 1000 high frequency (constant amplitude) fatigue loading cycles. OL_{cr} values are established at the point where the load/displacement values obtained from the peak values of the overload spikes are no longer linear. The characteristics of the load versus displacement curve from this test program are very similar to the curve shown in Figure 4 except that the data are discrete rather than continuous. Figure 7 illustrates the general



Steel	C	Mn	Cr	Mo	Ni
EX24	0.19	0.83	0.53	0.22	--
18CrMo4	0.20	0.89	1.04	0.22	--
EX55	0.19	0.82	0.55	0.74	1.88

Loading Rates (Load Converted to Stress)

S = 8.7×10^1 MPa/sec (1.3×10^1 ksi/sec)

M = 9.9×10^5 MPa/sec (1.5×10^5 ksi/sec)

F = 7.8×10^6 MPa/sec (1.2×10^6 ksi/sec)

Fig. 5 - Fracture Stress and OL_{cr} Values at Various Loading Rates

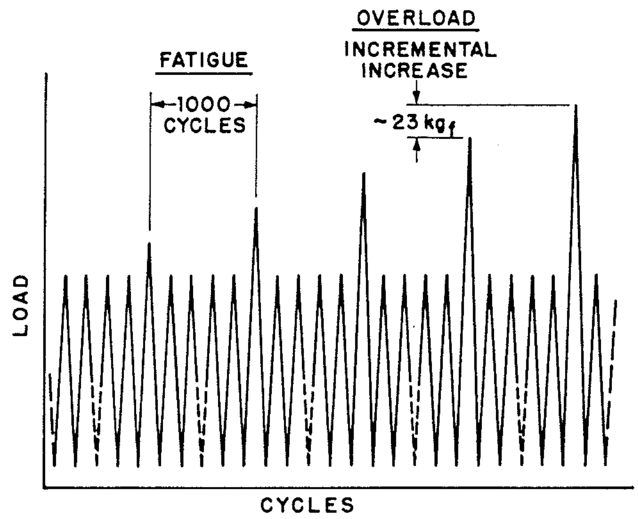


Fig. 6 - Schematic of Loading Regime for Combined Load Test

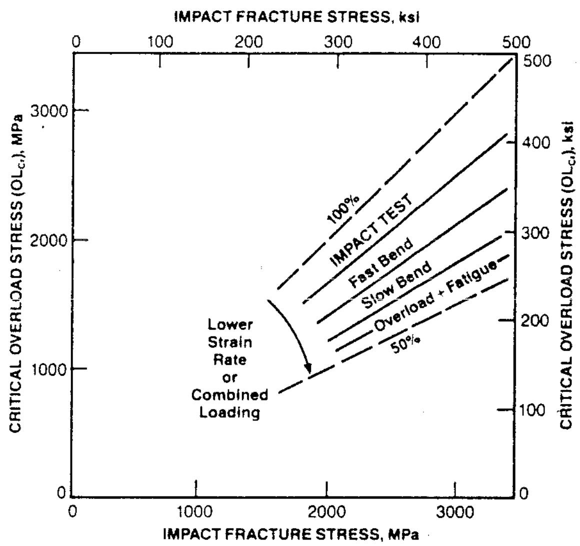


Fig. 7 - Relationship Between IFS and OL_{cr} for Various Loading Conditions

relationship observed between IFS values and the OL_{cr} values obtained at various loading rates and as obtained in the combined load tests. As the loading rate decreases or when there is combined loading, the OL_{cr} value approaches 50% of the measured IFS. The illustration also indicates that the higher the IFS value the higher the OL_{cr} value regardless of loading condition.

A brief evaluation of the influence of the high-cycle fatigue stress during the combined load test on measured OL_{cr} values was also undertaken. Results are shown in Figure 8 for two low alloy steels each tested at three different levels of fatigue stress. The data indicate that the OL_{cr} is directly related to

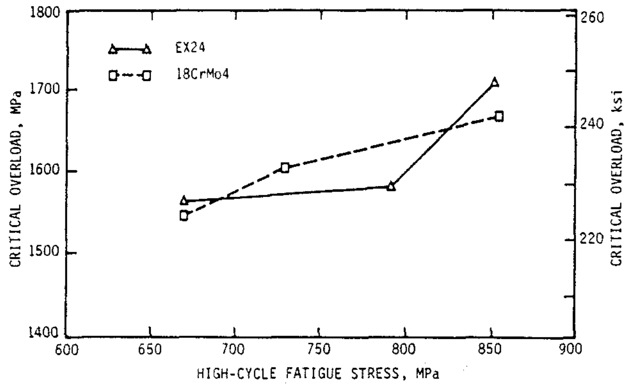


Fig. 8 - Effect of High-Cycle Fatigue Stress Level on Measured Critical Overload Value, OL_{cr}

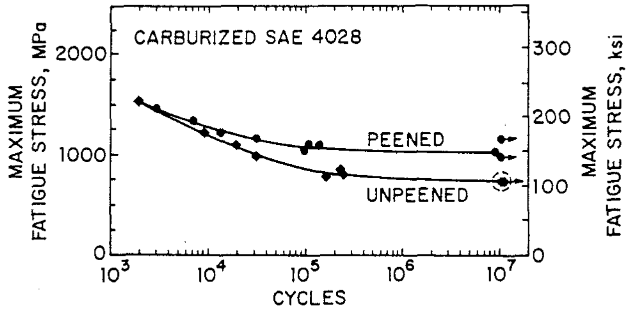


Fig. 9 - High-Cycle Fatigue Properties of SAE 4028 Before and After Shot Peening

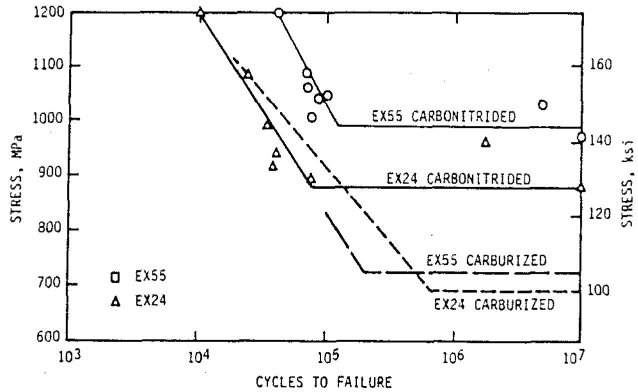


Fig. 10 - High-Cycle Fatigue Test Results for Carbonitrided EX24 and EX55 Compared with Carburized Results

the high-cycle fatigue load imposed. With the exception of this experiment, the fatigue loads were maintained at a constant value of 850 MPa (123 ksi).

