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Static and dynamic fracture behavior of A737 Grade B steel.

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STATIC AND DYNAMIC FRACTURE BEHAVIOR OF A737 GRADE B STEEL

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ABSTRACT

An experimental program was conducted on the strength and toughness of A737 Grade B carbon-manganese-columbium pressure vessel steel in two conditions of heat treatment and at two levels of sulfur content. The steel was tested in the normalized and in the quenched and tempered condition and was made to a normal (.023%) sulfur level and a low (.006%) sulfur level. The Charpy impact and tensile properties were measured between -96° and +23°C (-141° and +73°F). Static and dynamic fracture toughness using compact and bend specimens was measured over the same temperature range. Static K_{Ic} was determined from J_{Ic} at fracture, the J_{Ic} at maximum load and from J vs Δa curves. Dynamic K_{Id} was determined from the energy to fracture in an instrumented drop weight test.

The results of the tests show that both static and dynamic fracture toughness is improved by decreasing the sulfur content of the steel and by quenching and tempering rather than normalizing. Both the temperature of transition in toughness from low to high values and the absolute toughness level are improved. Static K_{Ic} values ranged between 200 MPa and 280 MPa (about 180 Ksi to 250 Ksi) in the ambient temperature range and decreased to between 110 and 220 MPa$\sqrt{in}$ (about 100 to 200 Ksi) at -96°C Dynamic fracture toughness, about equivalent to the static in the ambient range, decreases sharply at -40°C (-40°F) and below.

INTRODUCTION

When a new material is being developed for pressure vessel service, it is usually necessary to undertake a careful evaluation of the characteristics of the material before it is possible to establish the limits of its application and the specific benefits that it will provide. Such an evaluation will include determinations of strength, ductility and toughness over a range of temperature, fatigue behavior, response to heat treatment, weldability testing, and the effect of operating environment on these properties. While the material supplier or a potential user will often develop such data, it is also useful for an independent evaluation to be undertaken by a research organization that can bring to bear a wide range of experience on the evaluation. It was with this intent that the Pressure Vessel Research Committee of the Welding Research Council, through the Pressure Vessel Steels Subcommittee of the Materials Division, undertook in 1974 to begin the examination of a series of new steels for pressure vessel service. During the initial course of this investigation, portions of which were published as P.V.R.C. project reports,[1,2] relatively high strength steels were studied. In the more recent work, reported here, the properties of "microalloyed" carbon-manganese A737 steels of moderate strength but much higher toughness are included in the program.

Evaluation of any new material involves not only measure-

ment of the normal material properties but also, in some cases, the development of new test procedures to provide the kind of information required. In the research reported here, both aspects of the problem were given attention. For the materials included in this investigation, the property of greatest importance is toughness, and thus adequate measures of toughness had to be considered and utilized. On the other hand, the measurement of toughness is still only a means to an end, as the ultimate usefulness of the material rests on the properties measured: thus, the overall intent of this work was to develop the anticipated properties of one of the newer A737 micro-alloyed steels and to do so with a fracture toughness test technique compatible with its inherent high toughness.

Fracture toughness testing to control the brittle fracture resistance of materials received its early development during and after the World War II period when the Charpy V-notch impact test was first utilized to establish the toughness of ship plate. Although empirical in nature, this test procedure has served for many years to provide a satisfactory fracture control parameter for ships, pressure vessel, and more recently bridges and some buildings. Current evaluations of fracture toughness for pressure vessel service still utilize this test; however, the pressure vessel industry as a whole has begun to use the principles of linear elastic fracture mechanics as an alternate method to establish the toughness required in these

structures. Fracture mechanics has been widely employed to interpret the fracture behavior of high strength steels (yield strength > 200 Ksi) for which plane strain behavior can be obtained at room temperature in relatively thin section sizes. As fracture mechanics analyses are extended to tougher, low strength steels, increased plasticity causes difficulties in the application of the linear elastic model to these materials.

The steel examined in this study, of which more will be said later, is an example of precisely the type of material for which analyses by linear elastic fracture mechanics is difficult. The relatively high ambient toughness and low yield strength of the steel makes measurement of fracture toughness by the linear elastic criteria and methods of ASTM standard E399 virtually impossible. This standard specifies that the thickness (and other dimensions) of the specimen to be used to measure the plane strain fracture toughness, K_{Ic}, must fulfill the inequality:

$$B \geq 2.5 \left(\frac{K_{Ic}}{\sigma_y}\right)^2 \qquad \text{Eqn. 1}$$

where B is the specimen thickness and σ_y the yield point. Since the K_{Ic} is high relative to the yield point, not infrequently twice the yield point, the value of B is consequently very large, often on the order of 200-400mm (~8-16 in). Such a specimen size is not only impractical for testing, but often exceeds the thickness of the plate to be tested. Although the

steel selected for study in this investigation has a high level of toughness, it is by no means unique, because many pressure vessel steels have a ratio of K_{Ic} to σ_y which exceeds one in the service temperature range. In each of these cases the specimen thickness requirement becomes unrealistic, especially so when plate thicknesses are on the order of 25-75 mm (1-3 in).

The need to develop crack toughness measurement techniques which utilize smaller specimens became apparent more than fifteen years ago, and it was about ten years ago that serious work was done to provide an acceptable technique for performing and analyzing such tests. At the present time most of the efforts have used the same basic formulation as developed for linear elastic cases, i.e. a K_{Ic} is obtained experimentally and allowable stresses and/or flaw sizes determined from the experimental K_{Ic}. The difference lies in the fact that K_{Ic} is not measured directly but rather is estimated from an elastic-plastic crack toughness parameter measured on a small specimen. In this investigation, the K_{Ic} was estimated from the J-integral at the initiation of ductile tearing in a static compact specimen. Although other characterizations could have been used, the J-integral appears to give comparable results and has gained wide acceptance in the pressure vessel industry.

As is traditional for highly strain rate sensitive material, both static and dynamic toughness characterizations were desired and for this reason the K_{Id} was also determined.

Since the data obtained in these tests were not of the same type as the static tests, the K_{Id} was estimated from the energy to fracture absorbed by bend specimens impacted with a falling weight. Both the static and dynamic test specimens were so designed that they could be analyzed by linear elastic fracture mechanics procedures in the low temperature regime. Some tests were performed at low enough temperatures that valid K_{Ic} data were obtained.

As indicated above, the material tested in this program is of importance in and of itself. It is one of a class of low-alloy high-strength steels that utilizes relatively low carbon content and finely dispersed carbides to provide a strength and toughness level that is suitable for low temperature service. This type of steel has been used for piping and structural applications under several different specifications but has only recently been incorporated into ASTM pressure vessel specifications such as A734, A735 and A737. The grade tested meets the ASTM A737 Grade B specification. The specified alloy element for strength is columbium. The plates were 100 mm (24 in) thick.

Because the aim of this study was to fully characterize this type of steel, several variations on the basic chemical composition and heat treatment were employed. First, the steel was provided in both the mill normalized and mill quenched and tempered condition. Second, the steel was provided in several

heats, two made to a normal sulfur level, about 0.025%, and one to a low sulfur level, less than 0.010%. The intent of these variations was to produce steel with a range of fracture toughness at low temperatures, some conditions being quite high in toughness and others being more normal for a low carbon, high manganese steel. Previous experience with carbon-manganese steels has shownthat both quenching and tempering and control of sulfur contents to low levels are beneficial to Charpy impact toughness, the former lowering transition temperature and the latter raising upper shelf toughness. In this study, the aim was to determine the effect of these variables on typical fracture-mechanics parameters other than Charpy impact toughness. Thus the fracture toughness of all four conditions was determined over a range of temperatures, the final result being a comparison between the materials over the potential temperature range of service.

TEST MATERIALS

The materials under investigation were microalloyed C-Mn ASTM A737 Grade B steel having the chemical composition and mechanical properties listed in Table 1. Since the primary aim of this investigation was the toughness of the steel, mechanical properties were determined in the worst or transverse (T-L) orientation. The steel was studied in four variations including two normal sulfur heats, 0.023%, (Table 1) and one low sulfur heat, 0.006%, (Table 2). Both types were studied in the mill quenched and tempered and the mill normalized conditions. The plates were nominally 100 mm (4 in) thick. The steel was produced by the electric arc process using a cold scrap charge. The low sulfur heat was calcium treated. Rolling was by conventional practice. The plates were austenitized at 900°C (1650°F) and either cooled in still air for normalizing or water sprayed and tempered at 595°C (1100°F) for quenching and tempering.

TESTING PROCEDURES

Tension and Charpy Impact Tests

Standard 6.35 mm (0.250 in) diameter button head specimens in the transverse (T-L) and longitudinal (L-T) orientations were tested at room and low temperatures according to ASTM specification A370. A 44.4 KN (10,000 lb) Instron testing machine with a constant crosshead speed of 5 mm/min(0.2 in/min) was used. Low temperature tests were performed in a bath of 2-methylbutane cooled with liquid nitrogen. Charpy V-notch impact tests were performed on T-L quarter and center thickness specimens of plates from all four test conditions over a range of temperatures. A 325J (240 ft-lb) Satec model SI-1 testing machine was used and testing was done to the ASTM Specification E23. Specimens for the low temperature tests were cooled in a bath of 2-methylbutane and liquid nitrogen.

Fracture Toughness Tests

Compact specimens in 50 mm (2 in) thickness were prepared in the T-L orientation, precracked and tested statically according to the provisions of ASTM specification E399. The specimen used is seen in Figure 1. The specimens were tested over a range of temperatures between 23°C and -96°C (73°F and -141°F). Because of the relatively high toughness of the steel in the ambient range, many of the tests were invalid. The invalid test specimens were evaluated using the J-integral approach. The J_I value for these specimens was estimated using the approximation:[3]

$$J = \frac{2\lambda A}{Bb} \qquad \text{Egn. 2}$$

Here J is the J integral, A is the area under the load-load point deflection curve to the deflection of interest, B is the specimen thickness, b is the remaining uncracked ligament, and λ is a correction factor to allow for the tensile forces on the crack (primarily a function of $(a/W)^4$.

The static tests were run on a 553 KN (120,000 lb) Baldwin universal testing machine. The load-load line displacements were measured using a strain gage bridge mounted on a load cell in the loading train and on a clip-in displacement gage mounted on the specimen crack mouth. These data were recorded on a Hewlett-Packard X-Y recorder. The crack mouth displacements were subsequently converted to load-line displacements by assuming the crack faces rotate during testing around a point 0.45b from the crack tip into the ligament, b. The temperature of the specimen was measured and recorded using a copper-constantin thermocouple on the specimen surface and a Sargent strip chart recorder. Low temperature was achieved by spraying liquid nitrogen on the specimen surface with the specimen and grips in an insulated chamber. Test temperature was held 10-15 minutes prior to testing.

Four or five specimens were tested at each of the higher test temperatures with testing of each specimen discontinued after a predetermined (estimated) amount of crack growth was

achieved. After the specimen was loaded to the predetermined load or displacement, the specimen was unloaded and the crack position heat tinted by placing it in a furnace (in air) at 427°C (800°F) for two hours. The specimen was subsequently tested to failure and crack growth in the central portion of the specimen measured at three points and averaged to give the "crack growth", Δa, for the specimen. Both J vs Δa and maximum load J-integral data were measured. In order to increase the maximum load information, specimens tested at lower temperature and heat tinted were pulled to failure at higher temperature, thus providing crack growth information and maximum load data (at two different temperatures) with one specimen. Inherent in this procedure is the assumption that heat tinting did not materially affect the maximum load achieved in the specimen.

Determination of the fracture toughness, K_{Ic}, was done using the J vs Δa curves constructed from the test data (Figures 12-18). In each case the J_{Ic} for the initiation of ductile tearing was determined by fitting a line through the J vs Δa points and constructing a "blunting" line from the expression[5]:

$$J = 2\Delta a \sigma_f \qquad \text{Eqn. 3}$$

Here J is the J-integral, Δa is the displacement and σ_f is the flow stress of the material. The value of σ_f is approximated as being midway between the yield stress and ultimate tensile strength of the steel. The blunting line represents specimen displacement associated with plastic flow, not tearing. When

the data deviate from this line, displacement associated with true fracture occurs. Thus the intersection of the blunting line (Egn. 3) and the curve through the remaining data defines the Δa at fracture initiation and thus the true J_{Ic}. The K_{Ic} is calculated from J_{Ic} by the expression

$$K_{Ic} = \sqrt{\frac{J_{Ic} \; E}{1-\nu^2}} \qquad \text{Eqn. 4}$$

Here E is Young's modulus and ν is Poissons ratio.

