THE EFFECT OF INTERNAL SHRINKAGE DISCONTINUITIES ON THE FATIGUE AND IMPACT PROPERTIES OF CAST STEEL SECTIONS

RESEARCH PROJECT AT CASE WESTERN
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Steel Foundry Research Foundation

THE EFFECT OF INTERNAL SHRINKAGE DISCONTINUITIES ON THE FATIGUE AND IMPACT PROPERTIES OF CAST STEEL SECTIONS

SCOPE OF THE RESEARCH REPORT

Studies have previously been published by the Foundation relative to the effect of internal shrinkage on the properties of cast steel sections under static loading, The studies of this report are an extension of the previous studies except that the type of loading is confined to dynamic loading with investigation being made on cast steel sections containing shrinkage. Tests are made in bending and tension impact and bending and torsion fatigue.

The objectives of the research were to produce internal shrinkage in cast steel sections with various degrees of severity as specified by reference radiographs E-71 of ASTM. The final step was to determine the effect of the shrinkage discontinuities on the impact and fatigue properties of the cast steel sections. These studies were undertaken with the hope that design and materials engineers will take a realistic view of factual information in the interpretation of discontinuities by radiographic determinations.

SUMMARY OF THE RESEARCH REPORT CONCLUSIONS

The results of tests made on cast steel sections under dynamic loading in impact and fatigue provided significant information concerning the influence of discontinuities on the impact and endurance limit properties of cast steel.

1. The presence of shrinkage discontinuities reduces the level of fibrous fracture energy in bending impact specimens. This reduction is greater for normalized and tempered than for quenched and tempered cast steels. The amount of reduction increases with the severity of shrinkage.

2. The presence of shrinkage discontinuities has a greater effect on the behavior of cast steel sections tested in tension impact than in bending impact. This is particularly true for the slight form (Class 2) shrinkage that is located close to the centerline. Since this shrinkage does not reach the surface, it does not exert as damaging an effect on impact behavior in bending as in tension. The presence of shrinkage discontinuities in tension impact markedly lower the level of fiber fracture energy and raise the transition temperature noticeably.

3. The bending fatigue properties of cast steel sections were reduced because of the presence of shrinkage discontinuities. However, only a small difference in fatigue behavior existed because of Class 2, E-71 ASTM internal shrinkage. Only slight variations existed between Class 2 and the much more severe Class 6 shrinkage. The fatigue properties were considerably reduced, however, when both Class 2 and Class 6 shrinkage extended to the surface of the test specimen.

4. The presence of Class 2 and Class 6 internal shrinkage reduces to an appreciable extent the torsion fatigue strength of cast steel sections. The decrease in the ratio of the alternating shear stress to tensile strength at the endurance limit is about 17 percent for Class 2 shrinkage and 32 percent for Class 6 shrinkage for the high strength, quenched and tempered cast steel. The decrease was not so great for the lower strength annealed cast steel ; namely, 15 percent for Class 2 shrinkage and 20 percent for Class 6 shrinkage.

May 1969

PREFACE to the RESEARCH REPORT

This report continues the Steel Foundry Research Foundation's quest for factual information as to the effect of discontinuities on the load carrying ability of steel castings. The studies have been undertaken along two paths to reach the goal: 1) a study of the effect of the discontinuities concerning cast steel sections(1, 3, 5) and 2) studies on commercial steel castings containing discontinuities.(2,4)

It was learned by studying entire steel castings that the degree of severity of discontinuities, no matter how severe they were, had no effect on the load carrying ability of the casting unless the discontinuity was located precisely at the position of maximum stress concentration. Also, the presence of a severe surface discontinuity did not change the location of fracture upon destructive testing of the casting, from the stress concentration location dictated by Stresscoat and strain gage analysis.

Testing of casting sections refers to the casting in steel of slightly oversized tension, fatigue and impact specimens containing discontinuities followed by machining and grinding of the specimens to dimensions and undertaking the static or dynamic testing. These sections are small, and it is difficult to secure the desired size of the discontinuity. In most cases the surface discontinuities tested(3,5) were greater in severity than permitted by the authorized ASTM E-125 Reference Photographs for Magnetic Particle Indications.

The studies covering internal shrinkage of a previous report(1) and this report relied primarily on Class 2 and Class 6 shrinkage as determined by ASTM E-71 Reference Radiographs for Steel Castings up to 2 inches thick. In certain cases the internal shrinkage was brought to the surface of the casting section (test specimen) by machining. It was learned by these studies that when this took place the resulting discontinuity produced more severe results than if the shrinkage were entirely internal.

It is a well known fact that surface notches have a pronounced effect on the endurance strength and that surface discontinuities act as notches. Shrinkage of Class 2 and Class 6 which came to the surface was very severe, in fact, it was equivalent to a 40 to 50 percent loss in the endurance strength or a value somewhat comparable to the loss in endurance ratio between the unnotched and notched R. R. Moore fatigue specimen (35 percent reduction),

The internal shrinkage of Class 2 resulted in losses of 7 to 9 percent in bending fatigue and 12 to 16 percent in torsion fatigue depending on the strength level of the steel. The severe type of Class 6 internal shrinkage resulted in a loss of fatigue strength of 20 to 30 percent in torsion fatigue. This class is not permitted in purchase specifications.

Therefore, the notched fatigue endurance values of cast steel are good criteria for design and service requirements rather than severity classifications on the basis of non-destructive inspection employing reference radiographs to detail classes of severity. Thus, the results of this report confirm and support those of a previous report(3) of fatigue properties and surface discontinuities.

There seems to be considerable hesitancy by the engineering profession to draw comparisons between the Charpy V-notch impact energy and transition temperature with those obtained by testing unnotched test specimens in impact, bending and impact-tension containing severe discontinuities. Comparisons can be made only between the energy values and transition temperature of sound specimens and those containing discontinuities.

The impact studies show that internal shrinkage of Class 6 reduces the impact energy considerably. However, shrinkage of lesser degree of severity (Class 2) has in bending impact a good level of impact energy.

There is a definite difference in Class 2 and Class 6 shrinkages in tension impact, although these values are low when compared to sound impact specimens. Thus, internal shrinkage has a deteriorating effect on impact energy to a lesser extent than from serious surface discontinuities.

This report completes the series of studies and investigations on the effect of discontinuities on the static and dynamic properties of cast steel. The research was undertaken at Case Western Reserve University under the direction of Professor John F. Wallace. The Foundation is much indebted to him for the excellence of the research and the manner of its presentation.

CHARLES W. BRIGGS
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May 1969

THE EFFECT OF INTERNAL SHRINKAGE DISCONTINUITIES ON THE FATIGUE AND IMPACT PROPERTIES OF CAST STEEL SECTIONS

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Steel Foundry Research Foundation
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THE EFFECT OF INTERNAL SHRINKAGE DISCONTINUITIES ON THE FATIGUE AND IMPACT PROPERTIES OF CAST STEEL SECTIONS

Introduction

Failure of metal in fatigue results from repetitive or fluctuating stresses which are much less than the static breaking stress. Fatigue failures account for at least 90 percent of all service failures. As a result, precise information on the fatigue behavior of engineering materials is required.

Steel castings are used widely in structural components. Since fatigue stresses occur so frequently, detailed information on the behavior of steel castings in fatigue is needed. Prediction of casting performance may be based on fatigue tests of small cast laboratory specimens. However, the correlation between laboratory results and service behavior is often difficult to achieve. A significant size effect exists in bending and torsional fatigue that causes lower endurance properties for larger specimens. It is desirable to perform fatigue tests on structural components, but the cost of testing the full-scale parts is relatively high.

