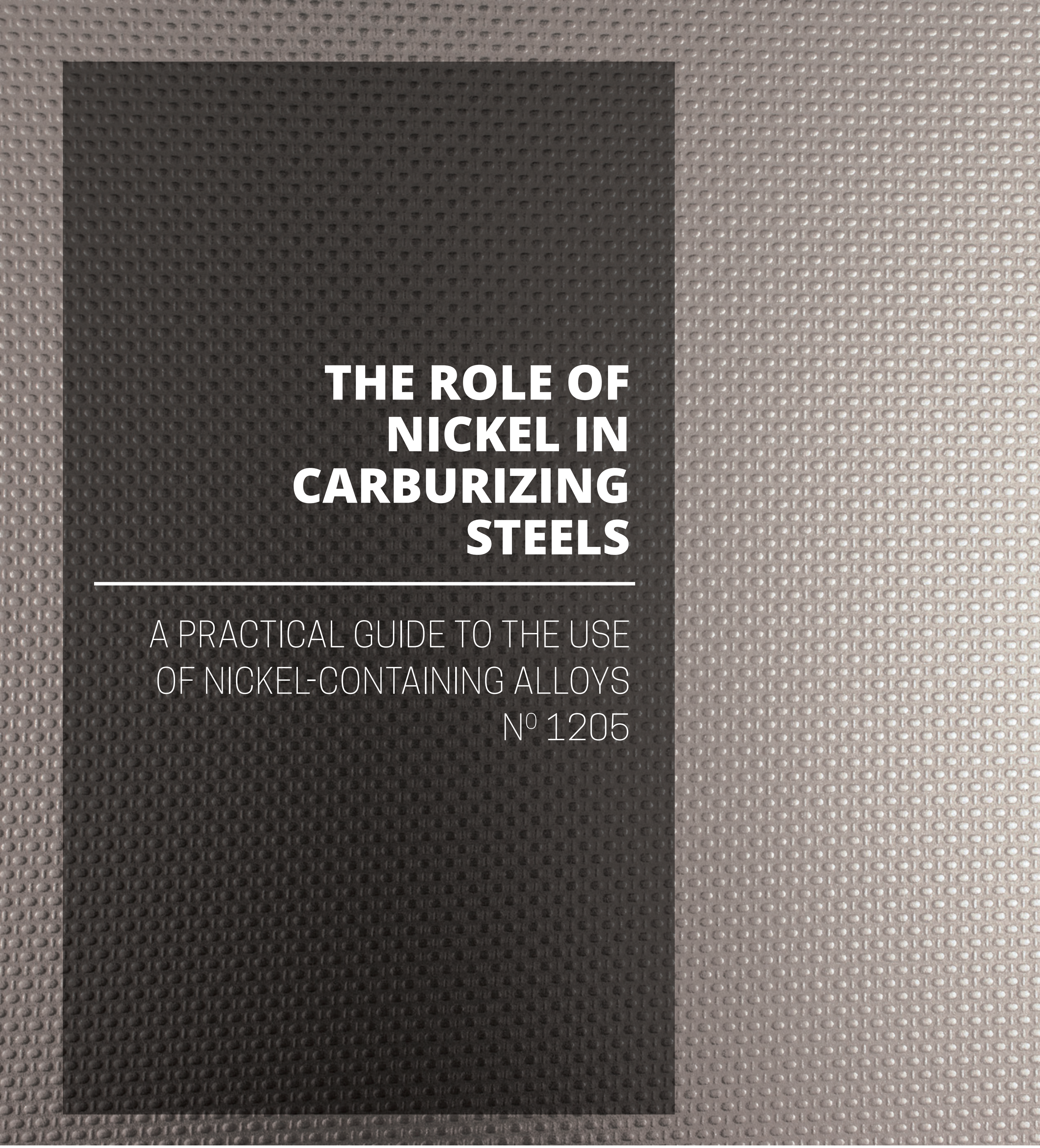

THE ROLE OF NICKEL IN CARBURIZING STEELS

A PRACTICAL GUIDE TO THE USE OF NICKEL-CONTAINING ALLOYS

Nº 1205

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"Although nickel has several favorable effects in carburizing steels, its primary attribute resides in a beneficial influence upon the fracture properties of the iron matrix. Recent alloy studies suggest that in this respect nickel may be unique."

The Role of Nickel in Carburizing Steels

R. J. Johnson, Sales Development
The International Nickel Company, Inc.

In the December 1973 issue of Metal Progress, International Nickel presented the latest of a series of papers describing recent researches on nickel carburizing steels. That paper provides an overview of a decade of study here and abroad of the effects of nickel in such steels. It summarizes the behavior of nickel steels in comparison with non-nickel alloys in laboratory programs involving six different conditions of mechanical loading and attempts an interpretation of the meaning of such comparisons to designers and engineers. As a body, these researches are impressive in their consistent message as to the superiority of carburizing steels containing nickel. The remarkable durability of nickel carburizing steels is attributed by various investigators to two main factors: (a) enhanced toughness of both case and core material in terms of ductility and resistance to brittle fracture, and (b) the presence of retained austenite in the carburized case and the benefits accruing through the strain-induced transformation of this constituent. The following discussion marshalls direct and indirect evidence from many sources in an attempt to elucidate further the mechanisms by which nickel may make its contributions to toughness.

CASE CHARACTERISTICS

Our understanding of carburized steels is complicated by the composite nature of these materials which combine a relatively shallow high carbon case of extreme hardness with a somewhat softer low carbon core or basis metal. The addition of carbon to the outer layers through conventional carburizing processes causes the case and core to respond individually to subsequent hardening operations. This differential response to heat treatment, in turn, causes volume changes which have a major influence upon the level and distribution of residual stresses in the finished parts. It is believed that residual compressive stresses are developed in the case and that these stresses are beneficial in that they tend to offset applied tensile loads thus improving durability. Although the actual level and distribution of residual stress is related to geometry, steel composition, heat treatment and the effects of finishing operations, we have taken the view that for a given geometry and processing the differences in residual stress will not obscure other influences of chemical composition and microstructure as discussed below. Krotine notes that the major influence of the residual stress is to pre-load the system and in this respect merely contribute to case-core interactions developed under applied loads.