Dynamic fracture toughness tests were performed, using T-L orientation, 50 mm (2 in) thick, fatigue cracked bend test specimens prepared according to the geometry requirement of ASTM specification E399 and tested in an instrumented drop weight tester. The specimens were cooled in a methanol or 2-methylbutane and liquid nitrogen bath and tested within 10 seconds after removal from it. The specimen was held at temperature for at least 10 minutes prior to testing. Half round 25 mm (1 in) diameter drill rod pads were placed on the specimen at the impact point to decrease the load rise time and reduce inertial effects. A smooth load-line trace without evidence of ringing was generally obtained, as shown in Figure 2. The data was recorded using a solid state transient recorder with the stored load-time pulse subsequently replayed on an X-Y recorder.

The impacting tup was machined from a high toughness steel heat treated to a hardness level of $R_c 50$. The testing fixture

provides two point support on a 400 mm (16 in) span. A 182Kg (400 lb) free falling weight supported by an electromagnetic release mechanism provided the impact load.

The dynamic fracture toughness was calculated using the concept that the nonlinear critical strain energy release rate (J_{cd}) is proportional to the area under the force-displacement curve up to the point of fracture initiation.[6] The critical dynamic stress intensity, K_{dt}, is then calculated from J_{cd} using equations 2 and 4, i.e.

$$K_{dt} = \sqrt{\frac{J_{cd}E}{1-\nu^2}} = \sqrt{\frac{2\ Wm\ E}{bB\ 1-\nu^2}} \qquad \text{Eqn. 5}$$

The work to maximum load, W_m, may be approximated by [6]:

$$W_m = \int_o^{xm} Pdx = \int_o^{tm} PVdt = Vo \int_o^{tm} Pdt \qquad \text{Eqn. 6}$$

In this it is assumed that the work to maximum load, Pmax, may be approximated from the load-time trace using the velocity at impact, Vo, and the time to failure, tm. The Vo at impact is calculated from:

$$V_o = 2gh \qquad \text{Eqn. 7}$$

where h is the height the weight is released from and g, the acceleration due to gravity. At the lowest temperatures tested, -96°C (-141°F), most of the specimens had flat fracture surfaces and the values obtained are believed to be valid in the

sense used in ASTM E399.

Metallographic Examination

The four material variations in the study were examined metallographically at centerline thickness in a longitudinal orientation plane. Standard polishing and etching procedures were employed with 2% nital used for the final etch. Photomicrography was done using a Zeiss Axiomat metallograph and Polaroid PN55 film.

RESULTS AND DISCUSSION

Tension and Impact Tests

The results of the tension tests on the four plates of A737 Grade B are listed in Table 3 and may be compared to the data of Tables 1 and 2. The same data are also plotted in Figures 3-5. As is evident from Table 3, all of the plates meet the minimum longitudinal (L-T) yield and tensile strength specifications for the grade. The quenched and tempered plates have higher yield and tensile strengths than their normalized counterparts, the most noticeable difference being in yield strength. The low sulfur plates appear higher in strength than the normal sulfur ones. This effect is probably due to the somewhat higher manganese and residual element content of this low sulfur heat rather than its sulfur content. Figures 3, 4, and 5 show that the yield and tensile strengths of the plates gradually increase with decreasing temperature. Between 23°C and -96°C (73°F and -141°F) the yield strength increases about 35% for the normalized material and about 30% for the quenched and tempered material. Tensile strengths increased about 25% over the same temperature range, the increase for the normalized steel again being somewhat greater. Tensile ductility shows a modest increase over the temperature range tested, except for the low sulfur heat where a slight loss is noted at -96°C (-141°F).

The impact test results are shown in Figures 6-9.

Although all four of the plates show good impact toughness at temperatures down to at least -50°C (about -60°F), the low sulfur plates are clearly superior in transition temperature and have a substantially higher upper shelf toughness. The improved shelf toughness is one of the chief benefits of low sulfur steels, and this is graphically illustrated in these cases. For each sulfur level, the quenched and tempered steel is lower in transition temperature and higher in shelf energy, although this effect is not as marked as the effect of decreased sulfur. When reviewing these figures, it should be emphasized that transverse (T-L) specimen data are being shown. Longitudinal specimen data would probably give somewhat higher toughness values. Center and quarter thickness specimen data are shown on Figures 6-9. The difference in toughness between specimens taken from these two locations is slight. In only one case does the quarter thickness location give higher toughness

Metallography

The microstructure of the four plates seen in Figures 10 and 11 appears to be generally consistant with the results of the tensile and Charpy impact tests. The quenched and tempered plates have much finer ferrite-carbide aggregates than the normalized ones, but are otherwise similar in structure. As might be expected, the hardenability of the steel is insufficient to form lower temperature transformation products; however

a substantial structural refinement occurs and is relatively uniform across the central two-thirds of the plate. The improvement in yield and tensile strength with quenching and tempering is undoubtedly a result. As indicated before, a decrease in transition temperature and an increase in shelf toughness results from this refinement.

From the standpoint of overall structure and uniformity, the low sulfur heat is, as expected, cleaner, i.e. has fewer inclusions. The inclusions that are present tend to be more rounded. However, it is also observable that the low sulfur heat has more pronounced ferrite-pearlite banding. The banding appears more pronounced in normalized than in the quenched and tempered condition. It is possible that the relatively high manganese content of this heat may have contributed to the banding tendency. Because of the nature of this experiment it is impossible to determine what effect, if any, the banding has on mechanical properties.

Static Fracture Toughness

The static fracture toughness data for the A737 Grade B steel are found in Tables 4 and 5. The J_{Ic} data obtained for each condition are of three types. At low temperatures, generally -96° to -100°C (-141° to -148°F), the values listed as J_{Ic} are based on a distinct fracture load. Because of the thickness of the specimen, they are not valid by the specifications of ASTM E399. The J_{Ic} was therefore determined for

these cases from the area of the P-Δ curve to fracture. At higher temperatures, no distinct fracture was observed. In these cases, the J vs Δa curve was constructed. These curves are found in Figures 12-18. A J_{Ic} was determined from the blunting line-data curve intersection. In addition, the single curve from the J vs Δa data set which had a deflection that extended to maximum load was selected and a J_{Ic} was calculated at maximum load for this sample. The summary column of K_{Ic} is calculated from the J_{Ic} using Eqn. 4 with the nature of the data indicated by a subscript, i.e. based on fracture, maximum load deflection or the J vs Δa curve.

The J vs Δa curves, Figures 12-18, proved to be relatively smooth with most of the data lying close to a straight line. In several cases, the data could have just as well fitted some other function. Data in the literature are occasionally plotted nonlinearly, but since there was no clear precedent for this, a straight line mechanical fit of the data was chosen here. The resulting J_{Ic} values determined from the intersection points were generally self consistent. For example, the K_{Ic} values for the low sulfur heat determined by this method were 234 MPa$\sqrt{m}$ (213 Ksi$\sqrt{in}$) and 241 MPa$\sqrt{m}$ (219 Ksi$\sqrt{in}$ at -46°and 23°C (-51° and 73°F), respectively, for the normalized condition. The quenched and tempered condition data were 275 MPa$\sqrt{m}$ (251 Ksi$\sqrt{in}$) and 279 MPa$\sqrt{m}$ (254 Ksi$\sqrt{in}$) at the same two temperatures. The relatively small effect of temper-

ature is consistant with the fact that the material is on the upper shelf of toughness over this temperature range in static tests. By way of comparison, the normal sulfur heats, which had a lower shelf toughness in the Charpy tests, had a K_{Ic} of 198 MPa$\sqrt{m}$ (181 Ksi$\sqrt{in}$ and 237 MPa$\sqrt{m}$ (215 Ksi$\sqrt{in}$ at 23°C (73°F) for the normalized and the quenched and tempered condition, respectively. At low temperatures, -96°C (-141°F) the materials rank in the same order, although the J_{Ic} is determined in this case from a definite fracture criterion in the test. The low sulfur steel once again had higher values of K_{Ic} in both conditions than the corresponding normal sulfur heat. For each sulfur level, the quenched and tempered value was greater than the normalized one. A summary of the K_{Ic} values on Tables 4 and 5 is shown in Figure 19.

Of some practical interest from the standpoint of testing is a comparison of the K_{Ic} calculated from J_{Ic} at maximum load and that calculated from the J_{Ic} intersection point on the J vs Δa curves. From Tables 4 and 5 it can be seen that the maximum load K_{Ic} is consistantly larger than that from the J vs Δa curves, the intersection point K_{Ic} being between 5% and 20% smaller. This implies that ductile tearing in this steel always preceeds the maximum load point in the test and suggests that a simplified test technique could be used. The maximum load J_{Ic} could be determined for the material using one or several specimens and a K_{Ic} calculated. This value could then be reduced by 20% to give the approximate K_{Ic} at

the initiation of tearing.

Dynamic Fracture Toughness

The dynamic fracture toughness data are found in Tables 6 and 7 where K_d based on maximum load and K_{dt} from Eqn. 5 are both listed. K_{dt} values are plotted on Figure 20. It is apparent that at ambient temperatures for the normal sulfur level steel, the dynamic fracture toughness level is about equal to that of the static. At lower temperatures, however, starting at 0°C (32°F) for the normalized material and at -45°C (-48°F) for the quenched and tempered, the fracture toughness decreases sharply. For temperatures at -45°C (-48°F) and below, valid K_{Ic} data are obtained using the maximum load in the test. At higher temperature the $K_d$max values are not meaningful. This result is somewhat surprising as the Charpy impact data indicate a relatively high toughness in the same temperature range; however, it is not inconsistant with the relationship between static and dynamic fracture toughness test data found in the literature. The temperature shift, T_s, between static and dynamic K_{Ic} data has been shown to be a function of the material yield point, σ_y, as follows[7]:

$$T_s(°F) = 215 - 1.5\sigma y \ (K_{si}) \qquad \text{Eqn. 7}$$

For the normal sulfur material studied here, the yield point is between 345 and 415 MPa (50 and 60 Ksi) and thus the shift should be between 70° and 80°C (125° and 145°F). This

is, in fact, in agreement with the data from Figures 19 and 20 in that a K_{Ic} for the normalized steel of about 150 MPa$\sqrt{m}$ (136 Ksi$\sqrt{in}$) occurs at about -70°C (-94°F) while the K_{Id} of the same value is at about 10°C (50°F), a shift of 80°C. The corresponding shift for the quenched and tempered steel is also about 80°C. These shifts can readily be seen on the summary curves, Figures 21 and 22. The difference between the Charpy impact results and the 50 mm (2 in) thick specimen data would then have to be attributed to a specimen size effect.

Fracture Toughness Summary

The fracture toughness data obtained in this investigation are summarized in Figures 21 and 22 for the normal and low sulfur A737B steel. The curves are plotted from the J vs Δa intersection data and fracture K_{Ic} data on Tables 4 and 5, as well as the dynamic K_{dt} data on Tables 6 and 7. An alternate approach to summarizing the fracture data obtained in this program could be to present the results on the basis of "crack toughness" rather than the fracture toughness alone[8]. The crack toughness parameter of greatest usefulness is the ratio of K_{Ic} to σ_y. This ratio is a fundamental measure of the plastic zone size at a crack tip during fracture and also, therefore, a measure of the plate thickness necessary for plane strain conditions at fracture. It appears in Eqn. 1 in this respect, and since it is a squared term, it exerts a significant influence. The data from Figures 21 and 22 are replotted

in Figures 23 and 24 utilizing this approach. For this analysis the dynamic yield point was estimated by adding 175 MPa (25 Ksi) to the static yield point at temperature. This is based on the elevation of the yield point by 35 MPa for each order of magnitude increase in strain rate between the two conditions.

On this basis, for example, plane strain conditions do not prevail for any material at any temperature examined in this program for plates up to 125 mm (5 in) thick in the static mode of loading. In the ambient range, static plane strain plate thicknesses exceed 765 mm (30 in). Dynamic plane strain plate thicknesses in the ambient range are on the order of 330 mm (13 in). In temperature range of -50°C (-68°F) dynamic plane strain plate thicknesses are much smaller because the K_{Id} is generally smaller than the K_{Ic} and the effective yield strength is elevated by strain rate. In spite of this effect, at temperatures above -40°C (-40°F) dynamic plane strain plate thicknesses are over 46 mm (1.0 in) with the exception of the normalized, normal sulfur heat. At very low temperatures, dynamic plane strain thicknesses decrease to 2-8 mm (.08 to .32 in).