These examples illustrate that the values of OL_{cr} and IFS will be very dependent on the circumstances under which they are determined. The results also suggest that, while these test results are related to the properties of the material, the OL_{cr} and IFS values are relative quantities and can be expected to vary from one application to another. Test results obtained so far, however, indicate that either the IFS or the OL_{cr} can be used as a reliable indication of the ability of a steel to resist crack initiation that would lead to premature fatigue failure.

RESULTS AND DISCUSSION

FATIGUE PERFORMANCE - In the evaluation of OL_{cr} characteristics, it became evident that, in general, alloying seemed to play a much greater role than processing, a situation similar to what had been observed for impact properties. However, high-cycle fatigue results seemed to show just the opposite trend. To illustrate the point, several examples of processing and alloying variations will be reviewed with respect to the magnitude of their influence on fatigue limit or OL_{cr} and IFS values.

Shot Peening - It is a commonly accepted fact that shot peening will usually boost the high-cycle fatigue performance of a carburized part. This has been demonstrated many times in laboratory tests and in field performance. The results in Figure 9, showing nearly a 50% increase in the fatigue limit for an SAE 4028 steel, are a typical illustration of the magnitude of the improvement that shot peening can produce(5). Though there may be several changes taking place at the surface as a result of the peening, the most significant is the dramatic increase in compressive residual stress which occurs at very shallow depths beneath the surface. Our research has shown that the compressive residual stress has a direct influence on fatigue properties and that it is of greatest value when it occurs at or very near to the surface of the part(6). Shot peening does produce this type of an increase in compressive residual stress at the very surface and, hence, the improved fatigue properties are to be expected.

Carbonitriding - Another process known to influence high-cycle fatigue (and other surface properties such as corrosion and wear) is carbonitriding, where a partial pressure of nitrogen is introduced during the carburization. Figure 10 illustrates the improvement in fatigue limit that can result from such a process. In this example,* carbonitriding, as compared to conventional carburizing, increased the fatigue limit of EX24 (a CrMo alternate for SAE 8620) by about 28% and that of EX55 (a high alloy NiCrMo carburizing grade) was increased by about 37%. In contrast to conventional carbonitriding, this process produced a high fraction of retained austenite in a very thin layer

*Carbonitriding performed by Komatsu, Ltd., using a specially designed "KH" process(7).

on the surface, approximately 0.2 mm (0.008 in.) thick. The layer was thin enough so that HRC hardness values were not influenced. However, under stress the austenite transformed to martensite, producing an increase in the compressive residual stress in a manner similar to shot peening. Retained austenite measurements before and after testing indicated austenite transformation occurred during testing. Though residual stress measurements were not obtained, the improvement in fatigue limit was probably related to the increase in compressive residual stress produced by the transformation of austenite under stress. Although the more highly alloyed EX55 had better fatigue properties than EX24, the percentage increase attributable to carbonitriding was greater than that associated with the change in alloy content, which illustrates the primary influence of processing and secondary influence of alloying on the high-cycle fatigue properties.

Deep Freezing - In the above instance, the nitrogen and, hence, the high retained austenite layer was confined to a thin layer on the surface. In the illustration of high-cycle fatigue data shown in Figure 11, the EX55 steel was carbonitrided using a more conventional process that produces deeper nitrogen penetration.(5) In the carbonitrided and tempered condition, the fatigue limit values were very similar to those obtained in Figure 10 for the EX55 steel. In contrast to the previous example, in this investigation the retained austenite was deeper, up to about 0.8 mm (0.03 in.), and surface hardness was adversely affected. The transformation of the retained austenite by sub-zero treatment and tempering resulted in a substantial fatigue limit reduction of about 60% as compared with the untreated condition. Residual stress measurements in the sub-zero treated steel showed a high tensile residual stress in the untransformed portion of the austenite phase which was assumed to be related to the poor fatigue performance(5).

Alloying - The above three examples illustrate the magnitude of the effect that processing can have on the fatigue performance of carburized or carbonitrided steels. Along with changes in processing, the assumption is often made that changes in the alloy content of a steel can also influence the high-cycle fatigue performance. However, the experience in this laboratory is that the influence of alloying variations (other than core carbon) would have to be regarded as a "second order" effect in comparison to that of processing unless that alloying significantly alters the microstructure or hardness at the surface of the carburized case. The following examples illustrate the point.

Figure 12 illustrates the high-cycle fatigue performance in a laboratory test of two low alloy steels (EX24 and 18CrMo4) and one high alloy grade (EX55). The steels were processed and tested in a similar manner, and it was apparent that the differences were not significant. In this instance, alloying did not play a major role in the fatigue performance. In another investigation, three carburized steels consisting of CrMo and NiMo types were processed and tested in a similar manner with results as shown in Figure 13. The hardenability range of these steels was between 41 and 56 mm (1.6 and 2.2 in.). Again, the conclusion was that the alloy variation did not have a major influence on fatigue performance.

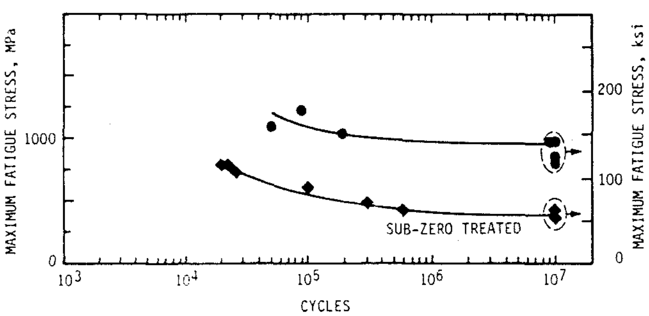


Fig. 11 - High-Cycle Fatigue Results for Carbonitrided EX55 Before and After Deep Freezing