The influence of discontinuities on the mechanical properties of cast steel is of significant interest. One type of discontinuity that occurs in steel castings is shrinkage. Shrinkage occurs in two general forms: a cavity type, and a relatively fine network type, located at the thermal mid wall of the casting section. Some indication of the extent of variation in internal shrinkage can be obtained from Group C, Classes 1 through 6 in the ASTM Radiographic Standards for Steel Castings, ASTM Designation E-71.

Some steel castings may at times be rejected for internal shrinkage without adequate knowledge of the effect of this shrinkage or of shrinkage severity on the mechanical behavior of the part. Investigations conducted by SFSA on the effect of shrinkage porosity on the static mechanical properties of cast steels showed that the presence of considerable shrinkage at or near the center of a bar or plate steel casting of uniform thickness does not significantly influence the strength of steel casting stressed in simple bending. This investigation suggested that the rejection of steel castings with shrinkage should be based on service performance and not merely on a radiographic interpretation.

The studies of this report were undertaken to determine the effect of shrinkage on the impact and fatigue properties of small cast steel sections in the shape of impact and fatigue test bars cast nearly to size and finished to test specimen dimensions by machining.

Materials and Procedures

Several steel heats were produced of Ni-Cr-Mo (8630) cast steel of a nominal composition: C 0.30, Mn 0.80, Si 0.30, Ni 0.55, Cr 0.45, Mo 0.25, P 0.027, S 0.030 percent. The molten steel was cast into green sand molds in the form of tension impact specimens, plates for bend impact specimens. plate bending fatigue specimens and torsion bar fatigue specimens. Standard ASTM keel blocks were cast with each heat for tensile and Charpy V-notch test specimens.

Internal shrinkage was produced by insufficient risering of the test sections and various degrees of severity of shrinkage were obtained and classified by ASTM reference radiographs E-71. Impact and fatigue specimens free from discontinuities were produced for control and comparison purposes.

Production of Impact Specimens . . . The bending impact specimens were machined to the test bar dimensions of 7 1/2 in. long by 1 in. wide by 1/2 in. thick from as cast plates that were 8 in. long by 1 1/4 in. wide by 5/8 in. thick. The plates were ground on a rotary vertical spindle and a Blanchard surface grinder using a selective grinding procedure to assure equal stock removal from opposite surfaces. This technique was closely monitored when grinding the bars containing shrinkage in order to maintain the shrinkage centrally with respect to the surfaces of the finished machined bar. Slow table and spindle speeds of 9 and 900 rpm, respectively, with a minimal automatic feed of 0.004 inch per minute were used. These slow speeds and feeds were used in conjunction with a resinoid bonded, cool cutting wheel to minimize generation of heat and residual tensile stresses in the bending specimens.

The tension impact spcimens were made by initial rough turning and finished by contoured wheel grinding. The finished machined dimensions of the tension impact specimens are shown in Figure 1. Charpy V-notch specimens were made to dimensions according to ASTM specification. The 0.010 in. radius at the base of the 45 degree included angle V-notch was lapped to

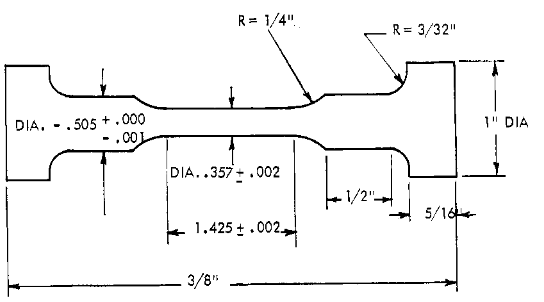

Figure 1—Schematic of test design (not to scale) for finish machined tension impact specimen.

remove marks of machining. The tensile specimens used to determine the static strengths of the various heats had a diameter of 0.357 in. and a gage length of 1.40 in.

The machined specimens were subject to various mechanical tests which included standard tensile, impact Charpy V-notch, impact tensile and impact bend testing. Tensile testing was performed as a control to ascertain the static strength and ductility response of the steel to the thermal treatments. The data obtained with the Charpy V-notch testing served as a control and provided a baseline for comparison with results of the impact testing with the scaled up bending specimens and with the tension impact testing. The Charpy testing was performed on a Widermann-Baldwin Pendulum Type Impact Tester with a 240 ft-lb capacity and a pendulum velocity at impact of 204 inch per second.

Bend testing of the scaled up specimens was completed at Watertown Arsenal, Watertown, Massachusetts, on one of the three largest pendulum impact machines in the world. The 2200 ft-lb energy capability of this testing apparatus allowed for a scale up to the bending specimens to dimensions as previously described. The arm length is 80 in. and swings through an angle of 161 degrees as measured from the rest position, The velocity generated at the pendulum striker anvil just prior to impact is 346 inch per second. The span length of the specimen holding fixtures was 4 7/8 in. Those bending specimens (specimen length equals 7.5 in.) which did not fracture were required to bend through an angle of 112 degrees to clear the holding fixture span.

A technique for tension impact testing was developed to measure and record drop weight velocities prior to and after fracture. From these data, the energies required to effect specimen fracture were calculated. The system which was used was presented in detail with illustrations in a previous Steel Foundry Research Foundation Report.(5)

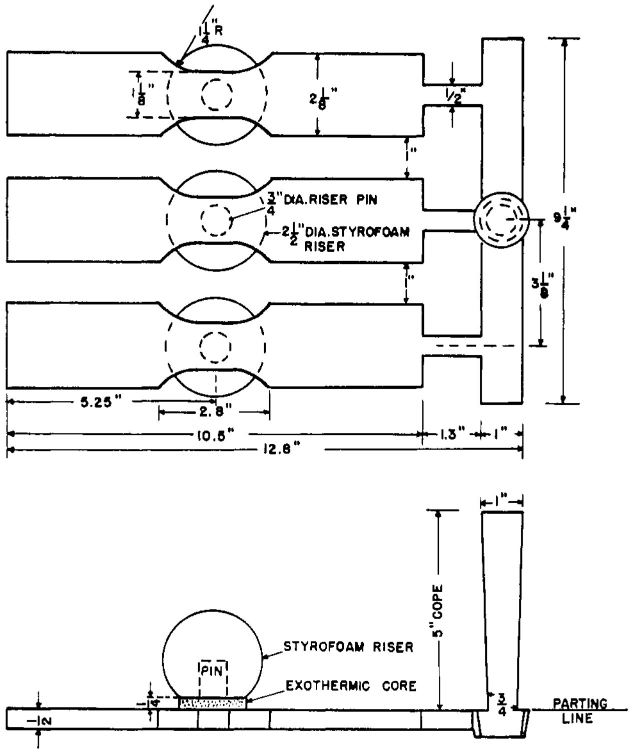

Figure 2—Gating and risering arrangement for plate bending fatigue specimens sections.

Production of Fatigue Specimens . . . The plate bending fatigue specimens were produced three to a mold using the gating and risering systems shown in Figure 2. A centrally located spherical polystyrene riser with an exothermic core at the riser neck was used. The exothermic core was employed to facilitate easy riser removal and assure efficient feeding of the test specimens so that the specimens were radiographically sound. Subsequent machining of the top surface of the plate bending specimens removed any surface effects on the exothermic riser neck.

A series of bend fatigue test specimens was poured to produce shrinkage porosity of Classes 2 and 6. The risers and chills were placed so that the type and extent of the shrinkage were controlled as desired. Radiographic examination was performed with a Fredrex 300 radiographic unit with several test bars on each film. Discontinuities were compared with ASTM Radiographic standards for steel castings, ASTM Designation E-71.

The keel block coupon legs were machined to tensile specimens with shoulder-type ends, a diameter of 0.212 in. and a gage length of 0.850 in.