CONCLUSIONS

From this investigation of the static and dynamic toughness of A737 Grade B steel in two conditions of heat treatment and at two levels of sulfur content, the following was concluded:

1. In terms of both Charpy impact transition temperature and Charpy impact upper shelf toughness, the low sulfur (.006%) heat of A737 B held a decided advantage over the normal sulfur (0.023%) heats. The transition temperature of the low sulfur heat was at least 30°C (54°F) lower than that of the normal sulfur heats and the shelf toughness about 100% higher. The quenched tempered condition plates were between 10° and 20°C (18° and 36°F) lower in transition temperature than their normalized counterparts. Shelf toughnesses were nearly equivalent for the two conditions.
2. In terms of static plane strain fracture toughness, the low sulfur heat was again higher in toughness than the normal sulfur heats over the range of temperatures tested, the difference between the two being about 20%. The quenched and tempered plates were also superior to the normalized ones for each sulfur level by about 20%. K_{Ic} values ranged between 200 MPa to 280 MPa (about 180Ksi to 250 Ksi) at ambient temperatures for the four conditions and between 110 and 220 MPa$\sqrt{m}$ (about 100 and 200 Ksi) at -96°C (-141°F). Fracture toughness determined from the

J_{Ic} at maximum load were higher than those determined from J vs Δa curves, the difference varying between 5 and 25%.

3. The dynamic fracture toughness for the plates tested was lower than the static values except in the ambient range. The same basic trends with regard to sulfur level and the effect of heat treatment on toughness seen in the static tests were followed in the dynamic ones, although the percentage differences were more variable. Plane strain fracture toughness values in 50 mm (2 in) specimens were obtained below -40°C (-40°F) for the normalized plates and at -96°C (-141°F) for the quenched and tempered ones. The shift of the toughness vs temperature curve as a result of the strain rate increase between the static and dynamic tests was about 80°C (145°F).

4. An analysis of the A737 Grade B steel in terms of the K_{Ic} to σ_y ratio shows that, in the ambient range, plane strain plate thicknesses are greater than 330 mm (13 in) for any condition tested. Plan strain plate thicknesses for static loading conditions remain above this level down -96°C (-141°F). Plane strain plate thicknesses under dynamic loading decrease sharply at -40°C (-40°F) and below, with values at -40°C (-40°F) ranging from about 25 to 75 mm (1 to 3 in) and at -96°C (-141°F), from about 2 to 8 mm (.1 to .3 in).

TABLE 1

Chemistry and Mechanical Property Data for A737B Steel - Normal Sulfur*

A. Chemical Composition

Plate	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	Cb
Normalized	.16	1.27	.007	.023	.22	.14	.15	.04	.26	.036	.033
Quenched & Tempered	.16	1.16	.012	.022	.19	.13	.14	.05	.25	.030	.025

B. Tension Test Properties (Transverse)

Plate	Yield Strength MPa	(Ksi)	Tensile Strength MPa	(Ksi)	Elong. %	R.A. %
Normalized	312	(45.4)	504	(73.1)	32.4	71.5
Quenched & Tempered	388	(56.3)	518	(75.0)	34.0	74.9

C. Charpy Impact Test Properties (Transverse)

	50 ft-lb (67.5J) Transition Temp. °C	(°F)	Upper Shelf Energy J	(ft-lb)
Normalized	-29	(-20)	122	(90)
Quenched & Tempered	-56	(-70)	143	(105)

*Data provided by Lukens Steel Company

TABLE 2

Chemistry and Mechanical Property Data for A737B Steel - Low Sulfur*

A. Chemical Composition

Plate	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	Cb
Normalized & Quenched & Tempered	.14	1.44	.009	.006	.19	.28	.22	.09	.27	.030	.025

B. Tension Test Properties (Transverse)

Plate	Yield Strength MPa	(Ksi)	Tensile Strength MPa	(Ksi)	Elong. %	R.A. %
Normalized	389	(56.4)	546	(79.3)	29	58.1
Quenched & Tempered	436	(63.3)	577	(83.7)	27.5	67.5

C. Charpy Impact Test Properties (Transverse)

	Energy at Temperature - Joules (ft-lb) (-50°F)		(-80°F)		(-100°F)	
Normalized	147	(109)	144	(107)	123	(91)
Quenched & Tempered	154	(114)			-	-

*Data provided by Lukens Steel Company

TABLE 3

Tension Test Data for A737B Steel

Plate, Orientation and Heat Treatment	Temperature °C	(°F)	Yield Sth. MPa	(Ksi)	Tensile Sth. MPa	(Ksi)	Elongation %
Normal Sulfur, Longitudinal, Normalized	22	(72)	351	(51.0)	505	(73.3)	38.1
	-46	(-50)	395	(57.3)	575	(83.4)	36.5
	-96	(-140)	482	(69.9)	643	(93.3)	38.1
Normal Sulfur, Transverse, Normalized	22	(72)	354	(51.4)	500	(72.5)	34.2
	-46	(-50)	373	(54.2)	576	(83.6)	38.8
	-96	(-140)	463	(67.2)	639	(92.8)	37.1
Normal Sulfur, Longitudinal, Quenched & Tempered	22	(72)	407	(59.1)	492	(71.4)	36.5
	-46	(-50)	465	(67.5)	591	(85.8)	36.6
	-96	(-140)	522	(75.8)	641	(93.1)	-
Normal Sulfur, Transverse, Quenched & Tempered	22	(72)	400	(58.1)	542	(78.6)	34.1
	-46	(-50)	391	(56.7)	560	(81.3)	36.5
	-96	(-140)	523	(75.9)	662	(96.1)	34.0
Low Sulfur, Longitudinal, Normalized	22	(72)	368	(53.4)	531	(77.0)	36.9
	-46	(-50)	451	(65.5)	630	(91.4)	38.6
	-96	(-140)	520	(75.2)	688	(99.8)	39.1
Low Sulfur, Transverse, Normalized	22	(72)	366	(53.1)	513	(74.5)	36.5
	-46	(-50)	432	(62.7)	606	(88.0)	40.0
	-96	(-140)	506	(73.4)	693	(100.6)	40.8
Low Sulfur, Longitudinal, Quenched & Tempered	22	(72)	444	(64.5)	568	(82.5)	31.1
	-46	(-50)	506	(73.5)	652	(94.6)	32.9
	-96	(-140)	586	(85.0)	722	(104.8)	32.6
Low Sulfur, Transverse, Quenched & Tempered	22	(72)	469	(68.0)	576	(83.6)	29.2
	-46	(-50)	545	(79.1)	681	(98.9)	32.1
	-96	(-140)	613	(89.0)	731	(106.1)	32.5

TABLE 4

Static Fracture Toughness Results for A737 Grade B
Normal Sulfur Heats - Transverse

Specimen No.	Temperature °C (°F)	Δa mm (mils)	J KJ/m^2(in-lb/in^2)	J_{Ic} KJ/m^2(in-lb/in^2)	K_{Ic} MPa$\sqrt{m}$(Ksi$\sqrt{in}$)
Normalized					
NC-1	23 (73)		102 (584)		
ND-1	23 (73)	0.015(0.6)	134 (768)		
NB-1	23 (73)	0.05 (2)	141 (804)		
NB-3	23 (73)	0.27 (11)	187 (1068)	187 (1068)*	208 (189)*
NA-2	23 (73)	0.83 (33)	274 (1562)		
NB-2	23 (73)	20 (80)	394 (2250)		
Graph	23 (73)			170 (975)+	198 (181)+
N-1	-50 (-58)		109 (626)	109 (626)#	160 (145)#
NC-3	-50 (-58)		240 (1369)	240 (1369)#	236 (214)#
NA-3	-96 (-140)		43 (248)	43 (248)#	100 (91)#
NC-2	-100(-148)		57 (327)	57 (327)#	116 (105)#
Quenched and Tempered					
4-2-C1	23 (73)		93 (534)		
4-2-D2	23 (73)	0.08 (3.3)	211 (1202)		
QT 1	23 (73)	0.38 (15)	270 (1531)		
4-2-B2	23 (73)	0.49 (19)	287 (1635)	287 (1635)*	259 (235)*
4-2-5	23 (73)	1.55 (62)	395 (2255)		
4-2-6	23 (73)	2.25 (90)	512 (2922)		
Graph	23 (73)			240 (1375)+	237 (215)+
4-2-C3	-41 (-42)	0.01 (0.4)	127 (726)		
4-2-B1	-41 (-42)	0.08 (3)	242 (1379)		
4-2-D1	-41 (-42)	0.46 (18)	360 (2054)	360 (2054)*	288 (263)*
QT 2	-41 (-42)	1.88 (75)	456 (2620)		
4-2-8	-41 (-42)	1.425(57)	383 (2183)		
4-2-9	-41 (-42)	1.25 (50)	381 (2171)		
Graph	-41 (-42)			227 (1300)+	230 (209)+
4-2-A3	-96 (-140)		118 (676)	118 (676)#	165 (151)#
4-2-C2	-100(-148)		73 (420)	73 (420)#	131 (119)#

* Max Load Value
\+ Intersection Point on Figures
\# Max Load Value - Fracture

TABLE 5

Static Fracture Toughness Data for A737 Grade B
Low Sulfur Heat - Transverse

Specimen No.	Temperature °C (°F)	-a mm (mils)	J KJ/m^2 ($in-lb/in^2$)	J_{Ic} KJ/m^2 ($in-lb/in^2$)	K_{Ic} $MPa\sqrt{m}$ (ksi/in)
Normalized					
5B-A3	23 (73)	0.21 (8)	250 (1425)		
5B-A1	23 (73)	0.46 (18)	289 (1650)		
5B-A2	23 (73)	0.75 (30)	410 (2339)	410 (2239)*	301 (274)*
5B-D1	23 (73)	0.77 (31)	432 (2464)		
Graph	23 (73)			250 (1425)+	241 (219)+
5B-D3*	-46 (-51)		232 (1508)	282 (1608)*	256 (232)*
5B-B3	-46 (-51)	0.162(65)	227 (1295)		
5B-D2	-46 (-51)	0.42 (17)	317 (1808)		
5B-B2	-46 (-51)	0.65 (26)	414 (2360)		
Graph	-46 (-51)			236 (1350)+	234 (213)+
5B-C2	-96 (-141)		76 (435)*	76 (435)#	147 (134)#
Quenched and Tempered					
5A-B1	23 (73)	0.37 (15)	369 (2106)	369 (2106)*	292 (266)*
5A-D2	23 (73)	0.40 (16)	320 (1824)		
5A-D3	23 (73)	0.50 (20)	403 (2297)		
5A-D1	23 (73)	1.20 (48)	566 (3237)		
Graph	23 (73)			336 (1925)+	279 (254)+
5A-C2	-46 (-51)	0.32 (13)	365 (2081)		
5A-B2	-46 (-51.)	0.50 (20)	443 (2524)		
5A-C1	-46 (-51.)	0.62 (25)	519 (2961)	519 (2961)*	346 (315)*
5A-B3	-46 (-51)	0.87 (35)	613 (3494)		
Graph	-46 (-51)			328 (1875)+	275 (251)+
5A-A1	-96 (-140)		226 (1291)	226 (1291)#	229 (208)#
5A-C3	-96 (-140)		250 (1426)	250 (1426)#	240 (218)#

* Max Load Value

\+ Intersection Point On Figures

\# Max Load Value - Fracture

TABLE 6

Dynamic Fracture Toughness Data For A737 Grade B Steel
Normal Sulfur Heats - Transverse