The outer or higher carbon case portion of carburized steels generated by conventional processes is not homogeneous in chemical composition or microstructure. Since the carbon is introduced at the surface of the steel at elevated temperatures, the physical laws governing diffusion require a carbon concentration gradient over the surface to core or basis metal interval. This produces a marked difference in the strength, ductility and wear resistance of the steel in the carburized surface layer. Secondly, the higher carbon contents of the case region affect austenite to martensite transformation characteristics to the extent that ordinary hardening operations can result in the retention of substantial quantities of austenite. Normally, some austenite persists after the final tempering treatment, and depending upon the carbon and alloy content of the case may run as high as 50 percent by volume. Hence, consideration of the deformation behavior of the case material must include an appreciation of the retained austenite as well as the martensitic matrix.

It is the aim of most commercial practices to produce carburized cases which are essentially martensitic with the admission of some retained austenite, the amount depending upon the end-use application. A minimum hardness of 58 Rc is frequently seen in specifications, and this precludes significant quantities of softer transformation products such as bainite or pearlite which can adversely affect performance, especially under the heavy contact loads applied to many gears and bearings. The grain size of carburizing steels is controlled by deoxidation practices employed in treating the molten metal so that the grain size of both case and core ordinarily remains uniformly fine, ASTM No. 7-9. However, there can be important differences in the morphology of the martensite within the grains depending somewhat upon the carbon content and final heat treatment. Recent research in this area indicates that higher carbon martensites are coarser in texture,

TABLE I

Ductility of High Carbon and Carburized Steels

Steel		Tensile Reduction In Area, %	Longitudinal Strain in Bending, %
High Carbon			
40XX (.25Mo)	0.85C	0.10	0.70
	0.95C	0.10	0.69
16MnCr5 (1Mn-1Cr)	0.95C	0.75	0.80
	1.05C	0.50	0.75
46XX (1.7Ni-.2Mo)	0.75C	0.40	1.55
	0.85C	0.15	0.84
48XX (3.4Ni-.2Mo)	0.75C	0.94	2.18
	0.85C	0.67	2.00
Carburized			
4027 (.25Mo)		5.5	7.0
16MnCr5 (1.2Mn-1Cr)		6.5	8.0
4620 (1.7Ni-.2Mo)		8.0	10.0
4817 (3.4Ni-.2Mo)		16.0	15.0

more highly stressed internally and lower in ductility. These are reasons why heat treaters attempt to limit case carbon contents to around 0.90 percent.

At this carbon level all of the standard carburizing steels contain retained austenite after ordinary quench and temper heat treatments. Some retained austenite persists even after refrigeration at −321°F. Specific information on the properties of carburized cases is scant, but the work by Krotine, McGuire, Ebert and Troiano provides helpful insight. These studies featured high carbon steels designed to simulate carburized cases in terms of chemical composition and response to heat treatment. Precise measurements of mechanical behavior under tension and bending loads were made on these high carbon through-hardening alloys and their conventionally carburized counterparts with the results given in Table I. The higher ductility values for the carburized steels are ascribed to case-core interaction which will be described later. Tensile stress-strain curves for the high-carbon steels are depicted in Figure 1 showing that regardless of carbon content, strength and ductility increase with nickel content.

RETAINED AUSTENITE

Ordinarily, processing is controlled so that the amount of retained austenite in carburized parts is less than about 40 percent because excessive quantities of this soft constituent may lead to rapid component wear and loss of working dimensions. The retained austenite found in the carburized cases on quenched and tempered finished parts is essentially unaffected by the temperatures normally encountered in service, say −50F to +350F. This is because interruption of the austenite to martensite transformation on quenching has a stabilizing effect on the austenite. Upon holding at room temperature this effect becomes more pronounced with time so that after several hours the retained austenite is quite resistant to further transformation on resumption of cooling. In fact, temperature reductions well below ambient are required to induce further transformation in tempered parts as indicated in Table II.

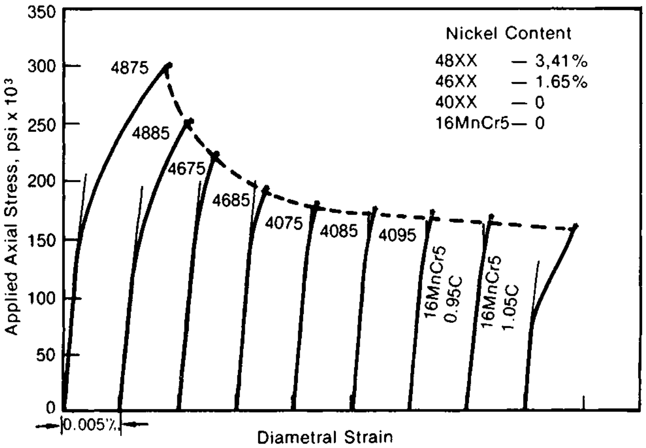


Fig. 1—Applied Axial Tensile Stress vs. Diametral Strain Curves for High Carbon Steels. (Krotine)

Some of the retained austenite does decompose during aging at room temperature but the amount so transformed is slight, no more than a few percent, and much of this occurs within two hours after the quench. The resultant small dimensional changes are generally not of commercial significance, but they may be in certain high precision end-use applications. The tempering cycles ordinarily employed in finishing carburized parts further the process of stabilization, and the general practice is to temper parts as soon as conveniently possible after quenching.