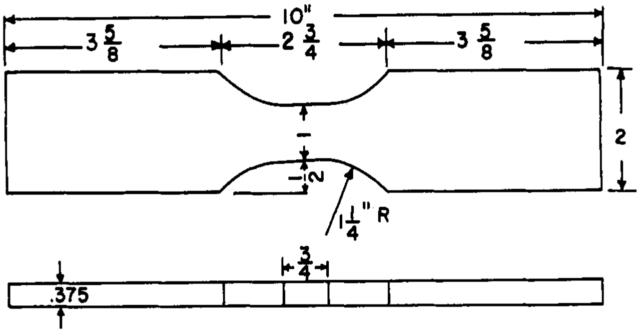

Figure 3—Plate bending fatigue specimen.

The bend fatigue specimens were machined in the heat treated condition to the dimensions illustrated in Figure 3. Specimens were completely machined from 5/8 in. thick plates with 1/16 in. metal removed from the rounded sides as well as the top and bottom. All plates were ground on a rotary surface grinder using a selective grinding procedure to assure equal removal of stock from opposite surfaces. The grinding procedure used minimized the generation of heat and residual stresses in the bending specimens. The edges of the reduced test section were machined by milling and grinding longitudinally. The final grinding operation yielded a surface finish of 4 to 10 micro-inch as measured by a profilometer.

After machining the sand cast bars, tensile, hardness, and fatigue tests were conducted. The fatigue tests were conducted on a constant load amplitude Sonntag SF-1-U fatigue machine operating at 1800 cycles per minute. All plate bending specimens were tested in reverse bending under four point loading. The specimens were considered to have failed when completely fractured. The fatigue tests were conducted at different stress levels to obtain curves of stress versus number of cycles to failure. Each S-N curve required from 8 to 12 specimens. The endurance limit for specimens was based on ten million cycles.

The torsion fatigue test bars were cast in green sand molds with three bars per mold as illustrated in Figure 4. The centrally located spherical risers of foamed polystyrene were employed along with semi-circular chills adjacent to the reduced section when sound specimens were desired. The risers and chills were displaced in varying degrees to obtain various severities of shrinkage discontinuities.

After lathe turning, the bars were ground using a centerless grinder for the straight sections and a contoured wheel for the test section. The surface finish of the test section was approximately 20 micro-inch after plunge grinding in two passes. The bars were 0.801 in. in diameter after polishing in the circumferential direction on a lathe with 220, 320, 400, and 600 grit abrasive papers to obtain the test specimen shown in Figure 5.

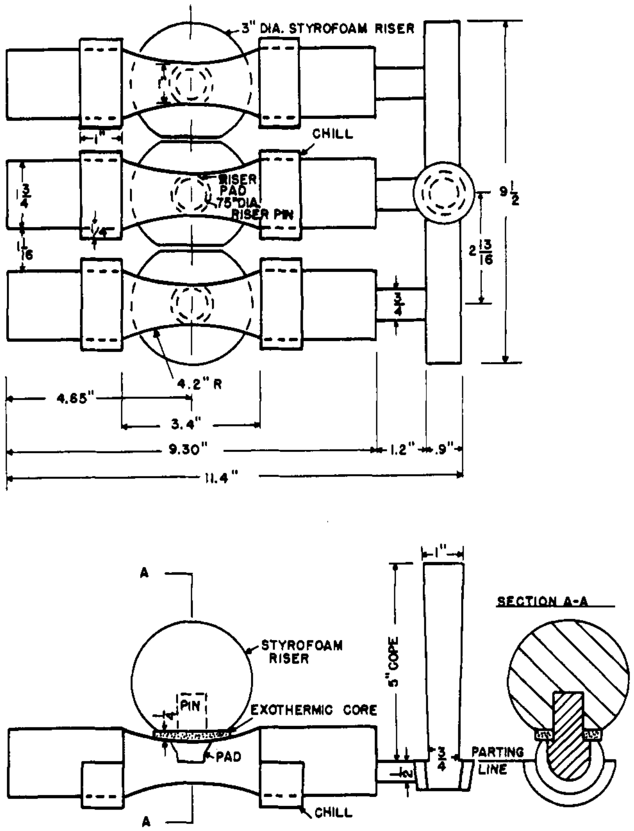

Figure 4—Gating and risering arrangement for torsion fatigue specimen sections.

The torsion fatigue tests were conducted on a constant load amplitude Sonntag SF-1-U fatigue machine at 1800 cycles per minute. The test arrangement for the torsion tests has been shown in previous SFSA publications. A lever arm connected to the vibrating platen transmitted the torque to collets gripping the torsion specimen. The torsion tests were terminated because of deflection limitations of the fatigue machine. This

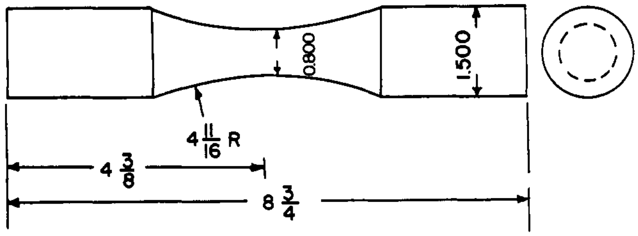

Figure 5—Torsion fatigue specimen.

deflection limitation was attained after the specimen had been severely cracked.

The fatigue tests were carried out at different stresses to obtain curves of stress versus cycles to failure. The number of specimens used for an S-N curve ranged from seven to eleven. The endurance limit was based on ten million cycles, so that specimens which did not fail after that number of stress reversals were considered to possess infinite life.

Heat Treatments . . . The tensile strength levels selected were 80,000 to 100,000 psi and 120,000 to 145,000 psi. These levels were obtained by heat treating the various test sections prior to machining.

Properties for Bending and Tension Impact

The mechanical properties of the Ni-Cr-Mo (8630) cast steels employed in the impact studies are shown in Table 1. The type of test and the severity of the shrinkage discontinuity were also recorded. Individual impact test data steel compositions and heat treatments are presented in Tables 7 and 8 in the appendix to the report. A summary of the impact results is shown in Table 2. Charpy V-notch impact values for the sound Ni-Cr-Mo cast steel are shown in Figure 6.

Bending Impact Results . . . The effect of shrinkage discontinuities on the bending impact results is shown in Figure 7. The actual test points are illustrated and the radiographically sound cast steel is compared with the sections containing Class 2-3, 4 and 5 -6 shrinkage.

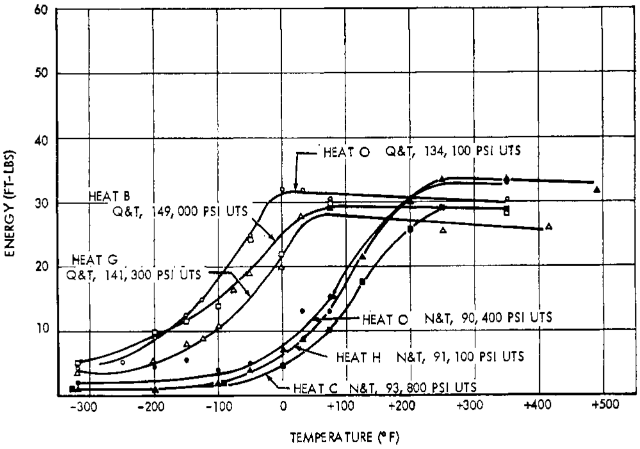

Figure 6—Charpy V-notch test results for three randomly selected heats of Ni-Cr-Mo (8630) cast steel.