Specimen No.	Temperature °C (°F)	Fracture Mode	K_D(max)E399 MPa√m Ksi√in	W_n Joules(Ft.Lbs.)	K_{dt} MPa√m(Ksi√in)
Normalized					
N-8	23 (73)	1	100 (91)		
4-1	23 (73)	1	163 (148)	3318 (2447)	211 (192)
4-1-5	23 (73)	1	147 (134)	2957 (2181)	200 (182)
Avg.	23 (73)	1	135 (124)	3138 (2314)	205 (187)
4-1-1	0 (32)	1	136 (124)	198 (146)	54 (49)
4-1-6	0 (32)	1	131 (120)	717 (529)	101 (92)
Avg.	0 (32)	1	134 (122)	(337)	77 (70)
N-3	-10 (14)	1	111 (100)	493 (364)	93 (75)
N-6	-45 (-48)	2	68* (62)	164 (121)	47 (43)
4-1-10	-45 (-48)	2	53* (48)		
Avg.	-45 (-48)	2	61* (55)	164 (121)	47 (43)
N-2	-70 (-94)	2	35* (32)	102 (75)	32 (29)
N-1	-96 (-141)	2	32* (29)	35 (26)	37 (34)
4-1-12	-96 (-141)	2	42* (44)		
Avg.	-96 (-141)	2	40* (36)	35 (26)	37 (34)
Quenched & Tempered					
Q-T-1	23 (73)	3	109 (99)		
4-2-11	23 (73)	1	177 (161)	3570 (2633)	219 (200)
4-2-12	23 (73)	1	127 (116)	2231 (1646)	190 (173)
Avg.	23 (73)		152 (129)	2900 (2139)	202 (186)
4-2-3	0 (32)	1	156 (171)	2251 (1660)	175 (159)
4-2-6	0 (32)	1	160 (145)	2551 (1882)	196 (169)
Avg.	0 (32)		158 (173)	2401 (1771)	185 (164)
QT-5	-10 (14)	1	129 (117)		
QT-8	-45 (-48)	1	98 (89)	823 (607)	105 (96)
42-10	-45 (-48)	1	109 (99)	683 (504)	97 (88)
Avg.	-45 (-48)		103 (94)	752 (555)	101 (92)
QT-2	-70 (-94)	2	38* (34)	57 (42)	28 (25)
QT-7	-96 (-141)	2	26* (24)	35 (26)	22 (20)
4-2-9	-96 (-141)	2	41* (37)		
Avg.	-96 (-141)		33* (30)	35 (26)	22 (20)

1 Ductile Fracture

2 Brittle Fracture

3 Crack Did Not Propagate

* Valid K_{Id} By Specimen Size Criterion

TABLE 7

Dynamic Fracture Toughness Data for A737 Grade B Steel
Low Sulfur Heats - Transverse

Specimen No.	Temperature °C	(°F)	Fracture Mode	K_D(max)E399 MPa√m	(Ksi in)	W_m Joules	(ft-lbs)	K_{dt} MPa√m	(Ksi√in)
Normalized									
5B-4	23	(73)	1	192	(175)	5256	(3882)	268	(244)
5B-7	-45	(-48)	1	145	(132)	306	(226)	67	(61)
5B-8	-45	(-48)	1	156	(141)	841	(620)	105	(96)
Avg.	-45	(-48)		150	(136)	573	(423)	86	(78)
5B-1	-96	(-141)	2	93*	(85)				
5B-2	-96	(-141)	2	90*	(82)	104	(77)	38	(35)
Avg.	-96	(-141)		92*	(83)	104	(77)	38	(35)
Quenched & Tempered									
5A-5	23	(73)	1	221	(202)	3141	(2327)	222	(203)
5A-6	23	(73)	1	199	(182)	3250	(2397)	222	(203)
Avg.	23	(73)		210	(192)	3195	(2362)	222	(203)
5A-7	-45	(-48)	1	119	(108)	697	(514)	98	(89)
5A-8	-45	(-48)	1	137	(125)				
Avg.	-45	(-48)		128	(116)	697	(514)	98	(89)
5A-1	-96	(-141)	2	90*	(82)	150	(111)	45	(41)
5A-2	-96	(-141)	2	94*	(86)	125	(92)	42	(38)
Avg.	-96	(-141)		92*	(84)	138	(101)	43	(39)

1 Ductile Fracture

2 Brittle Fracture

* Valid K_{Id} by Specimen Size Criterion

TABLE 8

Summary of Fracture Toughness Data for A737 Grade B Steel

Transverse Properties

Material & Condition	Temperature °C (°F)	K_{Ic} MPa$\sqrt{m}$(Ksi$\sqrt{in}$)	K_{dt} MPa$\sqrt{m}$(Ksi$\sqrt{in}$)	K_{Ic}/σ_y $\sqrt{in}$	K_{dt}/σ_y $\sqrt{in}$	Plain Strain Thick Static mm (in)	Dynamic mm (in)
Normal Sulfur							
Normalized	23(73)	199 (181)	205 (187)	3.54	2.46	785 (31)	380 (15)
	-41(-42)	198 (180)	47 (43)	3.33	0.61	710 (28)	24 (.9)
	-96(-141)	108 (98)	37 (34)	1.46	0.36	135 (5)	8 (.3)
Quenched & Tempered	23(73)	237 (215)	204 (186)	3.71	2.24	865 (34)	330 (13)
	-41(-42)	230 (209)	101 (92)	3.67	1.12	865 (34)	80 (3)
	-96(-141)	149 (135)	22 (20)	1.77	0.20	200 (8)	3 (.1)
Low Sulfur							
Normalized	23(73)	241 (219)	266 (244)	4.13	3.12	1090 (43)	618 (24)
	-45(-49)	234 (213)	86 (78)	3.38	0.89	735 (29)	51 (2)
	-96(-141)	147 (134)	38 (35)	1.83	0.36	215 (8)	8 (.3)
Quenched & Tempered	23(73)	307 (279)	222 (203)	4.10	2.18	1065 (42)	305 (12)
	-45(-49)	303 (273)	98 (89)	3.48	0.86	760 (30)	46 (2)
	-96(-141)	234 (213)	43 (39)	2.39	0.18	355 (14)	2 (.1)