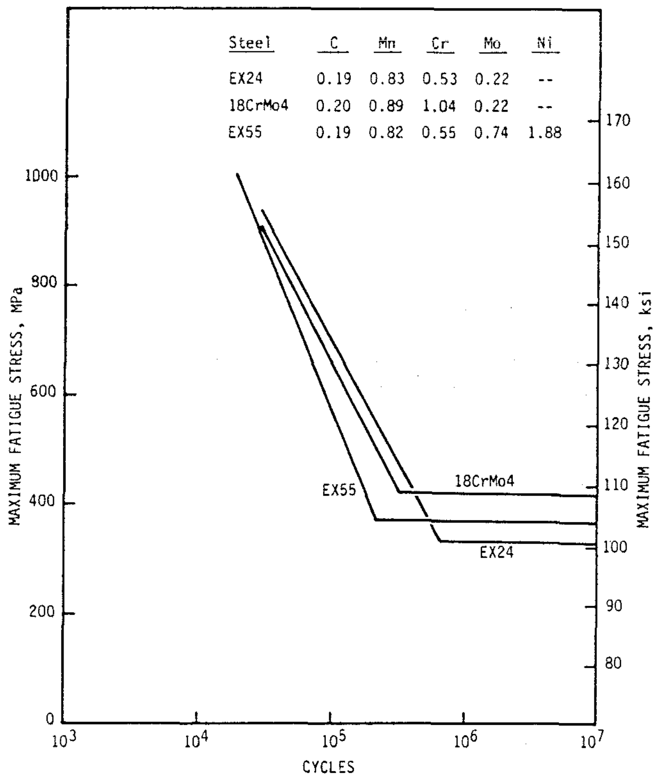


Fig. 12 - High-Cycle Fatigue Results for Similarly Processed Low and High Alloy Carburized Steels

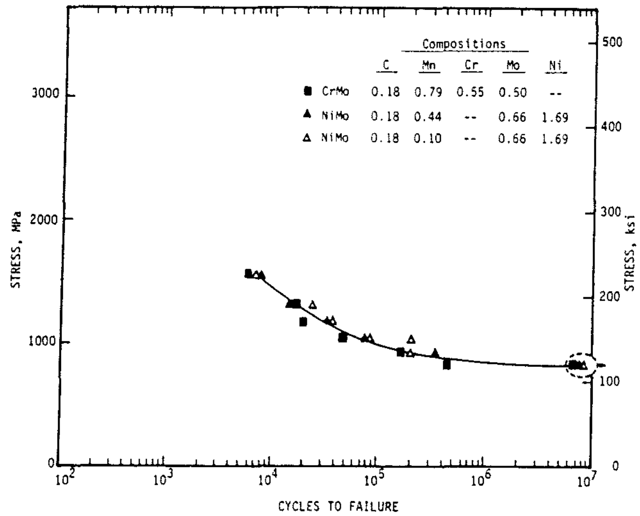


Fig. 13 - High-Cycle Fatigue Results for Similarly Processed Low Alloy Carburized Steels

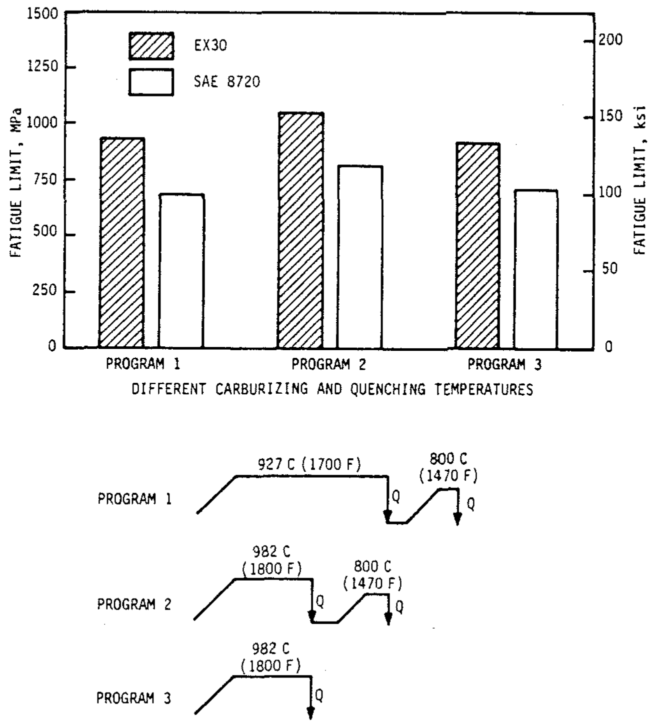


Fig. 14 - High-Cycle Fatigue Limit Values for Two Steels as a Function of Processing

Another investigation was directed at evaluating the effects on fatigue performance of two steels as a function of carburizing temperature, and reheat following carburizing(8). The data in Figure 14 illustrate the fatigue results following the programs shown at the bottom of the figure. The two steels were EX30 and SAE 8720. These steels have hardenability and core carbon levels as shown in Table 1. The results indicated that the EX30 had, on average, about a 30% higher fatigue limit than the SAE 8720 steel. At first glance one might conclude that alloying did have an effect on the fatigue performance of these steels. However, part of this difference could be related to the difference in the core carbon levels, since published work has shown that lower core carbon is favored for high-cycle fatigue properties(9).

The results from Figures 12-14 suggest that alloying variations do not have as large an effect on fatigue properties as various processing techniques. These tests do not take into consideration the effect of alloying on case hardenability, or on non-martensitic transformation that can occur in alloy (Cr and Mn) depletion zones at the surface. Therefore, it must be noted that alloying may very well influence fatigue performance, but in ways that are not apparent in most laboratory tests. However, based on the data that have been obtained, it is concluded that the effect of alloying on high-cycle fatigue performance is of secondary importance to that of processing.

Table 1

Composition and Hardenability of Two Carburized Steels

Steel	Core Hardenability, D_I, mm (in.)	C	Mn	Cr	Mo	Ni
EX30	6.4 (2.5)	0.15	0.74	0.51	0.50	0.80
SAE 8720	4.8 (1.9)	0.20	0.87	0.55	0.23	0.46

TOUGHNESS

Processing - Because published theoretical(10) and experimental(3) results have shown a relationship between fracture toughness characteristics of a carburized steel and the measured IFS and OL_{cr} values, the IFS and OL_{cr} values will be used as measures of the toughness of the steel in the carburized condition. IFS and OL_{cr} data are not available for all of the examples presented in the previous section. However, where these data do exist, they indicate that processing has only a secondary effect on the toughness and that alloying has a primary effect. A review of the IFS and OL_{cr} data from some of these earlier examples will illustrate that, in most cases, processes that influence fatigue performance do not have a major effect on toughness characteristics.