The effect of center shrinkage porosity on the bending impact fracture energy was pronounced, although comparatively not as severe as observed for the surface defects. Compared to the sound material, the completely fibrous transition temperature for the quenched and tempered condition increased by only 75 degrees and no change was observed for the normalized and tempered condition. In the transition range, the largest shift was noted for the ductility transition and 50 percent fibrous transition temperature; the temperature of complete ductility transition increased

TABLE 1

Mechanical Properties For Ni-Cr-Mo (8630) Cast Steels * for Impact Studies

Steel No.	Heat Treatment	Tensile Strength 1000 psi	0.2% Yield Str. 1000 psi	RA %	Elong. 1.4 in. %	Brinell BHN	Impact Specimens Type	E-71 ASTM Discontinuity
A	Quench & Temper	132.0	121.8	42.5	16.3	285	Bending	Sound
A	Norm. & Temper	88.0	58.8	33.1	20.6	170	Bending	Sound
B	Quench & Temper	149.3	141.1	25.6	13.2	319	Charpy V	
							Tension	Sound
							Charpy V	
C	Norm. & Temper	93.8	59.6	31.9	23.1	153	Tension	Sound
F	Quench & Temper	134.3	125.6	32.6	12.1	283	Bending	Shrink Cl 5-6
F	Norm. & Temper	79.8	48.8	28.2	25.0	152	Bending	Shrink Cl 5-6
							Charpy V	
G	Quench & Temper	141.3	131.2	27.0	12.9	298	Bending	Shrink Cl 2-3
							Bending	Shrink Cl 4
							Tension	Shrink Cl 3
H	Norm. & Temper	91.1	56.3	33.0	24.3	185	Charpy V	Sound
							Bending	Shrink Cl 2-3
							Bending	Shrink Cl 4
							Tension	Shrink Cl 3
I	Quench & Temper	134.5	123.7	31.8	13.9	283	Tension	Shrink Cl 2
I	Norm. & Temper	83.8	52.2	37.9	21.6	164	Tension	Shrink Cl 2

* Composition Range C 0.30 - 0.33, Mn 0.64 - 0.90, Si 0.21 - 0.38, Ni 0.50 - 0.60, Cr 0.45 - 0.60, Mo 0.19 - 0.25, P 0.026 - 0.030, S 0.028 - 0.032

TABLE 2

Summary of Impact Behavior

Heat No.	Condition	Type of Test	Discontinuity	Ductility Transition (ft-lbs)	Ductility Transition Temp (°F)	Transition Temp. (ft-lbs)	Transition Temp. Temp (°F)	90 - 100% Fibrosity Transition (ft-lbs)	90 - 100% Fibrosity Transition Temp (°F)
A	Quench & Temper	Bending	Sound	164	<−321	430	−300	840	−150
B	Quench & Temper	Tension	Sound	111	<−321	231	−250	385	−200
B	Quench & Temper	Charpy V-notch	Sound	10.0	−200	24.0	− 50	29.0	+ 50
A	Norm. & Temper	Bending	Sound	117	−250	480	−125	1260	− 50
C	Norm. & Temper	Tension	Sound	114	−250	245	− 80	370	− 20
C	Norm. & Temper	Charpy V-notch	Sound	3.0	−100	12.5	+ 75	28.0	+225
G	Quench & Temper	Bending	Shrinkage Class 2 - 3	90	−321	180	−175	710	− 75
G	Quench & Temper	Bending	Class 4	90	−321	230	−175	625	− 75
F	Quench & Temper	Bending	Class 5 - 6	60	−321	125	−150	420	− 75
H	Norm. & Temper	Bending	Class 2 - 3	41	−200	415	−100	690	− 40
H	Norm. & Temper	Bending	Class 4	41	−200	300	− 75	580	− 40
F	Norm. & Temper	Bending	Class 5 - 6	32	−200	170	− 75	350	− 40
I	Quench & Temper	Tension	Class 2	50	−250	65	−150	120	− 80
G	Quench & Temper	Tension	Class 3	25	−250	45	−150	75	− 80
I	Norm. & Temper	Tension	Class 2	50	−110	80	− 50	125	0
H	Norm. & Temper	Tension	Class 3	44	−110	40	− 50	100	0

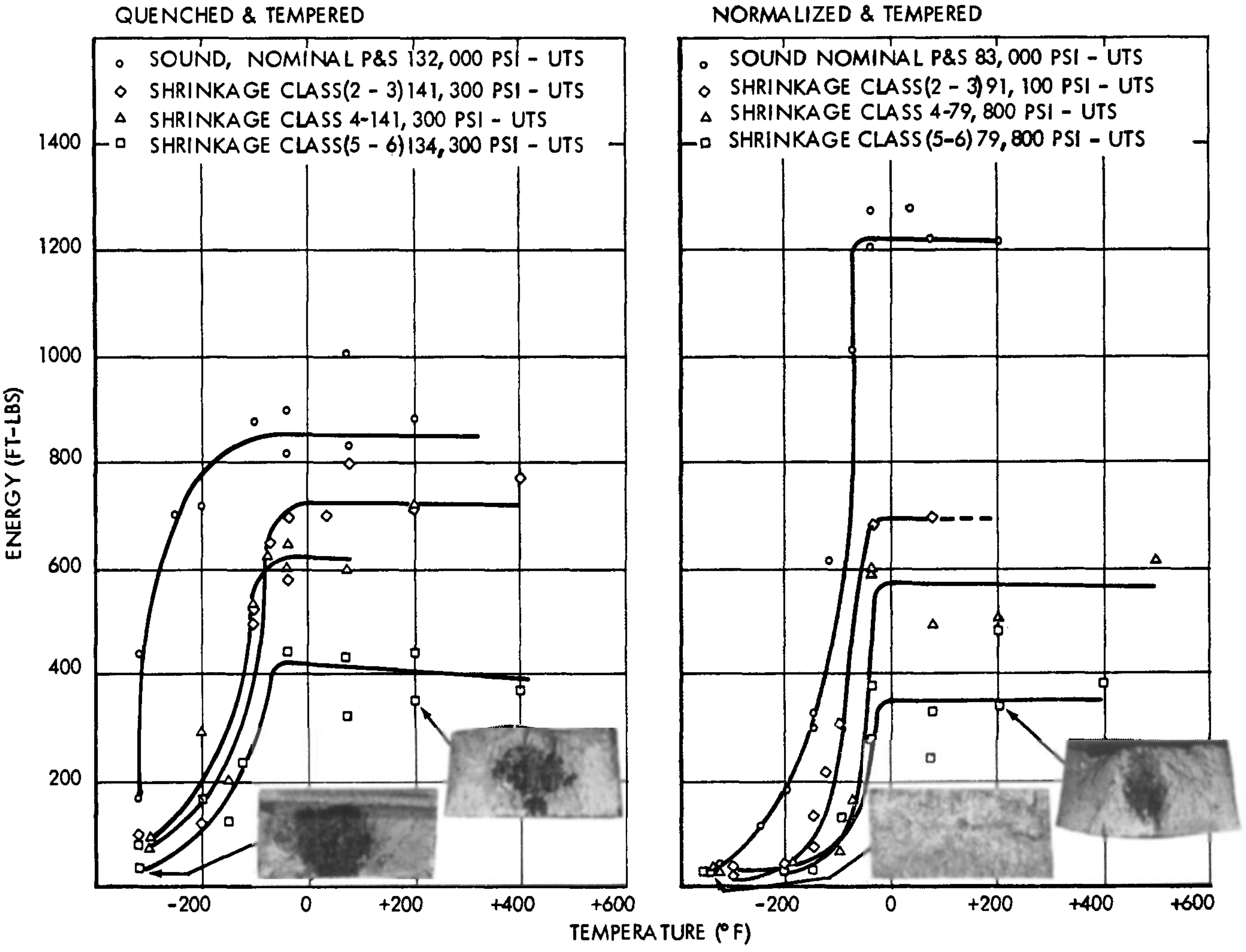

Figure 7—Bending impact test results with shrinkage discontinuities.

only slightly above that of the sound material. The temperature for the ductility and fracture appearance transitions increased moderately above that of the sound material for the quenched and tempered condition for the three severities of shrinkage investigated.