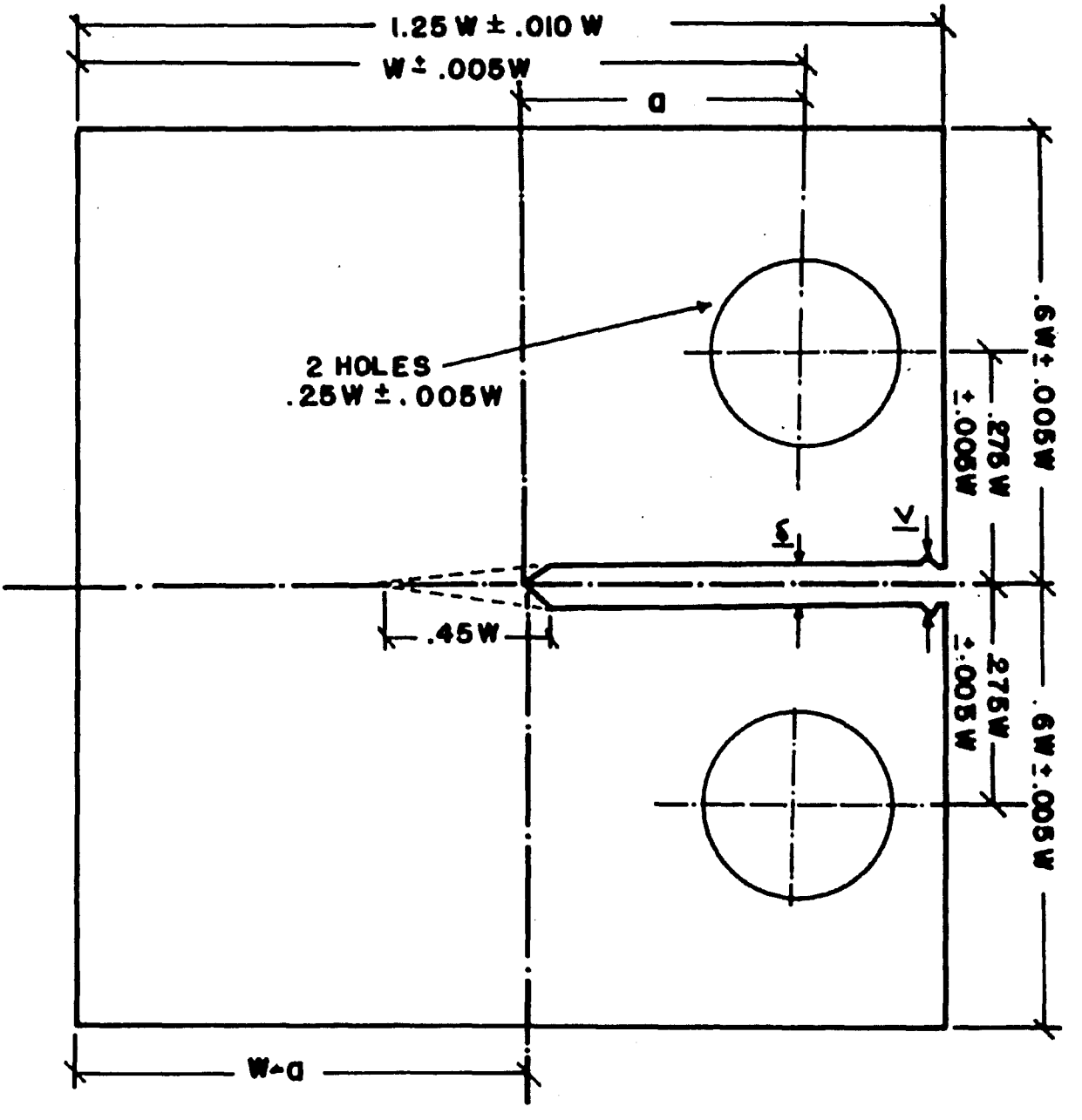

Fig.1 2-inch Thickness Compact Specimen

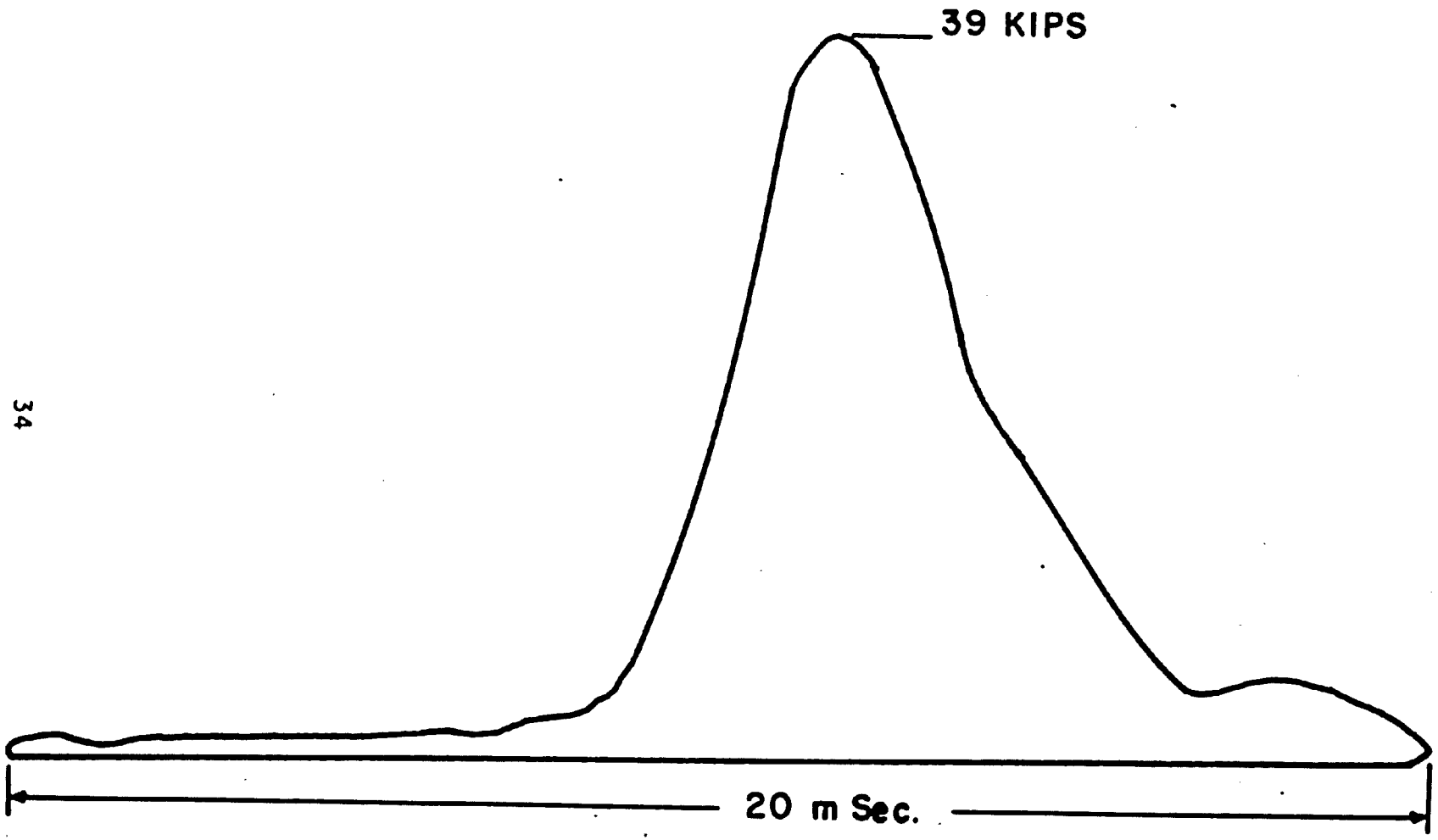

Fig.2 Time VS Load Trace of Dynamic Loading

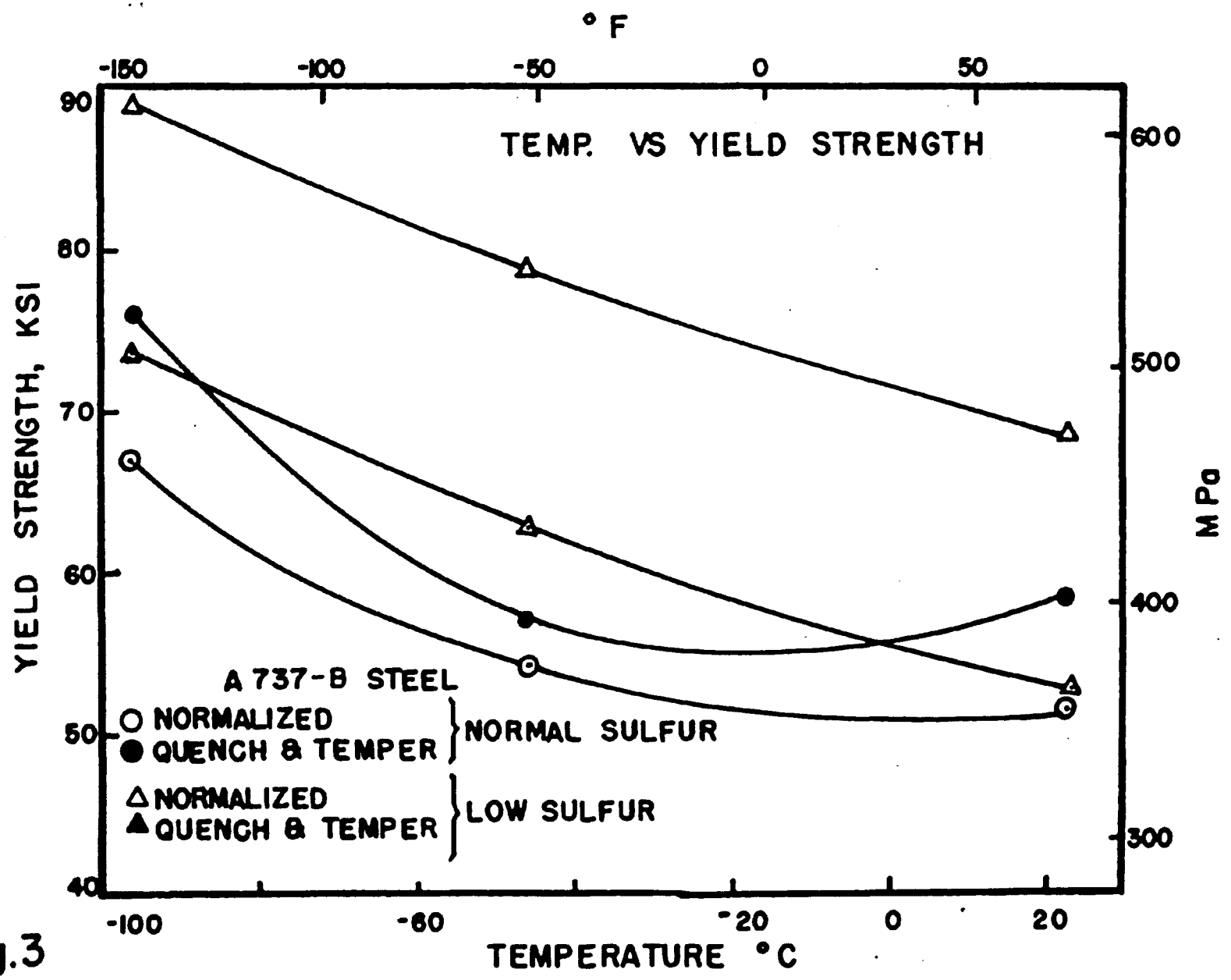
°F
-150
-100
-50
0
50
TEMP. VS YIELD STRENGTH
YIELD STRENGTH, KSI
90
80
70
60
50
40
600
500
400
300
MPa
A 737-B STEEL
○ NORMALIZED
● QUENCH & TEMPER
NORMAL SULFUR
△ NORMALIZED
▲ QUENCH & TEMPER
LOW SULFUR
-100
-60
-20
0
20
TEMPERATURE °C

Fig.3

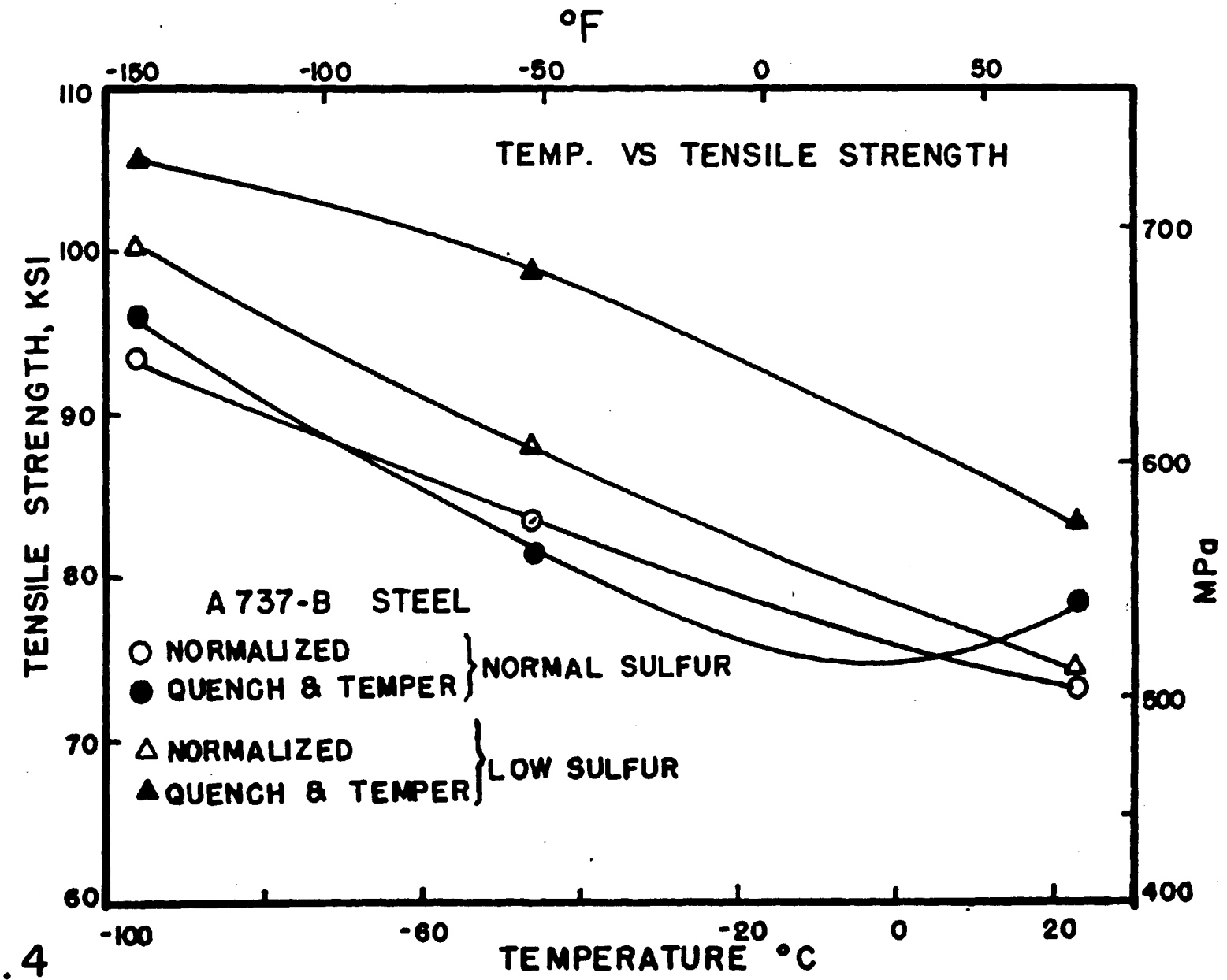
°F
-150
-100
-50
0
50
TEMP. VS TENSILE STRENGTH
TENSILE STRENGTH, KSI
110
100
90
80
70
60
700
600
500
400
MPa
A 737-B STEEL
○ NORMALIZED
● QUENCH & TEMPER
NORMAL SULFUR
△ NORMALIZED
▲ QUENCH & TEMPER
LOW SULFUR
-100
-60
-20
0
20
TEMPERATURE °C

Fig. 4

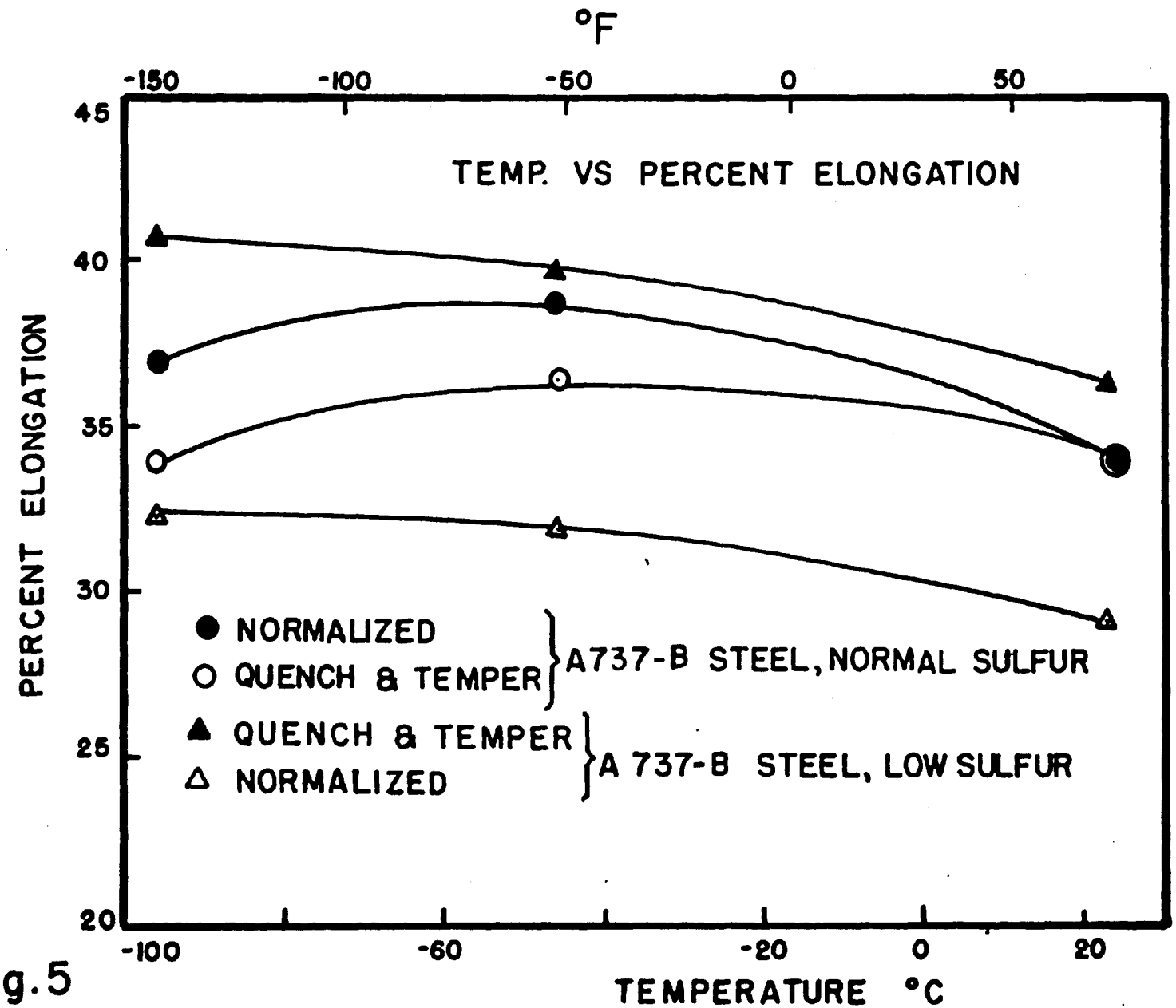
°F
-150
-100
-50
0
50
TEMP. VS PERCENT ELONGATION
45
40
35
30
25
20
PERCENT ELONGATION
NORMALIZED
QUENCH & TEMPER
A737-B STEEL, NORMAL SULFUR
QUENCH & TEMPER
NORMALIZED
A 737-B STEEL, LOW SULFUR
-100
-60
-20
0
20
TEMPERATURE °C