The effect of shot peening on toughness as compared with fatigue properties is shown in Figure 15. High-cycle fatigue limit values for carburized and tempered specimens (from Figure 9) are contrasted with the IFS values obtained before and after peening. Whereas the fatigue limit is increased by about 40% by peening, IFS values are unaffected.

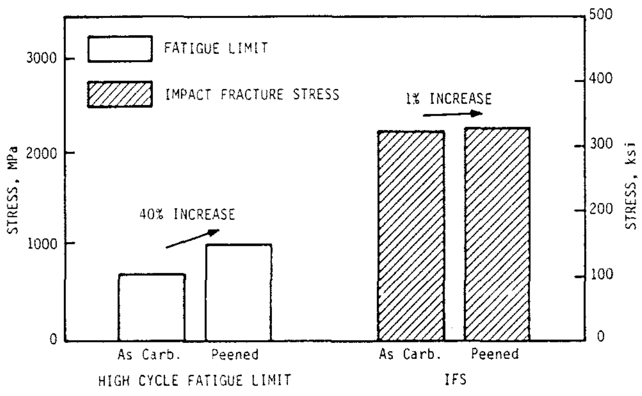


Fig. 15 - Comparison of the Effect of Shot Peening on Fatigue and Impact Properties of Carburized SAE 4028

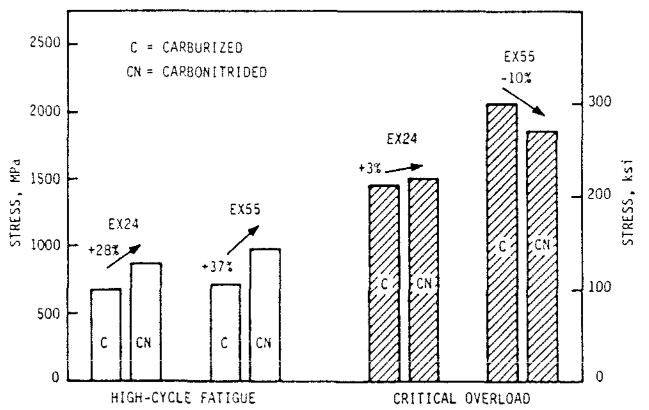


Fig. 16 - Comparison of High-Cycle Fatigue and Critical Overload (Combined Loading) Results for Carburized (C) and Carbonitrided (CN) Specimens of EX24 and EX55

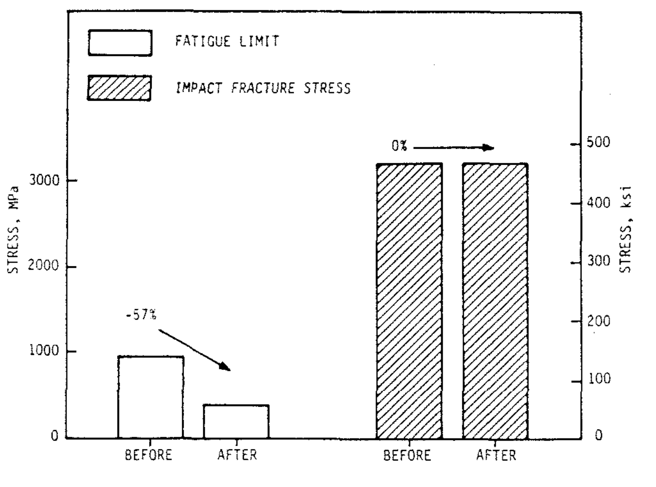


Fig. 17 - Comparison of High-Cycle Fatigue and Impact Fracture Results of Conventionally Carbonitrided EX55 Before and After Deep Freezing

A similar comparison is shown in Figure 16 for the effect of carbonitriding on fatigue and toughness properties. In this instance, a comparison is shown between the fatigue limit values (obtained from Figure 10) and the OL_{cr} values. As shown for shot peening, processing (carbonitriding) has a major effect on the fatigue properties and little or no beneficial effect on the toughness (critical overload stress). However, the difference in the OL_{cr} values between the two steels indicates that alloying has a major influence on the toughness of the carburized steel (but not on the high-cycle fatigue results). Note that the average OL_{cr} values for EX55 are 32% greater than those for EX24.

A comparison between the fatigue limit and IFS results for the sub-zero treated steels (introduced in Figure 11) is shown in Figure 17. The freeze treatment which dropped the fatigue limit of the EX55 by over 50% is shown to have no effect at all on the impact properties. In general, these three examples clearly illustrate that fatigue and toughness properties can vary independently of one another.

Results from Razim(2) mentioned earlier indicated that higher surface carbon levels would result in lower initial crack strength values. In this context, the surface carbon level would be considered a process related variable. Hence, this situation would represent an exception to the generalization that processing does not have a major effect on toughness characteristics. In a recent investigation, the influence of surface carbon level on OL_{cr} values was reexamined. Carbon concentration profiles for the steels involved are shown in Figure 18. Results of the investigation shown in Figure 19 compare the OL_{cr} values obtained in both slow bend (monotonic testing) and combined load (cyclic testing) for the two low alloy steels. As would be expected, results for the combined loading are lower and there is very good agreement in the trends between the monotonic and combined load test results. OL_{cr} values show a slight decrease with increasing surface carbon levels, but substantially less than that predicted by Razim(2). One of the reasons for the decrease in OL_{cr} with surface carbon in the present investigation could be because the case depth increased with surface carbon levels. The negative influence of case depth on toughness will be discussed subsequently.