The energy levels throughout the transition range were markedly reduced as shown by a comparison of the energy-temperature curves in Figure. 7. The highest impact energy levels were measured for the sound steel followed by that containing the least severe (Class 2-3) shrinkage for both the quenched and tempered and normalized and tempered conditions. This is to be expected since the Class 2-3 shrinkage was centrally located in the bar, near the neutral axis, away from the regions of high surface stress. The decrease in impact energies compared to the sound steel was more pronounced for the normalized and tempered condition. For the Class 2 - 3 severity shrinkage, approximately a 40 percent decrease in maximum fracture energy was observed for the normalized and tempered condition while for the quenched and tempered condition only a 15 percent decrease was noted. The fracture energies decreased further as the severity of shrinkage increased. The lowest fracture energies were obtained for the most severe shrinkage ratings of Class 5 - 6, impact values were reduced to approximately one-half and one-third of the sound material for the quenched and tempered and normalized and tempered materials, respectively. The Class 5 - 6 shrinkage was severe and observed to extend as thin stringers to the surface of the bend specimens. The Class 2-3 and Class 4 severities were contained wholly within the bar.

Tension Impact Results . . . The influence of shrinkage on tension impact properties is shown in Figure 8. The effect of this shrinkage on tension impact properties was more marked than for the bending tests. With Class 2 and 3 shrinkage located centrally in the tensile test bars, a more pronounced shift of the ductility transition was observed. This indicates that centerline shrinkage exerts more of a marked influence on the fracture initiation of bars loaded in tension. This behavior would be expected since the tensile stress distribution across the gage diameter of the tension impact bars is uniform. Therefore, the position of the flaw with respect to the specimen surface should not be a major factor, as is the case with tests performed in bending. The reduction in impact energy from shrinkage was also greater with the tension impact tests. As is shown in

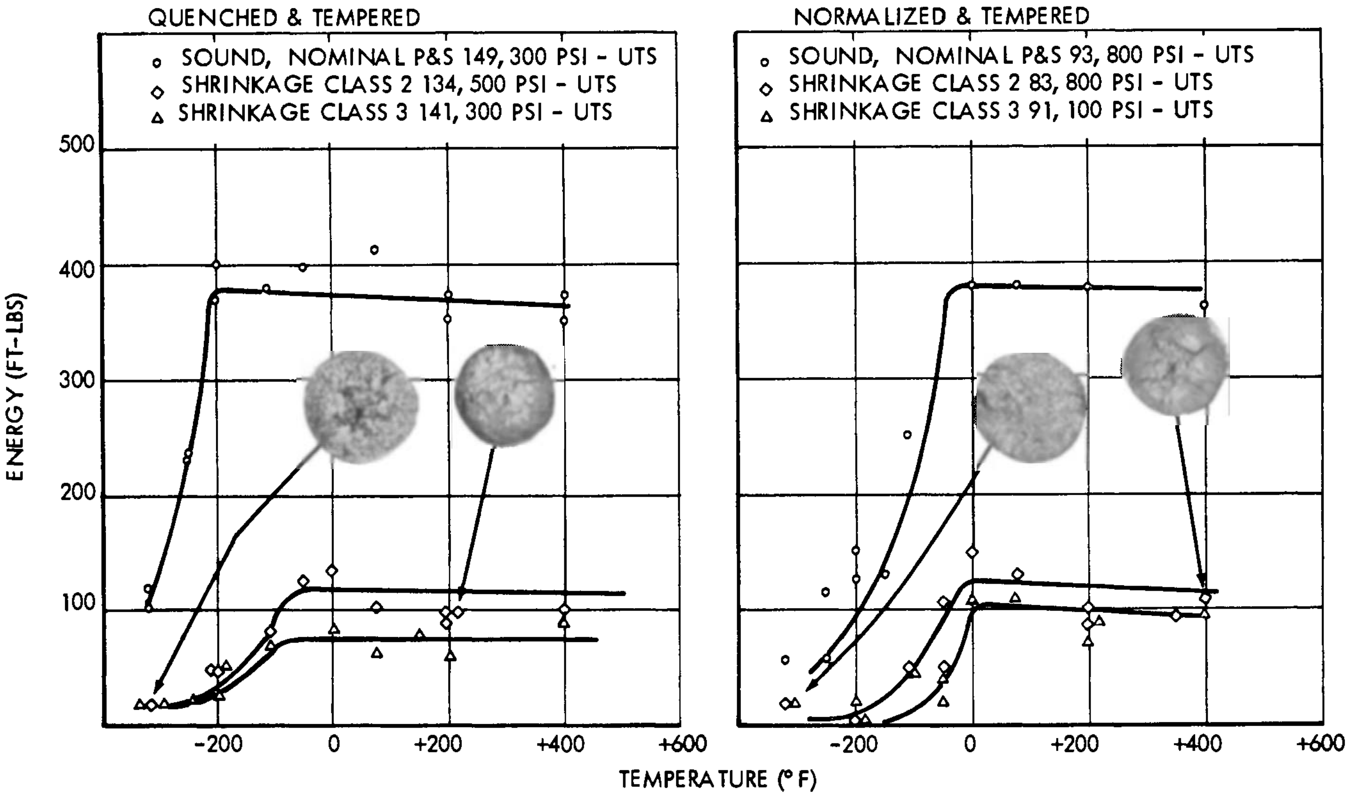

Figure 8—Tension impact test results with shrinkage discontinuities.

Figure 8 the energies above the completely fibrous transition temperature decreased to about 20 percent that of the sound material.

A previous study(1) to determine the effect of centerline shrinkage on static tensile properties showed that only a 10 percent decrease in ultimate strength resulted in a cast steel with Class 6 severity shrinkage in a one in. square test section. Under the static test conditions, the ductility of the steel was sufficient to minimize the occurrence of brittle fracture and almost the full strength level of the steel was attained.

Evaluation of Shrinkage by Impact Loading

Cast steel sections containing internal shrinkage were tested under bending and tension impact loads and the results were correlated with the degree of shrinkage severity and compared to sound sections. The findings may be evaluated as follows:

1. The presence of shrinkage discontinuities reduces the level of fibrous fracture energy in bending impact specimens. This reduction is greater for normalized and tempered than for quenched and tempered cast steels. The amount of reduction increases with the severity of shrinkage. The transition temperature is raised to some extent by shrinkage of increasing severity in the quenched and tempered steel but is not affected in the normalized and tempered steel.

2. The presence of shrinkage discontinuities has a greater effect on the behavior of steels tested in tension impact than in bending impact. This is particularly true for the slight form of shrinkage that is located close to the centerline. Since this shrinkage does not reach the surface, it does not exert as damaging an effect on impact behavior in bending as in tension. The presence of shrinkage discontinuities in tension impact markedly lowers the level of fiber fracture energy and raises the transition temperature to some extent in both quenched and tempered and normalized and tempered steels.