Fig.5

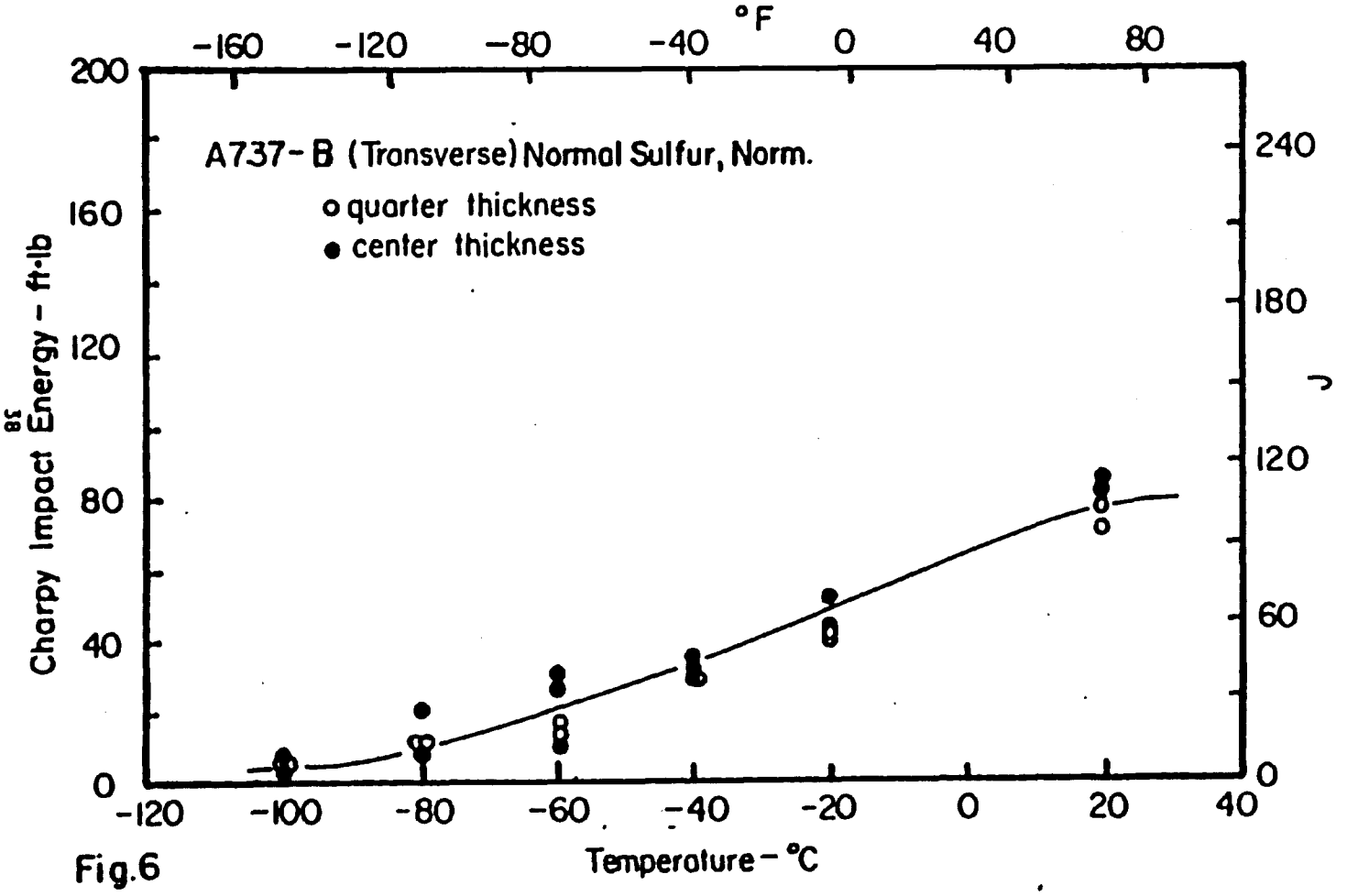
°F
-160
-120
-80
-40
0
40
80
200
160
120
80
40
0
A737-B (Transverse) Normal Sulfur, Norm.
o quarter thickness
● center thickness
Charpy Impact Energy - ft·lb
240
180
120
60
0
-120
-100
-80
-60
-40
-20
0
20
40
Temperature - °C

Fig.6

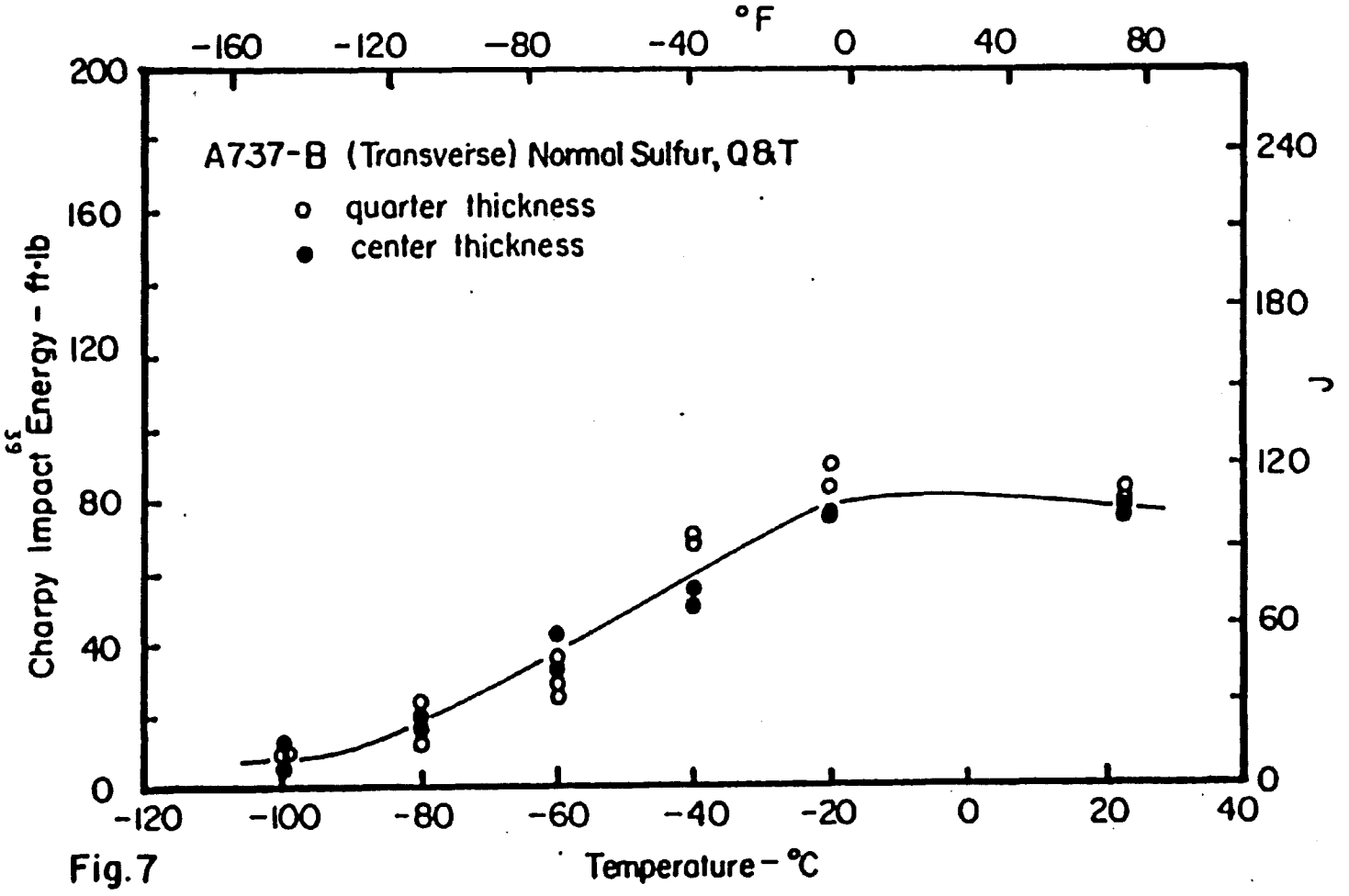
°F
-160
-120
-80
-40
0
40
80
200
160
120
80
40
0
A737-B (Transverse) Normal Sulfur, Q&T
o quarter thickness
● center thickness
Charpy Impact Energy - ft·lb
240
180
120
60
0
-120
-100
-80
-60
-40
-20
0
20
40
Temperature - °C

Fig. 7

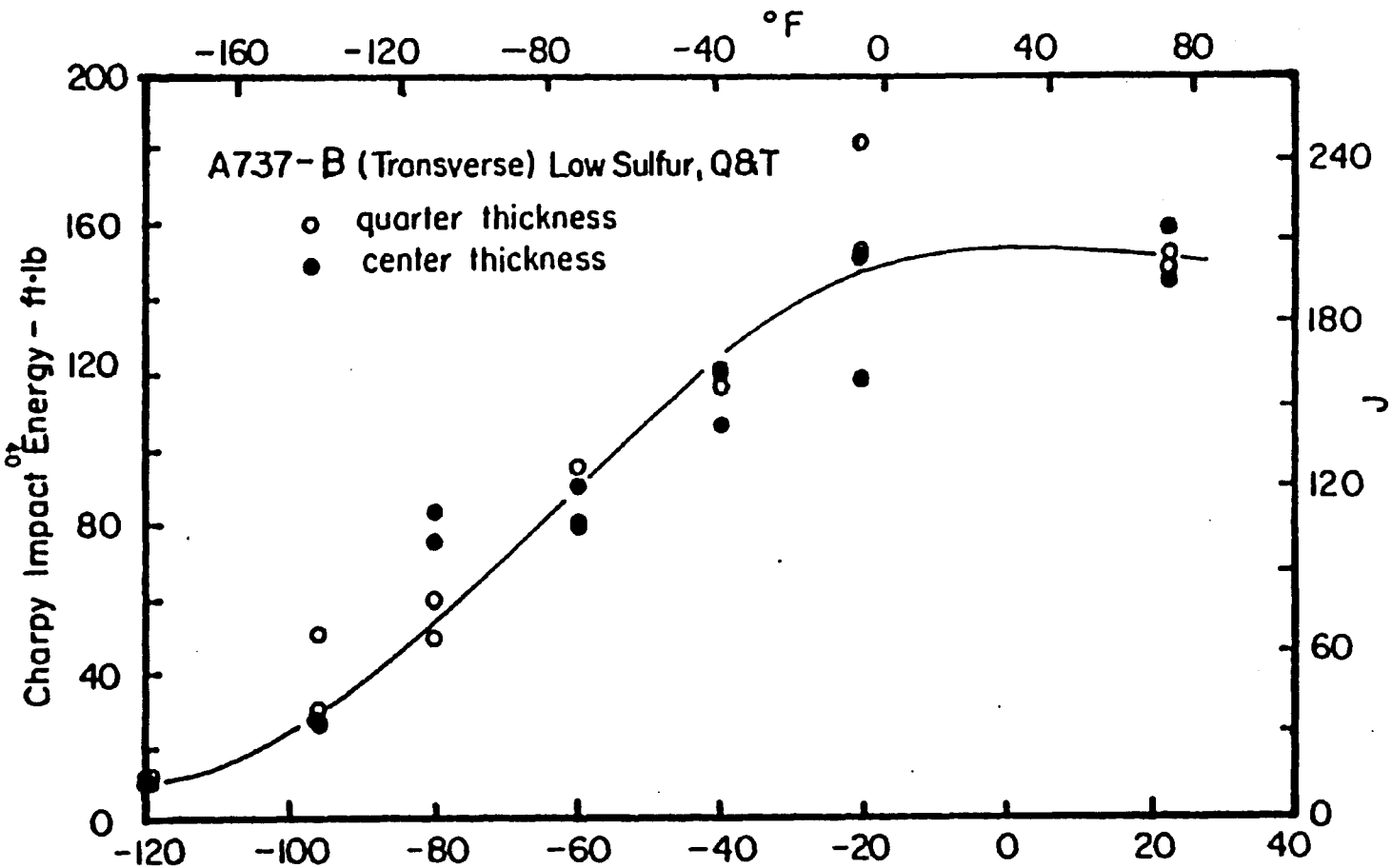
°F
-160
-120
-80
-40
0
40
80
200
160
120
80
40
0
A737-B (Transverse) Low Sulfur, Q&T
quarter thickness
center thickness
Charpy Impact Energy - ft·lb
240
180
120
60
0
J
-120
-100
-80
-60
-40
-20
0
20
40
Temperature - °C