Theoretical models have been employed to isolate the influence of factors such as compressive residual stress and fracture toughness on the fatigue and toughness properties of carburized steels(6,10). These models have shown that variables with a strong influence on surface compressive residual stress levels will also have a strong influence on the high-cycle fatigue properties. Conversely, those factors influencing fracture toughness will have a strong influence on impact properties. The examples described above illustrate the degree to which processing variations can influence

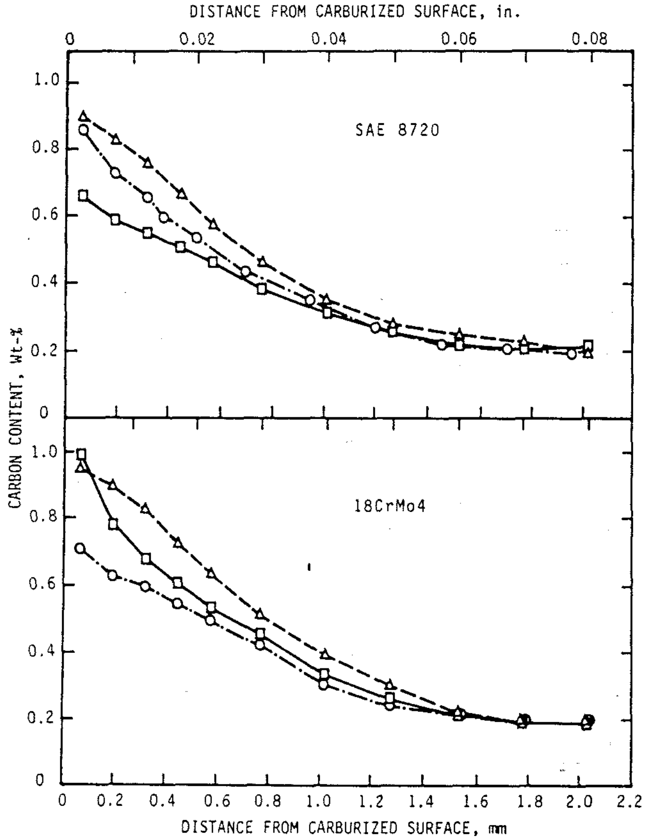


Fig. 18 - Carbon Profiles Obtained in Steels for Use in Combined Load Testing

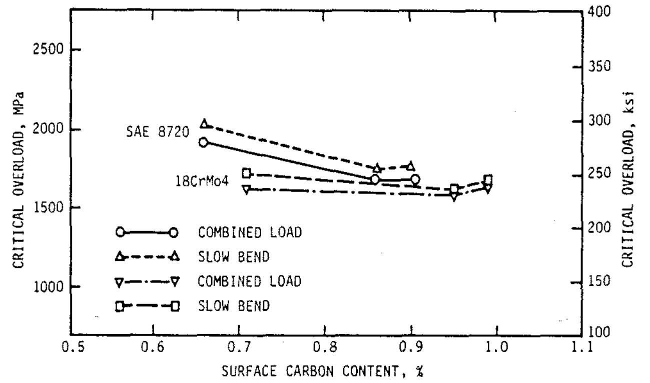


Fig. 19 - Influence of Surface Carbon Level on OL_{cr} Values Obtained in Slow Bend (Monotonic) and Combined Load Testing

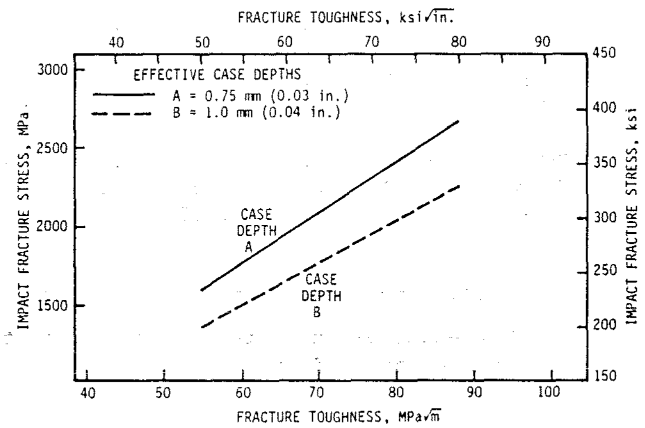


Fig. 20 - Relationship Predicted Between Core Fracture Toughness and Impact Fracture Stress at Two Case Depths

fatigue properties. The reason that the changes in processing do not produce changes in the impact properties is because there is insufficient change in the fracture toughness. The processing examples described in Figures 15, 16 and 17 influence the surface of the specimen and not deep in the case or the core.

Alloying - Changes in composition and core microstructure should be expected to produce differences in fracture toughness. The assumption made earlier was that changes in fracture toughness would be reflected in the IFS and OL_{cr} results. Figure 20 shows the behavior predicted from theoretical modeling(10) for the IFS with changes in the core fracture toughness for two carburized case depths. The model predicts lower values of IFS for deeper case depths (hence, the reduction in OL_{cr} with deeper case depths shown in Figures 18 and 19). However, there is a strong positive correlation between core fracture toughness and IFS values. Results from a series of laboratory investigations will be used to describe the actual magnitude of this effect.

One composition variable clearly associated with a reduction in fracture toughness is phosphorus content. Under most circumstances, higher phosphorus will result in substantially lower fracture toughness values. In a recent investigation, the influence of phosphorus and nitrogen levels on several MnCr and CrMo type steels was determined. Fourteen heats of steel with compositions as shown in Table 2 were carburized and tested. Average IFS and OL_{cr} values for the various types of steel are shown in Figure 21. Both nitrogen and phosphorus were shown to be detrimental to toughness. Though this investigation was undertaken to illustrate the advantage of molybdenum grade carburizing steels over MnCr types at similar impurity levels, the results also confirm the relationship shown previously in Figure 20 between fracture toughness and IFS values.

Although the deleterious effect of phosphorus on IFS can be expected, it is not so well known that core nitrogen levels also influence fracture properties. Earlier work published by this laboratory indicated that nitrogen could be deleterious(11). These results are also consistent with the reported use of boron in an