TABLE 3
Chemical Analyses of Ni-Cr-Mo (8630) Cast Steels for Fatigue Studies

Steel No.	% C	% Mn	% Si	% Cr	% Ni	% Mo	% P	% S	Acid Soluble % Al
10	0.35	0.21	0.15	0.69	0.74	0.40	0.016	0.017	0.19
11	0.25	0.50	0.35	0.54	0.62	0.22	0.015	0.015	0.005
12	0.32	0.84	0.57	0.60	0.69	0.19	0.010	0.032	0.04
13	0.29	0.80	0.52	0.45	0.60	0.21	0.027	0.028	0.07
14	0.30	0.64	0.21	0.45	0.55	0.25	0.027	0.030	0.10
15	0.30	0.64	0.24	0.45	0.50	0.20	0.020	0.020	0.03

Properties for Bending and Torsion Fatigue

The composition of the Ni-Cr-Mo (8630) cast steels employed in the fatigue test studies is presented in Table 3. The mechanical properities of these steels are tabulated in Table 4 together with heat treatment and shrinkage severity.

Bending Fatigue Results . . . A summary of the plate bending fatigue tests containing shrinkage discontinuities and sound sections is tabulated in Table 5. Since similar heat treatments produced a slight variation in tensile strength because of variations in composition, comparison of fatigue behavior requires conversion of the fatigue stress applied to each test to a ratio by dividing this stress by the tensile strength of each steel. This ratio has been plotted versus cycles to failure for comparative S-N curves.

TABLE 4
Mechanical Properties For Ni-Cr-Mo (8630) Cast Steel For Fatigue Studies

Steel No.	Heat Treatment	Tensile Strength 1000 psi	0.2% Yield Strength 1000 psi	R.A. %	Elong. 1.4 %	BHN	E-71 ASTM Discontinuity
10	Quench & Temper	136.5	116.6	25.5	11.8	271	Sound
11	Normalize	103.5	52.5	37.4	21.2	216	Sound
11	Anneal	83.1	42.7	46.7	32.4	160	Sound
12	Quench & Temper	137.9	115.5	22.7	11.2	294	Shrink Class 2 Shrink Class 6
13	Anneal	91.1	56.3	33.0	24.3	170	Shrink Class 2 Shrink Class 6
14	Quench & Temper	134.5	123.6	31.8	13.9	300	Shrink Class 2
14	Norm. & Temper	83.8	52.1	37.9	21.6	156	Shrink Class 2
15	Quench & Temper	132.6	90.8	40.6	15.9	290	Sound
15	Quench & Temper	100.0	79.6	57.8	27.1	202	Sound
15	Norm. & Temper	104.8	76.1	44.5	24.1	205	Sound
15	Anneal	84.0	72.6	41.5	28.2	156	Sound

TABLE 5

Summary of Plate Bending Fatigue Tests Containing Shrinkage Discontinuities

Steel No.	Heat Treatment	Tensile Strength psi	Endurance Limit psi	Endurance Ratio	E-71 ASTM Discontinuity
10	Quench & Temper	136,500	38,000	0.28	Sound
11	Norm. & Temper	83,100	29,000	0.35	Sound
12	Quench & Temper	137,900	23,000	0.17	Shrink Class 2*
12	Quench & Temper	137,900	18,000	0.13	Shrink Class 6*
13	Anneal	91,100	22,000	0.24	Shrink Class 2
13	Anneal	91,100	21,000	0.23	Shrink Class 6
14	Quench & Temper	134,500	36,000	0.27	Shrink Class 2
14	Norm. & Temper	83,800	27,000	0.32	Shrink Class 2

* Shrinkage came to the surface of the specimen on machining.

It is apparent that the strength level and heat treatment exert an appreciable effect on fatigue behavior. The strength levels utilized in this investigation fall into three ranges : 134,000 to 138,000; 103,000; and 82,000 to 91,000 psi. The two lowest strength levels, whether obtained by normalizing and tempering or annealing, consistently provided higher endurance ratios than the highest strength level. This behavior has been observed by several other investigators. No direct comparison between the effect of normalizing and tempering or annealing treatments on the fatigue behavior is available at identical strength levels. A somewhat better endurance ratio resulted from an annealing to the lowest strength level compared to the normalizing for the intermediate strength level in steel No. 11.

The influence of different types of shrinkage on fatigue properties can be evaluated by comparing the endurance ratios of the heats containing this shrinkage. This comparison should be at similar strength levels and for similar heat treatments. The endurance ratios of steels No. 12 and No. 14 in Table 5 provide such a comparison. The former endurance ratios are only about 50 to 60 percent of those of the later. However, the shrinkage was entirely internal in the specimens of Heat No. 14, whereas the shrinkage of the specimens for Heat No. 12 extended to the surface. Therefore, the reduction in the endurance ratio for the specimens of steel No. 12 can be attributed to the presence of shrinkage within the metal subjected to maximum tensile stress.

Only a slight decrease in endurance ratio resulted from the marked increase in severity of shrinkage from Class 2 to Class 6, as demonstrated by the results for steels No. 12 and No. 13 in Table 5. This slight effect is attributed to the fact that the shrinkage in the test specimens of these steels reached the surface during the machining operation. It becomes apparent that the location of shrinkage at the surface is far more critical than its classified severity by radiography.

The modified S-N curves in Figure 9 provide a comparison of the fatigue behavior of sound section specimens with those containing shrinkage of Class 2 and 6 for steel of high strength values. The reduction of fatigue properties from a sound steel to Class 2 internal shrinkage is slight. However, the loss is considerable when Class 2 shrinkage extends to the surface where a high concentration of tensile stress occurs.

Similar results are obtained by comparing sound

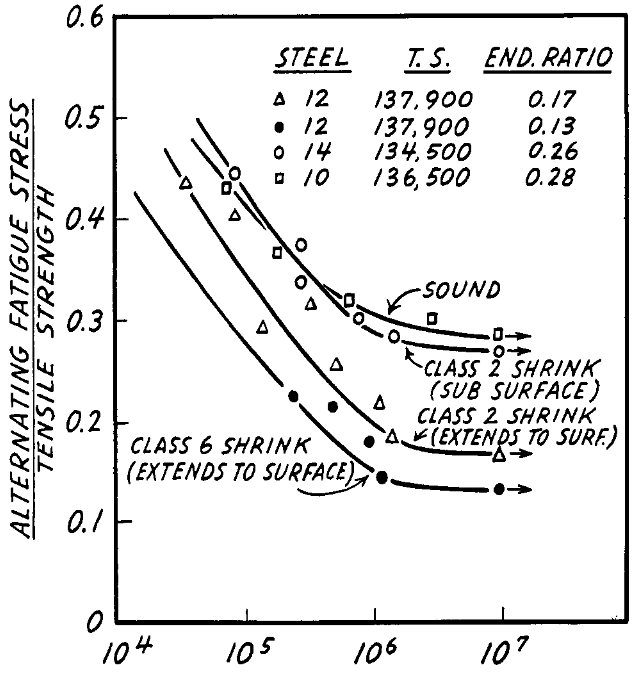

Figure 9—Effect of shrinkage on bending fatigue behavior of quenched and tempered Ni-Cr-Mo (8630) cast steel.

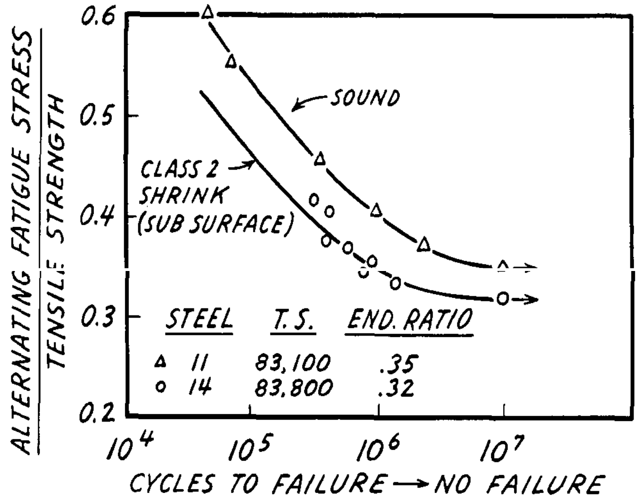

Figure 10—Effect of shrinkage on bending fatigue behavior of Ni-Cr-Mo (8630) normalized and tempered cast steel.

specimens with shrinkage specimens in the fatigue tests for normalized and tempered steels in the modified S-N curves plotted in Figure 10. The fatigue properties were only decreased to a mild degree by internal shrinkage of Class 2.