Fig. 8

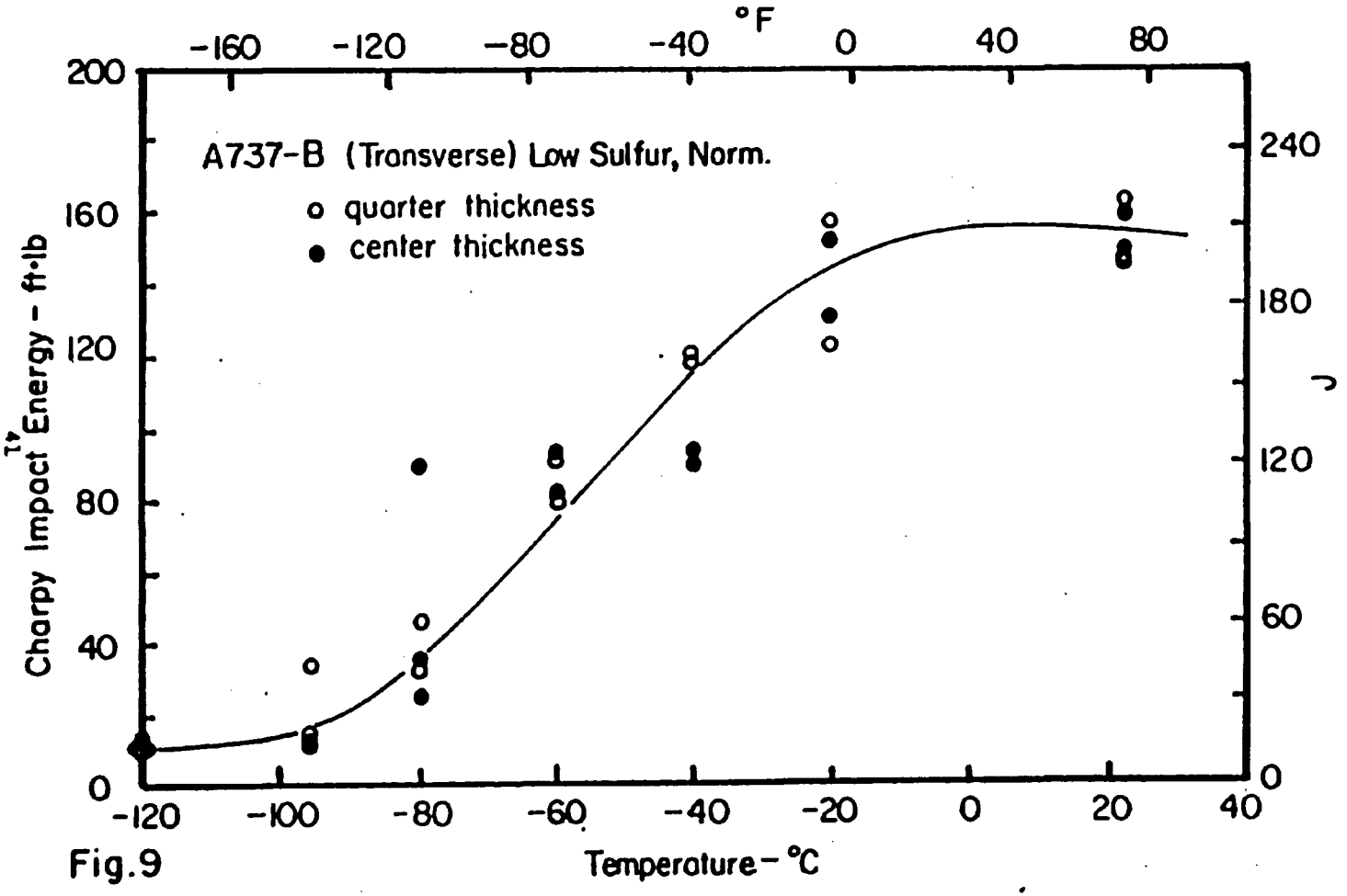
°F
-160
-120
-80
-40
0
40
80
200
160
120
80
40
0
A737-B (Transverse) Low Sulfur, Norm.
o quarter thickness
● center thickness
Charpy Impact Energy - ft·lb
240
180
120
60
0
-120
-100
-80
-60
-40
-20
0
20
40
Temperature - °C