Table 2

Compositions of Steels Used for Investigation of Nitrogen and Phosphorus Effects

Steel Type	Heat	Element, Wt-% C	Mn	Si	Mo	Cr	P	S	Al	N
MnCr	P2906A	0.21	1.30	0.21	<0.005	1.18	0.010	0.008	0.027	0.0018
MnCr+N	P3010	0.21	1.25	0.24	N.A.[a]	1.14	0.007	0.008	0.012	0.0112
MnCr+N	P2974	0.21	1.33	0.27	N.A.	1.20	0.012	0.006	0.007	0.0130
MnCr+N	P2706B	(0.21)[b]	1.61	(0.21)	(<0.005)	(1.18)	0.010	(0.008)	0.032	0.0094
CrMo+N	P2917B	(0.20)	1.62	(0.18)	(0.26)	(0.76)	0.005	(0.008)	0.036	0.0082
CrMo	P2919A	0.20	0.87	0.20	0.25	1.19	0.012	0.007	0.004	0.0019
CrMo+N	P2919B	(0.20)	1.20	(0.20)	(0.25)	(1.19)	0.011	(0.007)	0.006	0.0110
CrMo+N	P2975	0.21	0.86	0.26	0.25	1.16	0.012	0.006	<0.005	0.0119
CrMo	P2976	0.22	0.90	0.26	0.25	1.18	0.012	0.006	0.007	0.0020
MnCr	P2720A	0.20	1.32	0.26	<0.005	1.18	0.006	0.007	0.030	0.0016
MnCr+P	P2720B	0.20	1.33	(0.26)	(<0.005)	(1.18)	0.043	(0.007)	0.029	0.0020
CrMo	P2917A	0.20	1.30	0.18	0.26	0.76	0.005	0.008	0.034	0.0014
CrMo	P2921A	0.20	1.31	0.26	0.25	0.79	0.006	0.006	0.022	0.0018
CrMo+P	P2921B	0.20	1.27	(0.26)	(0.25)	(0.79)	0.044	(0.006)	0.021	0.0018

[a]N.A. = none added and not analyzed.

[b]Parentheses indicate values assumed to be identical to those obtained on Split A.

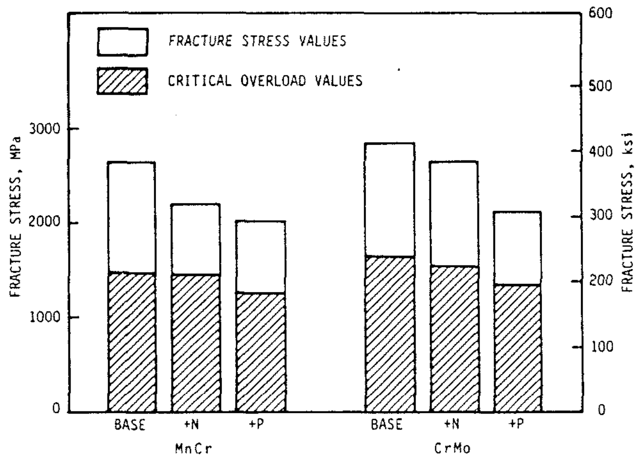


Fig. 21 - Comparison of Impact Fracture Stress (IFS) and Critical Overload Values for MnCr and CrMo Steels with High Nitrogen and Phosphorus Levels

unprotected addition to carburized steels to scavange nitrogen for improved toughness. The effect of nitrogen was not as drastic as that of phosphorus (for the range of N and P levels studied), but the magnitude of the effect was similar to the difference in IFS and OL_{cr} values between the MnCr and CrMo steels. So far the influence of phosphorus and nitrogen on high-cycle fatigue properties has not been determined.

Another alloying factor that has been shown to influence fracture properties is the aluminum content of the steel(11). Results in the upper graph of Figure 22 show an inverse correlation between aluminum content and the IFS values of five different steels. The graph in the lower portion of Figure 22 indicates that the effect of aluminum was actually an indirect effect in that changes in the aluminum levels resulted in variation in grain size. The grain size influence on hardenability (larger grain size produced higher hardenability) resulted in different core microstructures and, hence, differences in the core fracture toughness which registered as lower IFS values for finer grained steels.

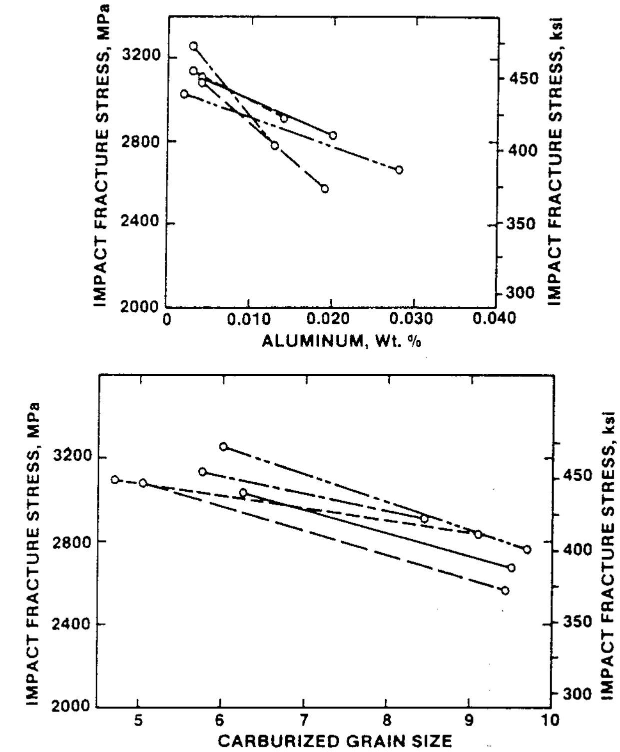


Fig. 22 - Influence of Aluminum on Impact Fracture Stress (IFS) Through Changes in Carburized Grain Size

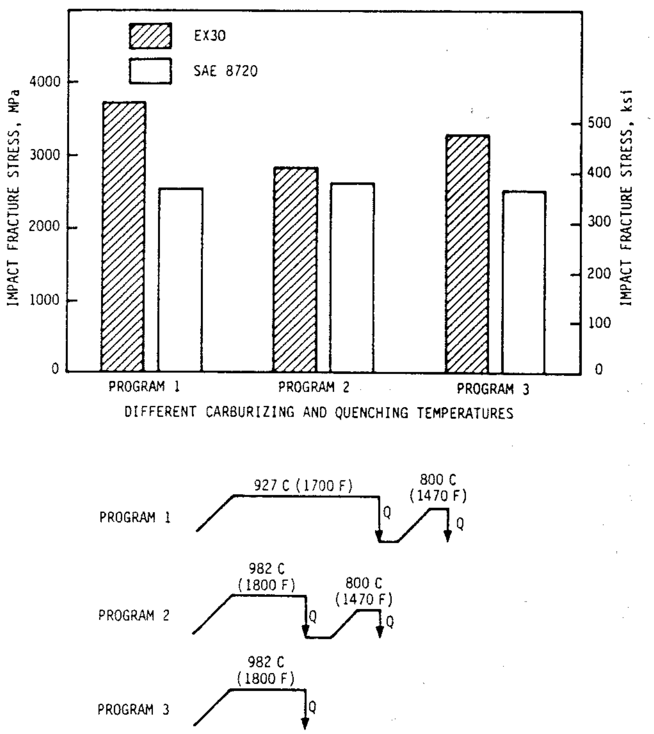


Fig. 23 - Impact Fracture Stress Values for Two Steels as a Function of Processing