Torsion Fatigue Results . . . A summary of the torsion fatigue tests recording the effect of shrinkage discontinuities is shown in Table 6. Plots of the ratio of the alternating shear stress to the tensile strength versus the number of cycles to failure are shown in Figures 11 and 12.

It is apparent that shrinkage reduces the endurance limit and the fatigue strength within the limited fatigue life range for this 8630 cast steel for both the water quenched and tempered and annealed conditions. The fatigue properties of specimens containing Class 2 shrinkage are inferior to sound steel and the fatigue strength is further decreased as the severity of the shrinkage increases from Class 2 to Class 6. The reduction in the ratio of alternating shear stress to tensile strength for a given fatigue life or for the endurance limit is higher for both types of shrinkage with the higher strength steel. Since higher

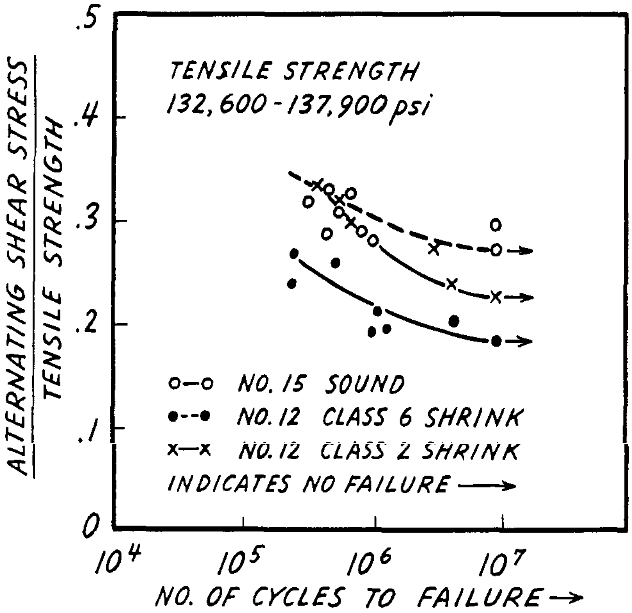

Figure 11—Effect of shrinkage on torsion fatigue properties of high strength Ni-Cr-Mo (8630) cast steel water quenched and tempered.

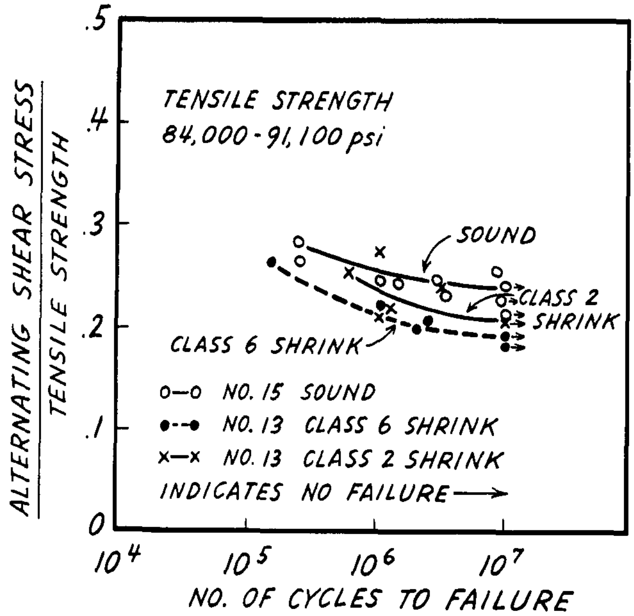

Figure 12—Effect of shrinkage on torsion fatigue properties of annealed Ni-Cr-Mo (8630) cast steel.

TABLE 6

Summary of Torsion Fatigue Tests Containing Shrinkage Discontinuities

Steel No.	Heat Treatment	Tensile Strength psi	Endurance Limit psi	Endurance Ratio	E-71 Discontinuity
12	Quench & Temper	137,900	31,700	0.23	Shrink Class 2
12	Quench & Temper	137,900	26,000	0.19	Shrink Class 6
13	Anneal	91,100	19,000	0.21	Shrink Class 2
13	Anneal	91,100	17,000	0.19	Shrink Class 6
15	Quench & Temper	132,600	37,000	0.28	Sound
15	Anneal	84,000	20,000	0.24	Sound

strength steels are generally considered to be influenced more markedly by the presence of notches, this effect of strength level is to be expected.

It is noted that the presence of Class 6 shrinkage in the high strength, quenched and tempered steel reduces the ratio of the alternating shear stress to the tensile strength at the endurance limit to 0.19 compared to a ratio of 0.28 for the sound material. The presence of Class 6 shrinkage in the annealed, lower strength steel reduces the ratio of the alternating shear stress to tensile strength at the endurance limit to 0.19 compared to 0.24 for the sound material. It is interesting to note that the endurance limit for the sound material is higher with the higher strength steel when measured under torsional stress. Bending fatigue studies have indicated that the endurance ratio is generally higher for the lower strength steel.

The reduction in torsional fatigue properties occurred consistently for the two strength levels and heat treatments even though the shrinkage cavities did not reach the surface or the most highly stressed portion of the torsion test specimen. Because of the round cross section of the bar and method of casting, the shrinkage pattern was toward the centerline of the bar. It was noted that the Class 6 shrinkage cavities were located closer to the surface of the test bar than for the Class 2 shrinkage.

Evaluation of Shrinkage by Fatigue Loading

Cast steel sections containing shrinkage discontinuities were tested in bending fatigue and torsion fatigue and the values secured were compared with those resulting from the testing of sound sections. The major observations were as follows:

1. The bending fatigue properties of cast steel sections were reduced because of shrinkage discontinuities. However, only a small difference in fatigue behavior existed in cast steel with Class 2 E-71 ASTM internal shrinkage. Only slight variations existed between Class 2 and the much more severe Class 6 shrinkage. The fatigue properties were considerably reduced, however, when both Class 2 and Class 6 shrinkage extended to the surface of the test specimen.

2. The presence of Class 2 and Class 6 internal shrinkage reduces to an appreciable extent the torsion fatigue strength of cast steel sections. The decrease in the ratio of the alternating shear stress to tensile strength at the endurance limit is about 17 percent for Class 2 shrinkage and 32 percent for Class 6 shrinkage for the high strength, quenched and tempered cast steels. The decrease was not so great for the lower strength annealed cast steel ; namely, 15 percent for Class 2 shrinkage and 20 percent for Class 6 shrinkage.

Conclusions to the Research Report

The results of tests made on cast steel sections made under dynamic loading in impact and fatigue provided significant information concerning the influence of discontinuities on the impact and endurance limit properties of cast steel.

1. The presence of shrinkage discontinuities reduces the level of fibrous fracture energy in bending impact specimens. This reduction is greater for normalized and tempered than for quenched and tempered cast steels. The amount of reduction increases with the severity of shrinkage.

2. The presence of shrinkage discontinuities has a greater effect on the behavior of cast steel sections tested in tension impact than in bending impact, This is particularly true for the slight form (Class 2) shrinkage that is located close to the centerline. Since this shrinkage does not reach the surface, it does not exert as damaging an effect on impact behavior in bending as in tension. The presence of shrinkage discontinuities in tension impact markedly lowers the level of fiber fracture energy and raises the transition temperature noticeably.