Numerous investigations have demonstrated that retained austenite will transform to martensite under applied loads and that the volume of austenite transformed is proportional to the amount of strain. The rate of transformation in carburized steels does not appear to be greatly influenced by alloy content as indicated in Table III. Reduction of retained austenite content by refrigeration prior to testing results in a slight deterioration of ductility.

The retained austenite contributes to the bend ductility of carburized steels as shown in Figure 2. This

TABLE II

Percent Retained Austenite In Carburized Steels Before And After Refrigeration In Liquid Nitrogen

Treatment	4027 (.25Mo)	16MnCr5 (1.2Mn-1Cr)	4620 (1.7Ni-.2Mo)	4817 (3.4Ni-.2Mo)
Carburized at 1700F, Oil Quenched and Tempered at 350F	20	26	16	24
Carburized at 1700F, Oil Quenched and Tempered at 350F and Refrigerated at −321F	16	18	10	13

contribution is the resultant of several factors related to the strain-induced transformation of austenite. Since the work-hardening rate of martensite is higher than that of austenite, a negative effect is introduced as fresh martensite is generated from the retained austenite under strain. This is offset by positive effects rising from a 3 to 4% volume increase which accompanies the austenite to martensite transformation. Firstly, this volume increase continuously supplements strain and thus delays the development of the critical failure stress. Secondly, the volume increase raises compressive stress in the case which is also favorable. Thus it follows that the availability of austenite for strain-induced transformation is generally beneficial, and the degree of its enhancement of ductility depends in a large measure upon the amount available.

Further to the above, it has been observed that contact loads of the type encountered in gear and bearing applications can result in metal flow and cold working with concomitant surface leveling, strengthening and improvement of wear resistance. Studies in our laboratory have confirmed these observations for carburized 8617 and 4620 steels. For example, 4620 containing 23 percent retained austenite was subjected to rolling contact fatigue of one million cycles under a Hertz stress of 400,000 psi. Subsequent X-ray inspection of the bearing path showed austenite contents in the order of 7 to 13 percent. The effect was superficial in that at a depth of 0.005 in. below the surface there was no difference in austenite content between the worked and unworked areas. A similar investigation involving 8617 steel revealed a surface hardness increase from 57 to 64 Rockwell C based upon microhardness determinations. The retained austenite content dropped from 15 to 25 percent to as low as eight percent under heavy rolling loads. This suggests a substantial upgrading of contact surfaces through cold-working and the generation of new martensite via strain-induced transformation of the retained austenite. Additionally, it seems likely that the microstructure of the worked area will be finer in texture and therefore more resistant to the initiation and propagation of pits or cracks. These impressions support findings by Troiano and Razim and most recently by Howes regarding the benefits of retained austenite in carburized cases.

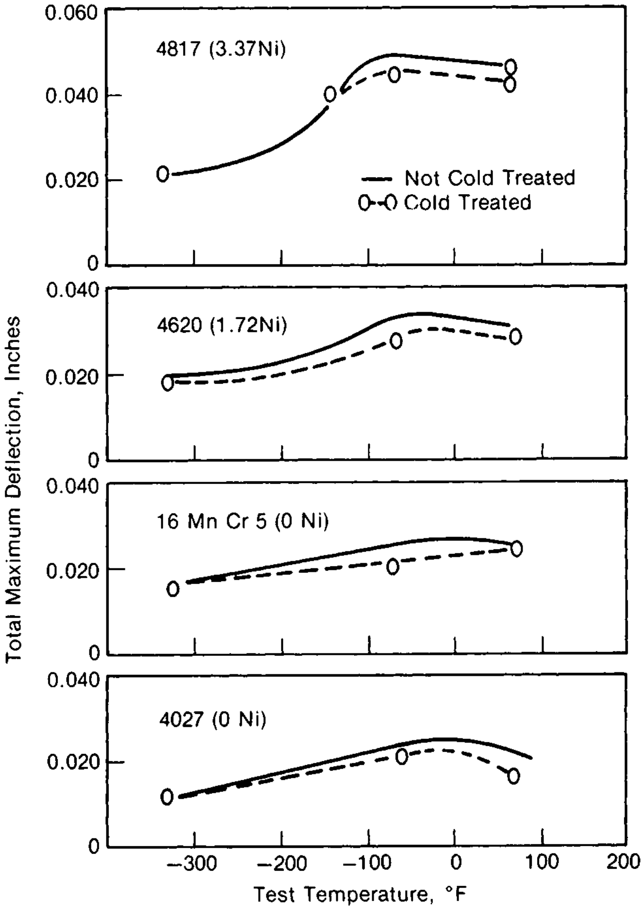


Fig. 2—Effect of Cold Treatment on Bend Ductility Transition Curves for Carburized Steels. (Krotine)

It is appropriate at this point to emphasize that the benefits of retained austenite apply for both non-nickel and nickel-containing steels. The process of austenite deformation and transformation under load simply carries further in the nickel steels as permitted by the higher intrinsic ductility of martensites alloyed with nickel.

TABLE III

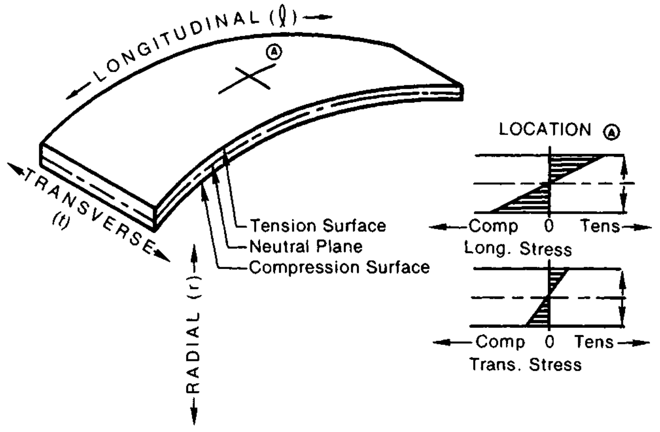
Rate Of Strain-induced Transformation,Of Retained Austenite In Carburized Steels