The above examples emphasize the influence of composition on IFS results. However, when processing has an effect on core microstructure, changes in fracture toughness can result and differences in IFS values might be expected. Changes in processing temperatures that were shown in Figure 14 to produce changes in fatigue properties also influenced IFS results as shown in Figure 23. The fact that EX30 was sensitive to different processing paths and SAE 8720 was not may be related to the core carbon level and the corresponding differences in Ac_3 temperatures of the steels. These results illustrate the difference between processes that influence only the outer case regions of the carburized part (i.e., shot peening, surface carbon level, retained austenite, etc.,) and those processes that influence both case and core (i.e., quench temperature and quenching rate). Those processes changing only surface characteristics of the case will have a dominant influence on fatigue but a negligible effect on toughness. However, processes that also change properties in the case-core or core regions can be expected to influence both fatigue and toughness results.

Because of the price of materials, one major concern is the extent to which alloy design influences performance. Results shown in connection with Figures 9 through 14 indicated that alloying has a relatively minor role in determining fatigue characteristics. The small test specimen size used for most laboratory testing is not very sensitive to differences in case hardenability and it tends to minimize effects of surface oxidation. These are areas in which alloying makes a significant contribution to fatigue performance. The overall influence of alloying, though, appears to be less important than that of processing to high-cycle fatigue performance. Conversely, alloying will have a primary influence on the fracture characteristics of a carburized steel. Because of the connection between the IFS and OL_{cr}, the toughness is more important in applications where loading is other than pure fatigue. In order to avoid premature fatigue failure under combined loading situations, it is necessary to avoid case cracking which is a toughness related property.

The influence of individual alloying elements on toughness is difficult to quantify because of the multitude of variables that must be controlled. Chromium has been identified in several instances as being detrimental to toughness related carburized properties(2,12). Conversely, nickel has been associated with improved toughness characteristics(1). In order to delineate the influence of molybdenum on fracture properties, the results for a large number of steel heats from prior investigations were evaluated. Values for the IFS for steels with more than 0.10% molybdenum were compared with steels with less than this amount as a function of the core hardenability level. Compositions for these steels are shown in Tables 3a and 3b. Since many investigations were involved, it was not possible to separate

Table 3a

Compositions of High (>0.10%) Mo Carburizing Grades Used in Analysis of Impact Fracture Range (in Figure 24)

Steel Heat[a]	Element, Wt-% C	Mn	Mo	Ni	Cr	Core Hardenability, D_I, mm (in.)	IFS, MPa (ksi)
P2450B	0.11	0.54	0.13	3.38	1.37	152+ (6+)	2920 (424)
P2487A	0.11	0.88	0.80	1.96	0.81	152+ (6+)	2940 (427)
P2471A	0.19	0.77	0.20	--	1.05	56 (2.2)	2970 (431)
SAE 4620	0.18	0.60	0.50	1.62	0.16	43 (1.7)	3070 (445)
SAE 8620M	0.21	0.82	0.16	0.40	0.44	38 (1.5)	2620 (380)
SAE 8620M	0.19	0.86	0.46	0.50	0.52	51 (2.0)	2700 (391)
EX24	0.19	0.90	0.25	0.10	0.52	43 (1.7)	2650 (385)
P2045A	0.20	0.94	0.25	--	0.38	30 (1.2)	2800 (406)
P2045B	0.19	1.02	0.26	--	0.52	41 (1.6)	2250 (327)
P2046B	0.19	1.12	0.26	--	0.54	46 (1.8)	2980 (432)
P2046A	0.19	0.83	0.26	--	0.50	38 (1.5)	2320 (337)
P2048A	0.19	0.80	0.26	--	0.78	43 (1.7)	2390 (347)
P2048B	0.19	0.80	0.26	--	0.92	48 (1.9)	2410 (350)
P2049A	0.20	0.81	0.20	0.55	0.54	43 (1.7)	2760 (400)
P2049B	0.20	0.81	0.52	0.55	0.53	61 (2.4)	2880 (418)
P2841	0.16	0.53	0.26	3.5	0.01	71 (2.8)	2770 (402)
P2842	0.16	0.86	0.53	0.86	0.54	61 (2.4)	2920 (423)
P2873	0.15	0.84	0.73	0.85	0.56	91 (3.6)	2740 (398)
P2874	0.16	0.84	0.53	1.36	0.55	89 (3.5)	2660 (386)
P2552	0.21	0.82	0.28	0.55	0.51	43 (1.7)	2970 (431)
P2553	0.21	0.87	0.32	--	0.56	43 (1.7)	2900 (421)
SAE 4028	0.27	0.80	0.24	0.15	0.14	41 (1.6)	2250 (327)
EX55	0.19	0.99	0.74	1.78	0.65	127 (5.0)	3230 (468)
P2519B	0.20	1.09	0.21	--	0.56	41 (1.6)	2830 (411)
P2520B	0.20	0.88	0.38	--	0.46	46 (1.8)	2910 (422)
P2527B	0.19	0.72	0.21	--	0.96	46 (1.8)	3120 (453)
P2528B	0.18	0.58	0.37	--	0.81	41 (1.6)	2780 (403)
P2447A	0.10	0.66	0.54	1.23	0.61	56 (2.2)	2910 (422)
P2451A	0.07	0.50	0.74	1.80	0.51	66 (2.6)	2830 (410)
P2451B	0.10	0.60	0.80	1.93	0.63	117 (4.6)	3100 (450)
P2447B	0.10	0.77	1.06	2.0	0.81	152+ (6+)	2900 (421)
P2487B	0.11	1.0	0.98	1.96	0.98	152+ (6+)	3220 (467)

[a]P = laboratory heat. Other designations refer to commercial steel heats.

the effects of case depth and surface carbon variables. The results of a least squares fit of the IFS versus D_I data are shown by the bands (representing one standard deviation) at the top of Figure 24. Only a limited amount of data has been obtained on the OL_{Cr} (combined loading) as a function of hardenability. This is shown in the central portion of Figure 24 represented by the scatter band covering the range over which values have been obtained. The parallel relationship with the IFS is very evident. Also shown in this figure is the scatter band for the high-cycle fatigue limits. The results shown in Figure 24 do not include steels with intentional aluminum, phosphorus or nitrogen variations, and the results may be considered representative of a wide range of carburizing grades.