3. The bending fatigue properties of cast steel sections were reduced because of the presence of shrinkage discontinuities. However, only a small difference in fatigue behavior existed because of Class 2 E-71 ASTM internal shrinkage. Only slight variations existed between Class 2 and the much more severe Class 6 shrinkage. The fatigue properties were considerably reduced however when both Class 2 and Class 6 shrinkage extended to the surface of the test specimen.

4. The presence of Class 2 and Class 6 internal shrinkage reduces to an appreciable extent the torsion fatigue strength of cast steel sections. The decrease in the ratio of the alternating shear stress to tensile strength at the endurance limit is about 17 percent for Class 2 shrinkage and 32 percent for Class 6 shrinkage for the high strength, quenched and tempered cast steel. The decrease was not so great for the lower strength annealed cast steel; namely, 15 percent for Class 2 shrinkage and 20 percent for Class 6 shrinkage.

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APPENDIX I

TABLE 7

Unnotched Bending Impact Test Results for Shrinkage

Temperature (°F)	Energy (ft-lbs)	Lateral Contraction (%)	Percent Fibrous
Heat A—Data given Foundation Report September, 1967(4) Table 9, Page 44			
Shrinkage Class 5 - 6 Heat F—Normalize & Temper 79,800 psi - U.T.S.			
Composition. C .30, Mn .62, Si .23, Cr .45, Ni .55, Mo .25, P .027, S .030			
−321	28	0	0
−321	24	0	0
−200	32	0.2	0
−150	32	0.2	10
−100	131	4.5	40
−40	278	4.7	70
−40	377	5.5	90
+75	331	5.9	100
+75	243	5.5	100
+200	485	7.3	100
+200	346	6.9	100
+400	385	6.9	100
Shrinkage Class 5 - 6 Heat F—Quench & Temper 134,300 psi - U.T.S.			
−321	74	0.4	20
−321	32	0.2	10
−200	164	1.8	40
−150	117	1.5	50
−125	229	2.9	60
−100	—	4.5	80
−40	—	3.6	100
−40	443	5.2	100
+75	309	4.0	100
+75	429	6.4	100
+200	350	5.5	100
+200	440	5.0	100
+400	372	4.7	100
Shrinkage Class 2 - 3 Heat G—Quench & Temper 141,300 psi - U.T.S.			
Composition: C .32, Mn .84, Si .37, Cr .60, Ni .60, Mo .19, P .030, S .032			
−321	90	1.1	30
−200	117	1.6	30
−100	494	6.7	80
−100	520	7.0	90
−75	650	6.8	90
−40	577	6.2	100
−40	697	—	—
+35	702	7.9	100
+75	797	8.0	100
+200	700	10.3	100
+400	773	9.0	100

TABLE 7—(Continued)

Temperature (°F)	Energy (ft-lbs)	Lateral Contraction (%)	Percent Fibrous
Shrinkage Class 4 Heat G—Quench & Temper 141,300 psi - U.T.S.			
−321	95	0.8	30
−321	85	0.4	30
−200	293	3.0	40
−150	200	4.0	60
−100	526	6.4	90
−75	620	9.3	100
−40	646	8.3	100
−40	600	6.9	100
+75	600	7.0	100
+200	711	6.6	100
Shrinkage Class 4 Heat H—Normalize & Temper 79,800 psi - U.T.S.			
Composition: C .32, Mn .80, Si .52, Cr .45, Ni .60, Mo .21, P .027, S .028			
−321	32	0	0
−321	37	0	0
−200	41	0.3	10
−100	70	0.8	20
−75	164	1.1	50
−40	600	7.4	80
−40	590	7.4	90
+75	494	6.8	100
+200	512	6.5	100
+500	620	6.2	100
Shrinkage Class 2 - 3 Heat H—Normalize & Temper 91,100 psi - U.T.S.			
−321	37	0	0
−321	24	0	0
−200	41	0.2	10
−150	135	1.0	10
−150	80	0.9	10
−125	309	5.5	40
−100	415	7.5	50
−40	683	8.8	90
+75	702	9.5	100

TABLE 8
Unnotched Tension Impact Test Results

Sound
Heat B—Quench & Temper
149,300 psi - U.T.S.

Composition: C .33, Mn .89, Si .38, Cr .45, Ni .55, Mo .25, P .027, S .030

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	104	2.1	0.56	30
−321	118	—	—	30
−250	228	20.6	—	50
−250	234	22.1	7.30	50
−200	370	22.6	9.55	90
−200	400	—	—	100
−110	378	24.6	12.92	100
−110	—	27.5	13.48	100
−50	398	29.4	—	100
+75	416	38.5	13.48	100
+200	352	35.8	11.23	100
+200	374	24.1	12.36	100
+400	374	40.7	11.23	100
+400	350	—	—	100

Sound
Heat C—Normalize & Temper
93,800 psi - U.T.S.

Composition: C .37, Mn .64, Si .26, Cr .45, Ni .55, Mo .25, P .026, S .029

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	58	0	0	0
−250	58	0	0	0
−250	114	—	—	10
−200	150	8.7	12.36	20
−200	127	—	—	20
−150	130	17.1	—	30
−110	254	19.1	15.73	30
−110	—	31.2	—	30
0	380	—	—	90
+75	378	38.0	24.14	100
+200	382	39.4	25.26	100
+400	360	38.5	23.58	100

Shrinkage Class 3
Heat G—Quench & Temper
141,300 psi - U.T.S.

Composition: C .32, Mn .84, Si .37, Cr .60, Ni .60, Mo .19, P .030, S .032

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	18	0	0	0
−321	16	0	0	0
−250	25	1.6	0.56	20
−200	25	1.6	0.56	40
−200	50	1.6	0.56	40
−110	70	2.2	0.56	80
0	86	3.3	1.12	100
+75	62	3.3	1.69	100
+150	80	4.9	2.25	100
+200	58	7.1	1.12	100
+400	90	8.2	2.25	100

TABLE 8—(Continued)

Shrinkage Class 3
Heat H—Normalize & Temper
91,100 psi - U.T.S.

Composition: C .32, Mn .80, Si .52, Cr .45, Ni .60, Mo .21, P .027, S .028

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	18	0	0	0
−200	19	0	0	0
−200	6	0	0	0
−110	—	0.5	0.56	10
−110	44	0	0	10
−50..	18	2.2	—	50
−50	38	2.2	0.56	50
0	110	8.7	—	90
+75	112	10.3	4.46	100
+200	70	10.3	4.46	100
+200	90	17.1	8.43	100
+400	94	6.6	—	100

Shrinkage Class 2
Heat I—Quench & Temper
134,500 psi - U.T.S.

Composition: C .30, Mn .64, Si .21, Cr .45, Ni .55, Mo .25, P .027, S .030

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	18	0	0	0
−250	—	1.6	0.56	10
−200	48	1.6	0.56	20
−200	50	—	0.56	30
−110	80	3.8	0.56	80
−50	125	2.2	1.12	90
0	134	3.8	1.69	100
+75	106	8.2	1.69	100
+200	100	7.6	2.25	100
+200	92	6.6	1.69	100
+200	100	9.3	2.25	100
+400	105	15.0	3.37	100

Shrinkage Cless 2
Heat I—Normalize & Temper
83,800 psi - U.T.S.

Temperature (°F)	Energy (ft-lbs)	% R.A.	% El	% Fibrous
−321	18	0	0	0
−200	6	0	0	0
−200	10	0	—	10
−110	50	0.5	—	10
−50	110	—	—	50
−50	50	6.3	—	50
0	154	9.3	3.93	90
+75	130	11.9	4.49	100
+200	90	10.9	2.81	100
+200	100	16.6	5.62	100
+350	94	17.1	6.74	100
+400	110	17.1	4.49	100

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