	4027 (.25Mo)	16MnCr5 (1.2Mn-1Cr)	4620 (1.7Mn-.2Mo)	4817 (3.4Ni-.2Mo)
Volume percent of retained austenite transformed per percent longitudinal strain in bending (tension side)	9.5	10.5	8.0	7.5

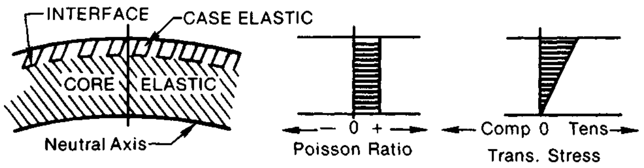
CORE CHARACTERISTICS

In the preceding description of the metallurgical characteristics of the material comprising the case portion of carburized parts we have alluded to rheological interactions between the case and core components under load and to the complex stress states which control fracture and the performance of such parts in service. These interactions derive from shifts in Poisson's ratio, or the contractural tendencies of the case and the core, as the test specimen or machinery component is loaded. Ebert and McGuire have developed the sequence of events in terms of models of the type shown in Figures 3 and 4.

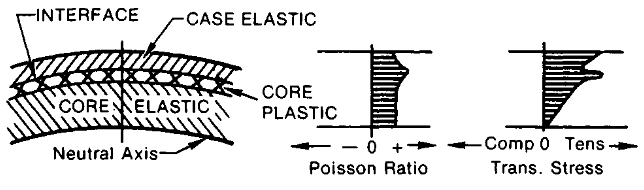
According to Krotine's description, when the applied stress causes plastic flow in the softer core while the case is still behaving elastically, Poisson's ratio for the core will deviate from 0.3 approaching 0.5, while that of the case remains near 0.3. Thus the core will tend to contract more than the case, and transverse stress will be generated under requirements for strain compatibility, especially at the case-core interface. This produces a tensile triaxial stress state in the core which places a premium on core toughness in resisting crack initiation. The situation resembles the stress state produced in mechanically notched members.



a. Bending directions and schematic stress distributions



b. Distribution of Poisson ratio and transverse stress on tension side of a bent carburized bar behaving elastically (schematic)



c. Distribution of Poisson ratio and transverse stress on tension side of bent carburized bar after onset of plastic flow at case-core interface (schematic)

Fig. 3—Schematic Illustrations of Basic Concepts Regarding Transverse Stress Distributions in Bent Carburized Bars. (McGuire)

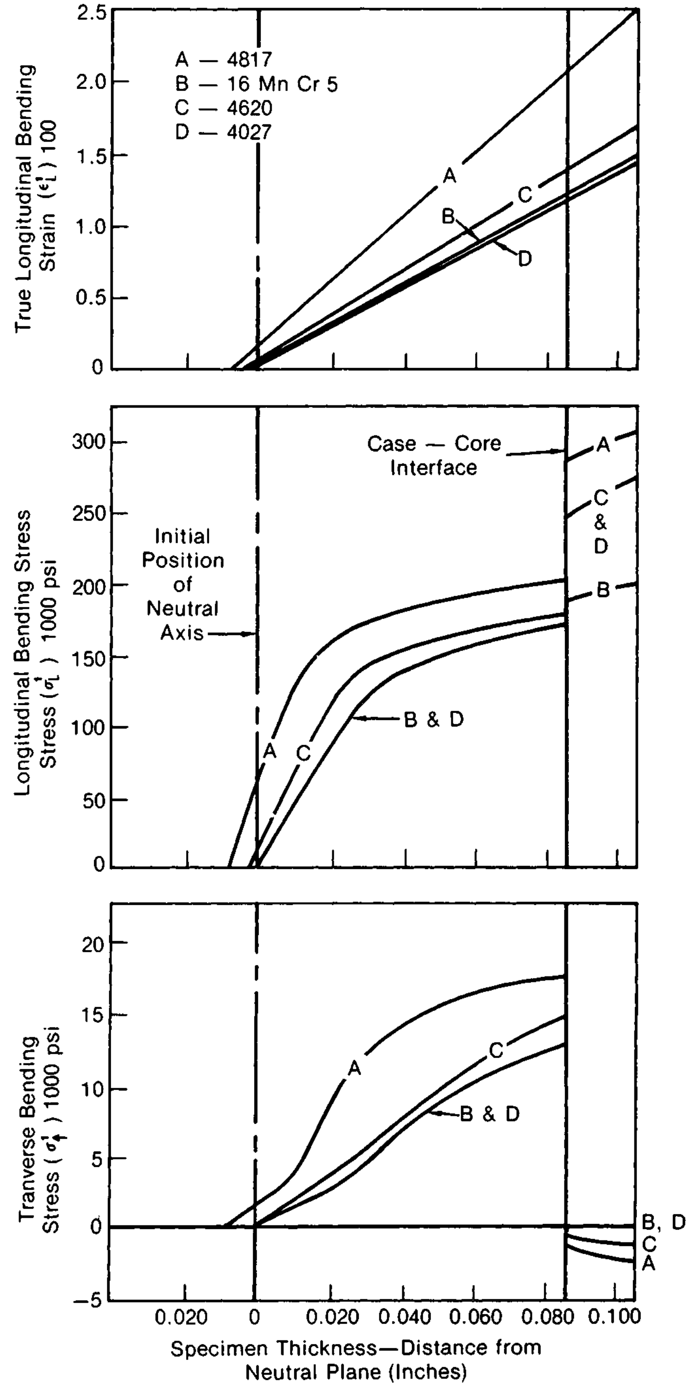


Fig. 4—Comparison of Stress Distributions of Various Carburized Steels at Fracture. (McGuire)

Figure 5 compares temperature transition data for several steels showing the beneficial influence of nickel content on core properties and the capabilities of identical steels as carburized.