Figure 24 describes the relationship of alloying (or hardenability) to fatigue and toughness properties and clearly illustrates why toughness is important to fatigue performance in combined loading applications. Results presented earlier stressed that fatigue properties were controlled to a greater extent by the processing than the alloying combination or hardenability. Hence, Figure 24 shows no increase in fatigue limit with hardenability. Above the fatigue limit, though, the effect of alloying on the OL_{Cr} value is apparent. Thus it is clear that once stresses above the fatigue limit are encountered, the variables governing performance are no longer those related to processing but, instead, those associated with the toughness characteristics of the steel. Stated differently, the steel can be processed for

Table 3b

Compositions of Low (≤0.10%) Mo Carburizing Grades Used in Analysis of Impact Fracture Range (in Figure 24)

Steel Heat[a]	Element, Wt-% C	Mn	Mo	Ni	Cr	Core Hardenability, D_I, mm (in.)	IFS, MPa (ksi)
P2450A	0.09	0.48	0.10	3.11	1.17	109 (4.3)	2680 (388)
P2435	0.19	1.12	--	--	1.22	64 (2.5)	2850 (414)
SAE 3120[b]	0.18	0.57	0.05	1.68	0.57	38 (1.5)	3030 (439)
SAE 3120[c]	0.19	0.58	0.10	1.70	0.65	51 (2.0)	2850 (413)
P2041A	0.19	0.93	--	--	0.80	33 (1.3)	2250 (326)
P2042A	0.20	1.21	--	--	0.79	41 (1.6)	2080 (301)
P2042B	0.19	1.34	--	--	0.80	51 (2.0)	1960 (285)
P2044A	0.20	1.20	--	--	0.50	30 (1.2)	2610 (378)
P2044B	0.19	1.19	--	--	0.63	36 (1.4)	1840 (267)
P2041B	0.18	1.14	--	--	0.90	41 (1.6)	2100 (305)
P2518B	0.19	1.29	--	--	0.66	41 (1.6)	2570 (373)
P2526B	0.19	0.84	--	--	1.12	41 (1.6)	2680 (388)
P2448A	0.10	0.40	--	3.3	0.68	64 (2.5)	2780 (404)
P2448B	0.12	0.48	--	3.6	0.88	117 (4.6)	2700 (391)
P2449A	0.07	0.76	--	3.4	1.58	152+ (6+)	2960 (430)
P2449B	0.10	0.90	--	3.66	1.70	152+ (6+)	2760 (400)

[a] P = laboratory heat. Other designations refer to commercial steel heats.

[b] Also contains 0.11%V.

[c] Also contains 0.10%V.

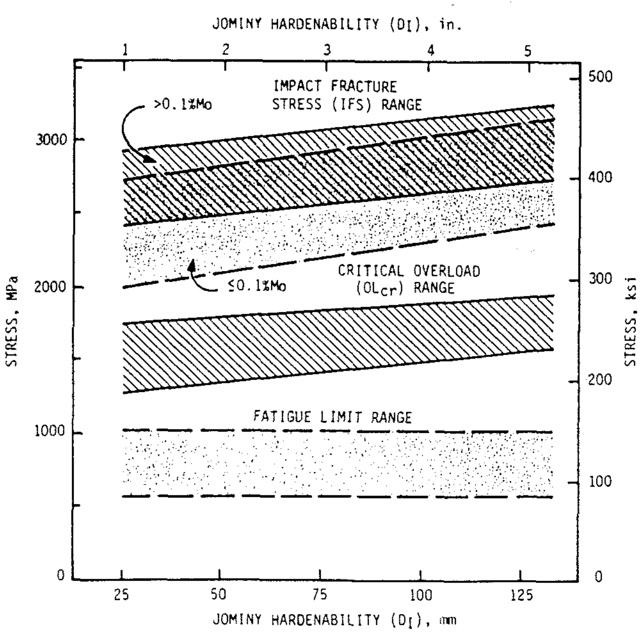


Fig. 24 - Relationship of Core Hardenability to IFS, OL_{cr} and High-Cycle Fatigue Limit

optimum high-cycle fatigue performance, but, to the extent that stresses above the fatigue limit are encountered, the alloy must be designed with adequate toughness.

The illustration in Figure 24 also provides an explanation of how the performance of a carburized steel may be governed by the toughness and yet fail in circumstances which appear to be of a fatigue nature. In many combined loading applications, stresses in the range of the OL_{cr} will be responsible for initiating a crack which will propagate under the fatigue load imposed. Clearly the part will have failed in fatigue, but the failure was a result of insufficient toughness in the form of an inadequate OL_{cr} value for the application. In this illustration improving the fatigue properties would not improve the performance of the part because of the relative independence of fatigue and toughness properties. It is really the toughness of the part which needs to be improved. Hence, when a failure does occur, it is essential to determine whether loads above the fatigue limit were encountered in order to determine which property needs to be improved.

SUMMARY

Specific examples have been used to illustrate the relative independence of high-cycle fatigue and toughness characteristics of carburized steels. Processes such as shot peening, carbonitriding and deep freezing influence only the outer surface of the case and, therefore, only change the fatigue characteristics. Though alloying has only a secondary influence on fatigue properties, it is almost completely responsible for determining the toughness of the carburized part.

From the standpoint of failure analysis, then, it is most important to identify the reason for the crack initiation event, i.e., whether from an inclusion or an overload. It is not adequate to indicate that the crack propagated in fatigue. In carburized materials this is often very difficult. Hence, an adequate analysis may require that the loads on the part be analyzed to determine whether stresses above the fatigue limit are being encountered. Once the loading conditions can be compared with fatigue limit and OL_{cr} values for the material and process involved, then recommendations for proper remedial action can be made.

The research on combined load and impact fracture testing has shown that the value of either the IFS (impact fracture stress) or OL_{cr} (critical overload) can be used as a reliable but relative measure of the toughness of a carburized steel. This testing has also shown that the value of the OL_{cr} stress will be sensitive to the loading conditions encountered in the application.

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