Although uniformly martensitic core microstructures have the best combination of strength and ductility, such structures frequently are not obtained in commercial practice. Figure 6 shows the influence of partial transformation to ferrite which could occur as a result of marginal hardenability or slack quenching. In this work Ebert carburized tensile specimens and treated them as follows to produce controlled amounts of ferrite:

Reheat To 1500F

a) Oil quench to 1200F, hold 45 minutes, oil quench to room temperature. Mixed structure.
b) Oil quench to room temperature. Martensitic structure.

The variation in transition temperature clearly demonstrates that the fully martensitic core provided the case-core composite with higher toughness.

In the foregoing we have shown that ultimately the performance of carburized machinery components depends upon the fracture toughness of both the case and the core, and that nickel directly benefits the behavior of these individual elements and the composite as well. If we look beyond residual stress patterns, retained austenite effects and rheological interactions between case and core the matter is reduced to consideration of the ductility of martensites at two carbon levels. What, then, can be postulated as mechanisms to explain the observed toughening effect of nickel in these constituents?

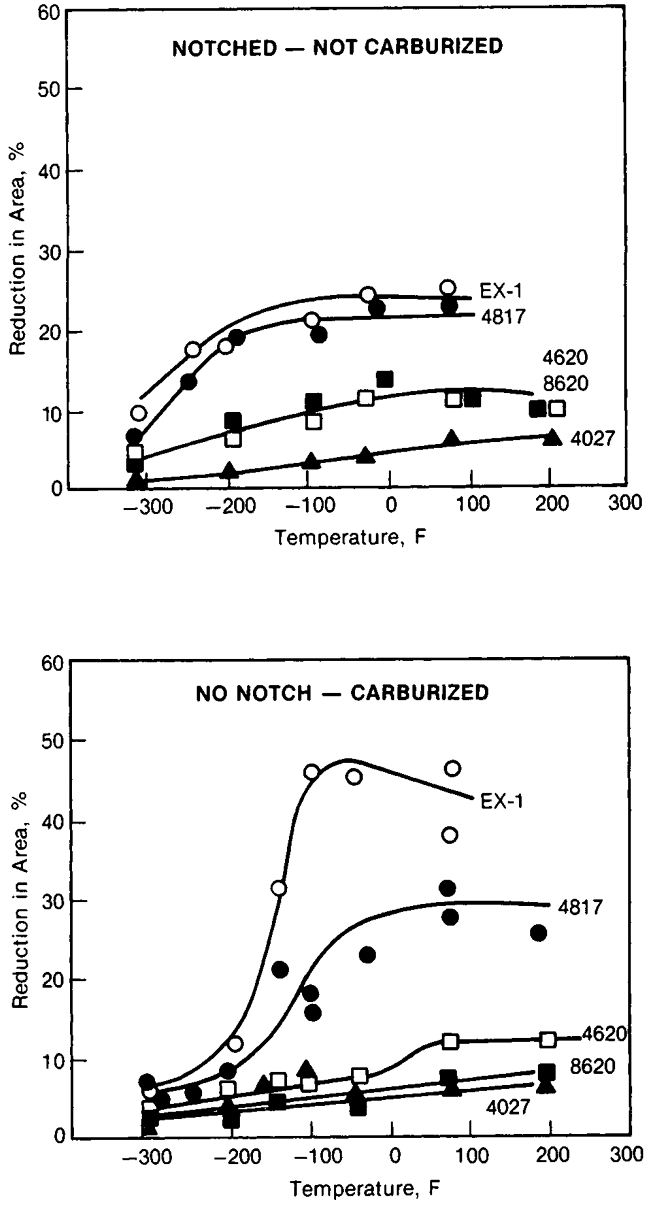


Fig. 5—Temperature Transition Curves for Various Carburizing Steels Tested in Tension. (Ebert)

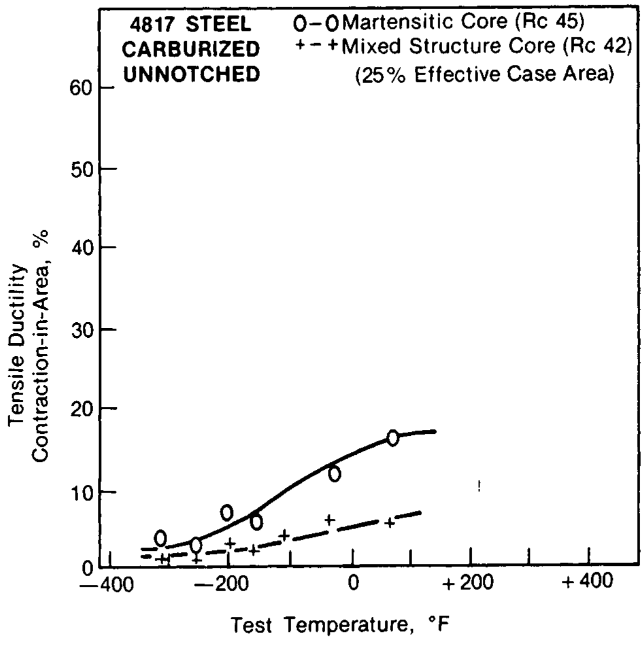


Fig. 6—Ductility Transition Curves for Carburized 4817 Steel with Two Different Core Microstructures. (Ebert)

IRON-NICKEL STUDIES

The general relationships of nickel and iron have been studied for many years and much work has been done in delineating influences on iron allotropy and the characteristics of the various transformation products, the latter gaining much with the recent advent of electron microscopy. Other parameters such as grain size and deformation mode have been examined, and it now appears that an explanation of the effect of nickel on the fracture toughness of steel involves a combination of several independent though interrelated factors. Much of the research in this area has been conducted on high purity binary and ternary systems in the interests of simplicity and clarity. It is possible to relate findings from these studies to commercial alloys in a general sense only, and interpretations applicable to carburized and hardened steels are even more difficult. This is because the quenched and lightly tempered structures characteristic of carburized steels represent metallurgical systems which are complex constitutionally and far from equilibrium in various aspects. For example, the martensites comprising case and core differ in terms of dissolved carbon and carbide precipitates, both of which are strong in their effects upon mechanical properties.

MARTENSITE RESPONSE TO TEMPERING

Referring initially to the martensite comprising the core, there are indications that carbon at the nominal 0.20 percent level remains mostly in solid solution even after tempering at about 300F. It appears that tempering temperatures higher than those normally used for carburized parts are required for decomposition of such low carbon martensite via precipitation of epsilon carbide and the eventual formation of cementite in a ferritic matrix. One is left with an analysis of the fracture behavior of a martensite of low tetragonality containing modest amounts of carbon and alloying elements in solid solution with no second phase present as carbide or retained austenite. Since there is little evidence to the contrary, it is assumed that the alloying elements are uniformly distributed in the iron. We would also conjecture that those aspects of fracture mechanics involving the interstitially dissolved carbon are comparable in steels such as 8620, 4620 and 4817. Hence, the matter may possibly be reduced to consideration of the effects of alloying elements on the fracture strength of iron. This subject will be discussed later.

The driving force for martensite decomposition increases with carbon content so that there is a tendency for the martensite of the high carbon steel comprising the case portion of carburized and hardened material to precipitate some carbon during the quench. This formation of carbide continues very slowly on holding near room temperature after the quench and will be accelerated somewhat during the tempering treatment. However, the relatively short times and low temperatures normally employed in tempering carburized components do not permit equilibrium, and much of the carbon remains in solution.

Studies such as those of Langer and of King and Glover indicate that alloying elements interact with the dissolved carbon and that nickel tends to decrease the stability of epsilon carbide whereas chromium and molybdenum have an opposite effect. Furthermore, nickel seems to retard the tempering reaction so that a given tempering cycle might be expected to result in less epsilon carbide precipitate and more carbon in solution in alloy martensites containing a preponderance of nickel.

These observations relative to the chemical and microstructural changes which occur during tempering are complimented by a partial relaxation of the microstresses associated with the formation of martensite during the quench. Stress relaxation is accompanied by marked increases in strength and ductility.

It remains then, to consider the effects upon case mechanical properties of (a) the noted drop in the amount of carbon in solution in the martensite and (b) the generation of an increased quantity of epsilon carbide. As shown by Winchell and Cohen, the strength of martensite is largely dependent upon carbon content. It is known that low carbon martensite is more ductile than its high carbon relative, hence it may be assumed that the ductility of the case material will be upgraded as this martensite loses carbon from solution during tempering. Here, it is tempting to advance the notion of weighing the opposing influences of the alloying elements normally found in carburizing steels on the progress of the tempering reaction. Unfortunately, the information available does not permit positive statements on this line.

Tending to offset the beneficial effect of decreased carbon in solution in martensite is an associated increase in the amount of epsilon carbide which will tend to raise strentgh and hardness and lower fracture toughness. This effect is related to lattice coherency strains or the compatibility of the crystal structures of the carbon-containing iron matrix and the epsilon iron carbide precipitate. King and Glover reason that since nickel increases the lattice spacing of iron, the coherency strain should be lower in such alloys. Since the matrices of nickel steels better accommodate the presence of epsilon carbide, it follows that the cases of carburizing steels which contain nickel as the major alloying element should be more ductile.

This portion of the discussion is closed with a comment by Nutting who notes that knowledge of the relationship of the tempering mechanism to ductility is rudimentary. There is no quantitive understanding, and the role of alloying elements on the changes which occur during aging at room temperature or on tempering is an important topic for future study. Kerlin observed that further elucidation of the problem of martensite decomposition seems to await the development of research techniques more powerful than those presently available.

MATRIX BEHAVIOR

The toughening effect of nickel in iron is now widely recognized, and recent reports such as those by Wulleart, Jolley and Floreen have done much to identify the mechanisms responsible for the observed improved mechanical properties of nickel-containing ferrites. Since ferrite is the continuous phase in tempered martensite, the nickel toughening mechanisms established for ferritic and pearlitic steels ought to be examined as they might relate to the improved properties of carburized and hardened nickel steels. The main parameters to be considered include solid solution strengthening, grain refinement, and the influence of nickel on deformation and fracture.

SOLID SOLUTION STRENGTHENING

We have already touched briefly on interstitial solutes and their possible interaction with substitutional alloy solutes in relation to tempering reactions and martensite decomposition. The behavior of substitutional alloy elements can be attributed in part to interstitial binding energies involving carbon and nitrogen atoms. Alloying elements having interstitial binding energy larger than that of iron tend to inhibit precipitation. This leads to smaller particles than would exist in iron without the substitutional element. Moving dislocations, in encountering these small particles, concentrate slip on a few widely spaced slip planes. The alloys are embrittled in this condition due to the formation of massive dislocation pile-ups within the crystallite and large slip steps at the grain surfaces. Nickel has the opposite influence. Lutjering and Hornbogen show that increasing nickel content in iron leads to larger carbide particles which results in more homogeneous, uniformly distributed slip. This has the effect of increasing ductility.

McEvily proposed that since nickel slightly distorts the ferrite lattice, carbon in solution may become trapped at these strain centers and therefore not contribtue to dislocation locking. This would lower the yield strength and alter dislocation velocity. For example, a decrease in flow stress of five percent due to the presence of nickel would increase the dislocation velocity for a given stress by about 400 percent, enough to influence fracture under dynamic loading by blunting cracks. Experimental evidence for a decrease in the magnitude of dislocation locking with nickel has been provided by Stoloff, Gladman and Pickering, Tetelman and McEvily, and Jackson and Winchell. Figure 7 depicts the relationship between nickel and the yield stress in some iron-carbon alloys.

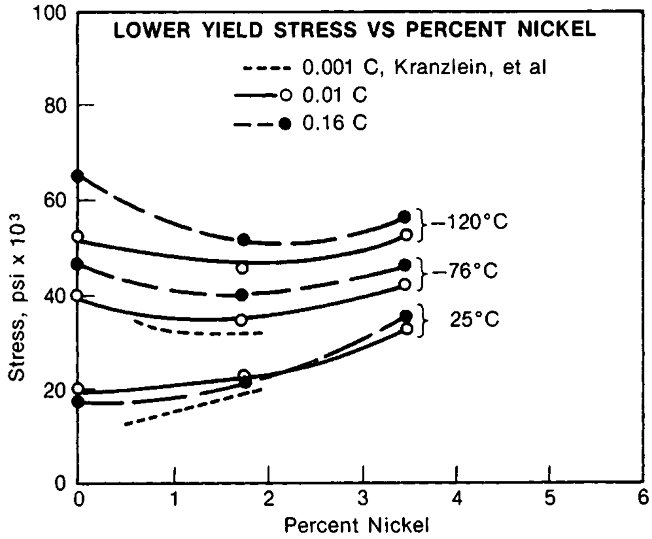


Fig. 7—The Effect of Nickel on the Yield Stress of Iron-carbon Alloys. (Stoloff and Kranzlein)

In addition to the above involvement with interstitial solutes, nickel attributes solid solution hardening due to its larger atomic size and the resultant strain created by lattice misfit. The solid solution strengthening of iron by nickel has been studied by Davies and Ku. Other alloy solutes have a similar effect on iron but by comparison with the powerful strengthening influence of carbon the contributions of alloy solutes are small.

GRAIN REFINEMENT

Nickel is an austenite stabilizer and as such lowers the temperature at which austenite decomposition will occur on cooling. Normalized steels benefit from the

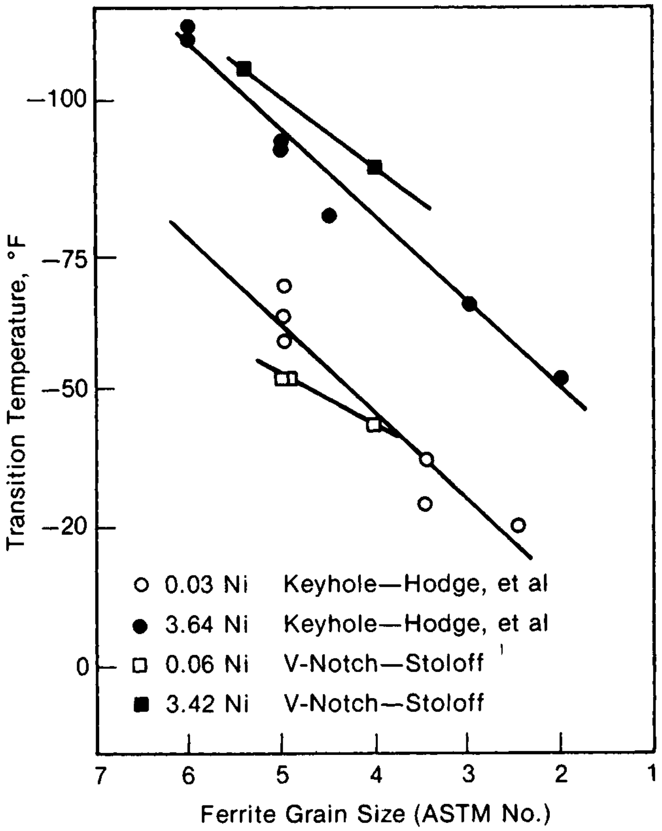


Fig. 8—The Effect of Ferrite Grain Size and Nickel on the 40 ft-lb Transition Temperature of a 0.02 Percent Carbon Steel. (Hodge and Stoloff)

resultant grain refinement in terms of enhanced toughness. However, the grain size of quenched and tempered steels is largely controlled by austenitizing temperature and time, with certain limitations imparted by aluminum deoxidation. Since most carburizing is done in the range 1650-1700°F, both case and core grain size remains fine. Above this range, grain coarsening is likely and mechanical properties may be affected adversely. Grange has proposed modified heat treatments featuring very short austenitizing times for grain refinement in çarburizing steels. In their studies Gensamer, Hodge and Stoloff (Figure 8) all observed a pronounced downward shift in ductile-to-brittle transition temperature (DBTT) associated with nickel induced grain refinement of ferritic steels. However, this grain refinement could not account for all the reduction in DBTT, and it was concluded that *there is an intrinsic effect of nickel in lowering DBTT beyond that associated with reduced grain size.*

FRACTURE TOUGHNESS

Of the elements commonly used for alloying steel, only manganese and nickel improve both room temperature yield strength and notch impact properties. According to recent work by Jolley, manganese only increases the toughness of Fe-Mn-C alloys by refining carbides. It has no toughening effect on carbon-free iron. Thus it appears that nickel may be unique in its beneficial influence upon the fracture properties of iron. The lowering of DBTT beyond that attributable to grain size refinement has been explained in the following terms:

(a) Nickel influences the yield behavior by facilitating cross slip (Figure 9). The result is a more homogeneous distribution of slip throughout the metal crystals, and this is reflected as increased toughness.

(b) Nickel decreases the dependence of yield strength on temperature (Figure 10).

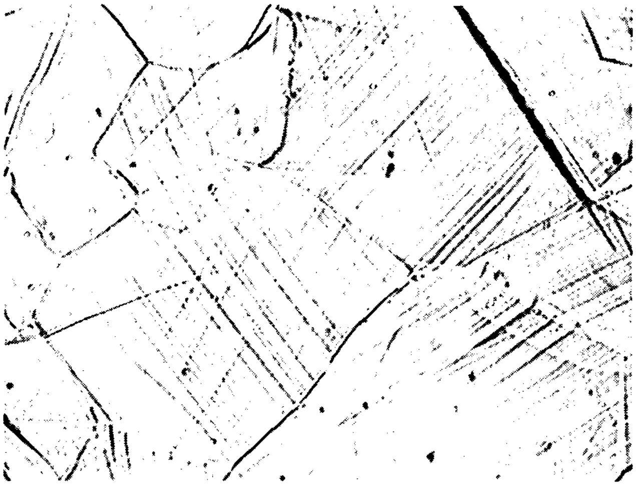
(c) Nickel decreases the dependence of yield strength on strain rate (Figure 11).

(d) Nickel raises the cleavage strength (Figure 12).

The theoretical aspects ofthese complex and interrelated phenomena have been discussed by Brown and Ekvall, Arsenault, Jolley and (especially) Wulleart.

The information provided by the research work referenced herein has been useful in advancing our understanding of the behavior of steels under high strain rates, low temperatures and complex stress states. It has also been helpful in explaining, at least in part, why the various steels used in carburized components respond differently to unusual loading situations and why nickel steels are frequently selected for service where durability and safety are important.

While the practical benefits of nickel in carburizing steels have been appreciated for many years, in the main, users have held only qualitative impressions as to its attributes. Recently, however, designers and engineers have insisted on more quantitative information which is now forthcoming. Our purpose here has been to rationalize some of the more recent scientific investigations of iron-nickel alloys as they might further our understanding of the behavior of carburizing steels. We hope that the researchers cited will be tolerant of this extension of their conclusions.



Surface slip traces on chemically polished iron sheet tensile specimen strained 5 pct at −320F (−196C). Slip traces are planar and restricted to one type of slip system. Magnification 175 times.

Surface slip traces on chemically polished Fe-3.28 pct Ni sheet tensile specimen strained 5 pct at −320F (−196C). Slip traces are wavy. Magnification 215 times.

Fig. 9—Effect of Nickel on the Deformation Mode of Iron at −320F (−196C). (Jolley)

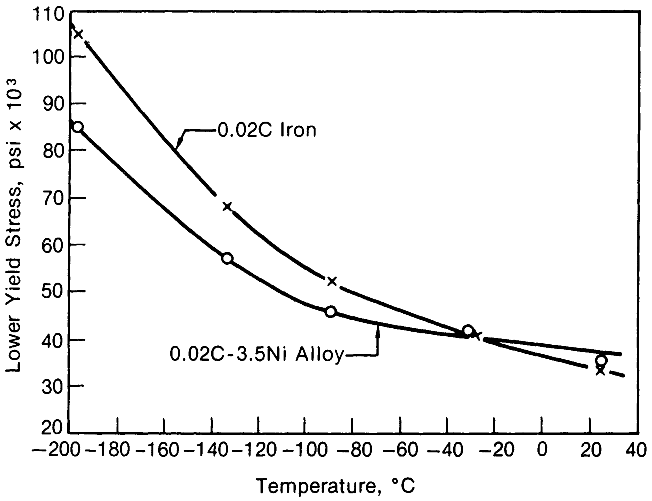


Fig. 10—The Lower Yield As A Function Of Temperature At A Strain Rate Of 2.6 × 10^{-3} Sec^{-1} For The 0.02C And 0.02C-3.5Ni Steels. (Wulleart)

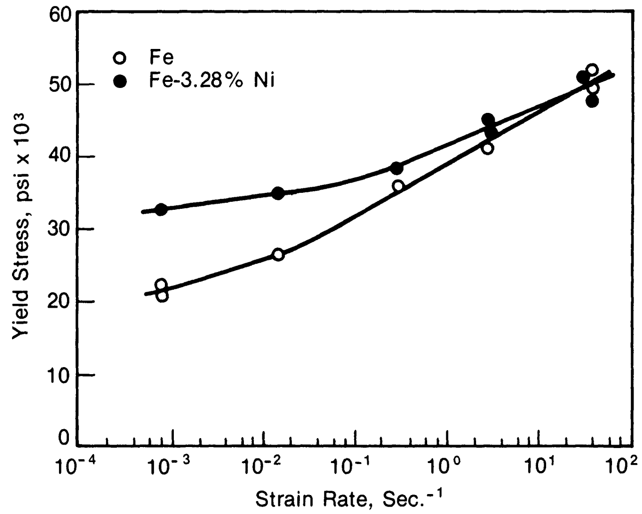


Fig. 11—Strain Rate Dependence of the Room-Temperature Lower Yield Stress of the Iron and Fe-3.28 pct Ni Alloys. (Jolley)

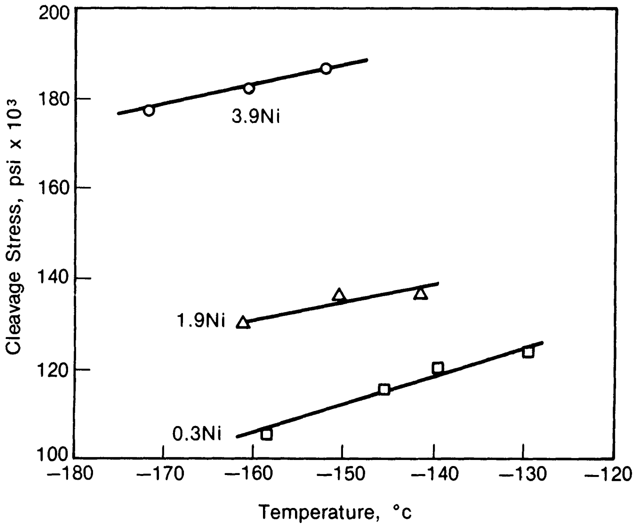


Fig. 12—Effect of Nickel on the Cleavage Strength of Several Low Carbon Irons. (Floreen)

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