Fig.9

QUENCHED AND TEMPERED

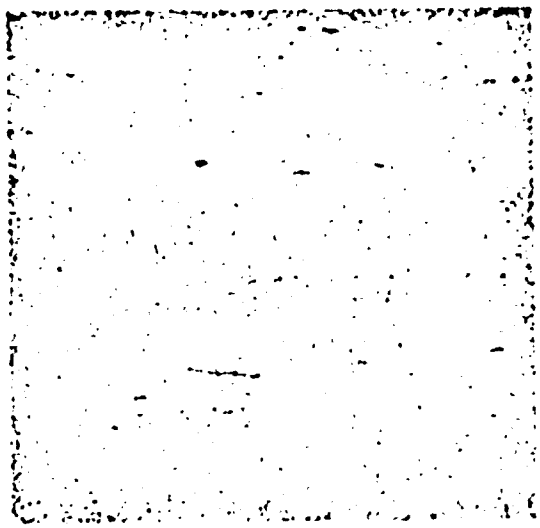

Fig. 10 A-100X

NORMALIZED

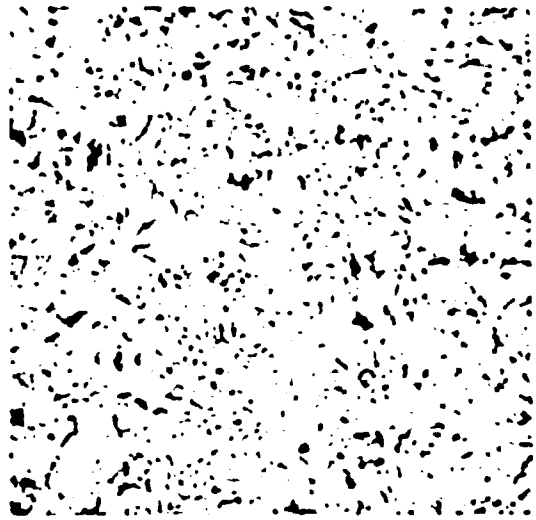

Fig. 10 C-100X

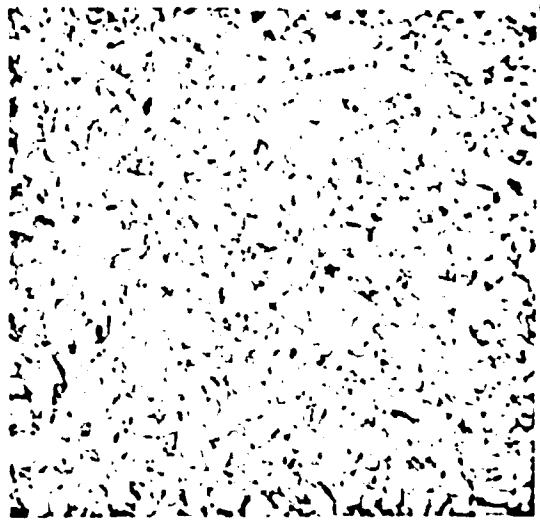

Fig. 10 B-500X

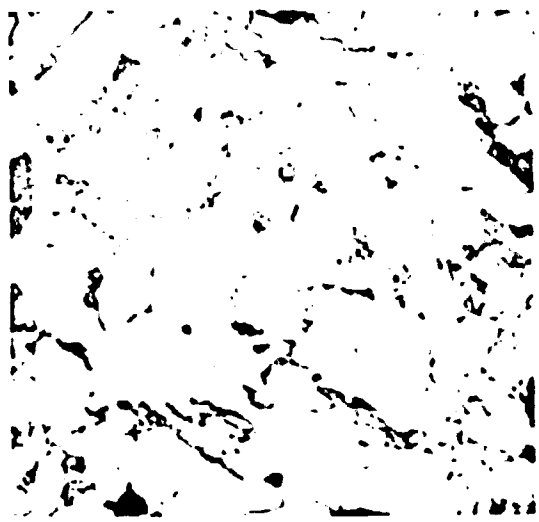

Fig. 10 D-500X

2% Nital Etch

Figure 10 Microstructure of the Normal Sulfur A737-B Steel

QUENCHED & TEMPERED

NORMALIZED

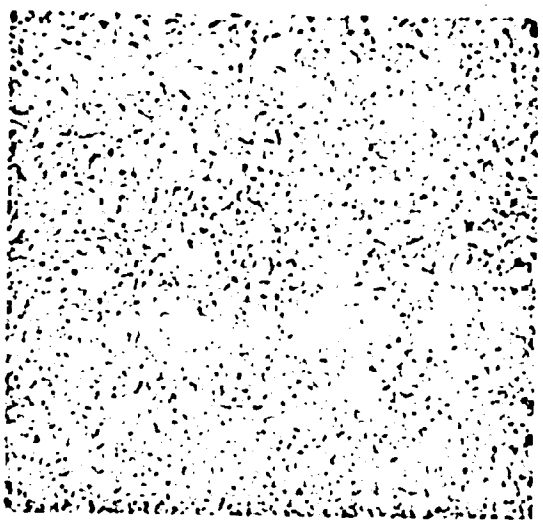

Fig. 11 A-100X

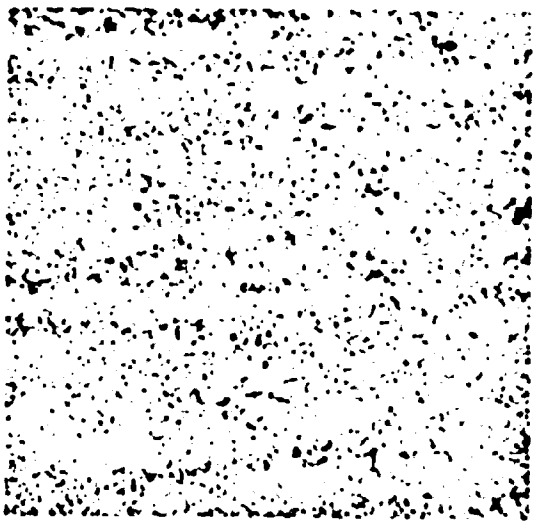

Fig. 11 C-100X

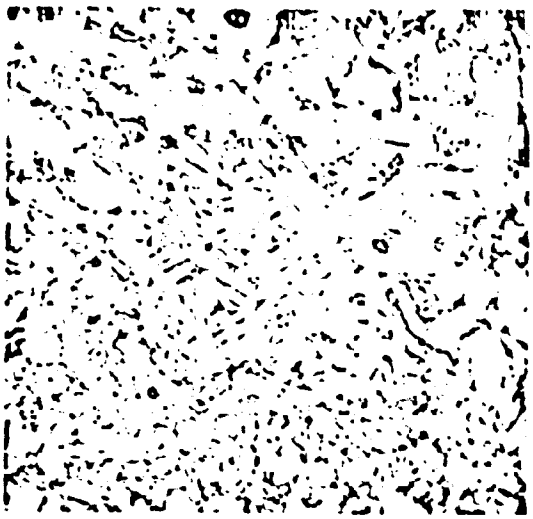

Fig. 11 B-500X

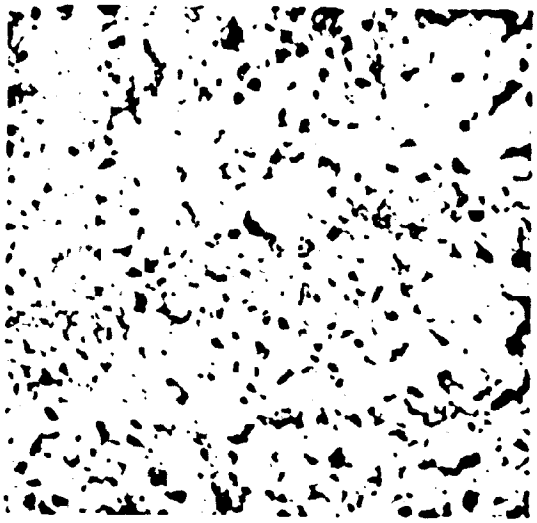

Fig. 11 D-500X

2% Nital Etch

Figure 11 Microstructure of the Low Sulfur A737-B Steel

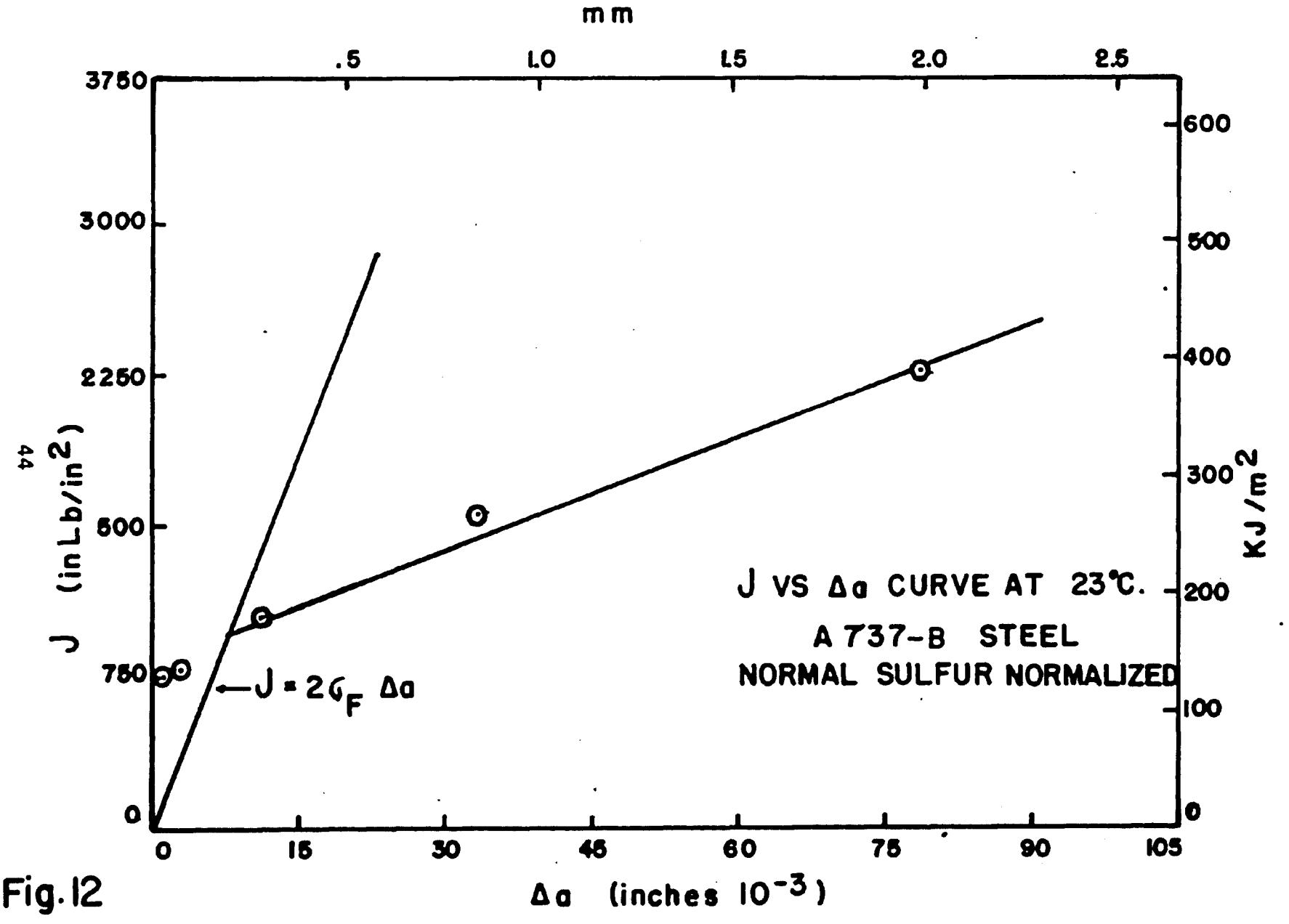
mm
.5
1.0
1.5
2.0
2.5
3750
3000
2250
1500
750
0
J (inLb/in²)
600
500
400
300
200
100
0
KJ/m²
J VS Δa CURVE AT 23°C.
A 737-B STEEL
NORMAL SULFUR NORMALIZED
J = 2σF Δa
0
15
30
45
60
75
90
105
Δa (inches 10⁻³)

Fig. 12

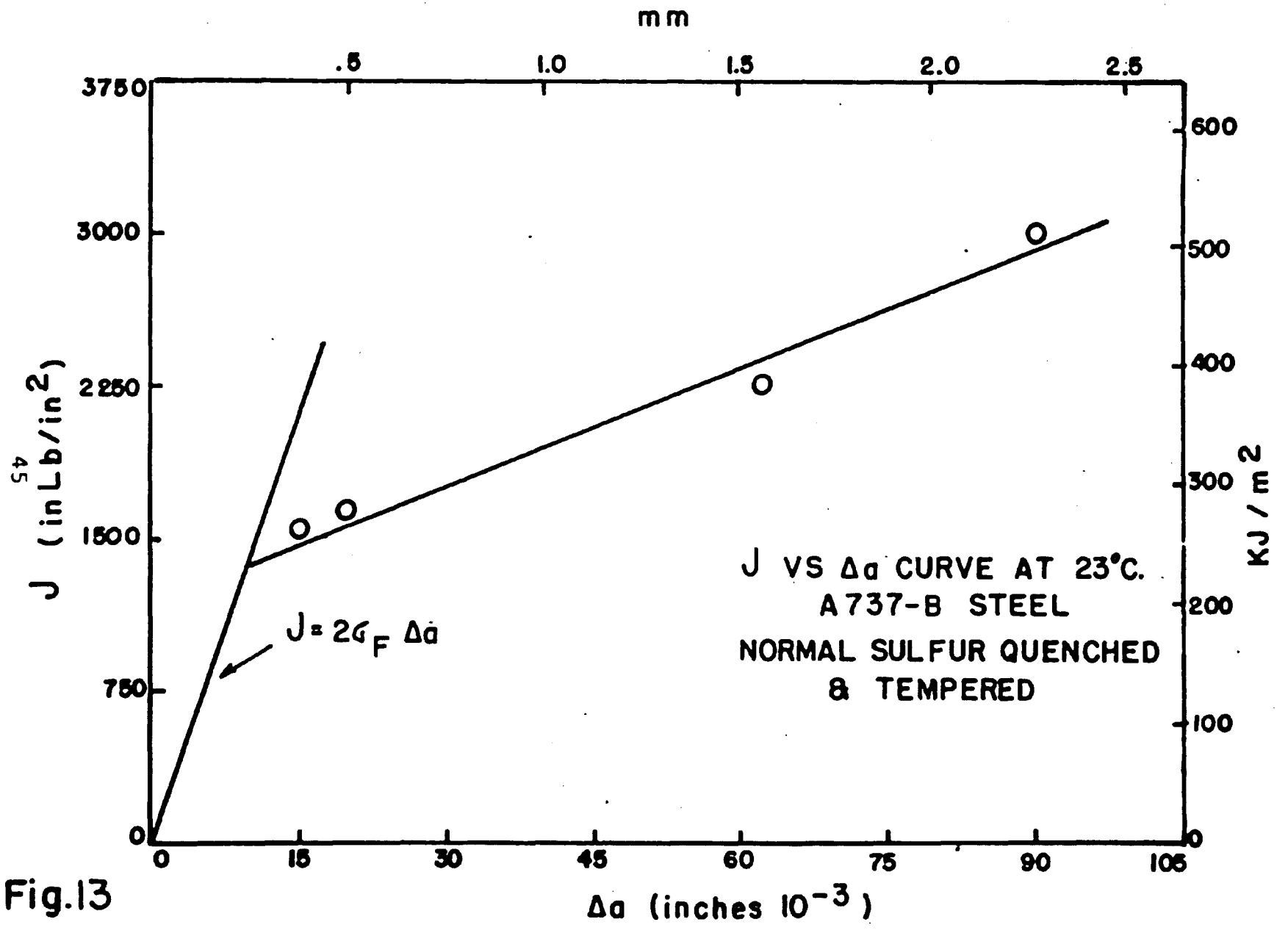
mm
.5
1.0
1.5
2.0
2.5
3750
3000
2250
1500
750
0
600
500
400
300
200
100
0
15
30
45
60
75
90
105
J (inLb/in²)
KJ / m²
Δa (inches 10⁻³)
J = 2G_F Δa
J VS Δa CURVE AT 23°C.
A737-B STEEL
NORMAL SULFUR QUENCHED
& TEMPERED

Fig.13

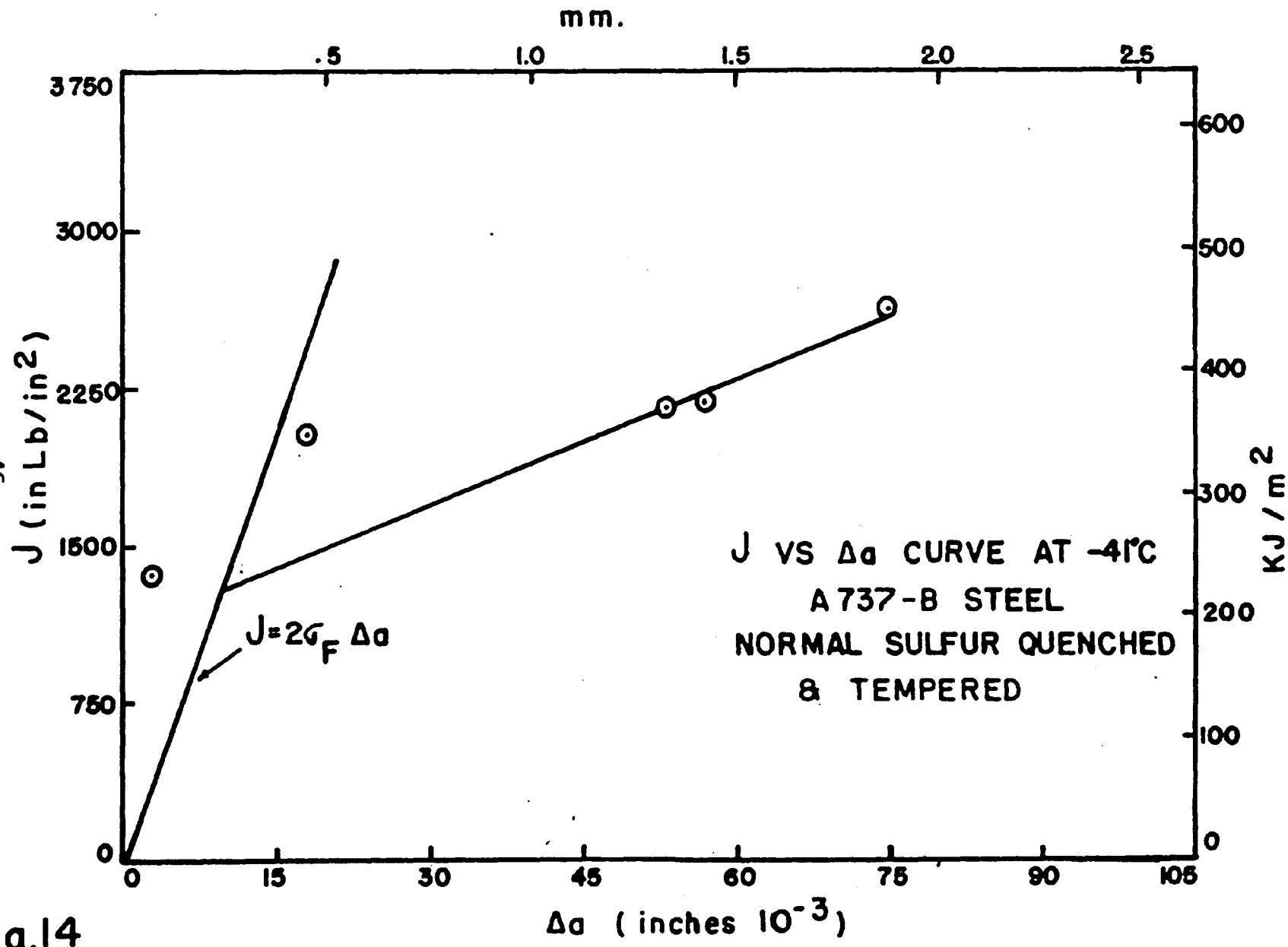
mm.
.5
1.0
1.5
2.0
2.5
3750
3000
2250
1500
750
0
600
500
400
300
200
100
0
J (in Lb/in²)
KJ/m²
J=2σF Δa
J VS Δa CURVE AT -41°C
A737-B STEEL
NORMAL SULFUR QUENCHED
& TEMPERED
0
15
30
45
60
75
90
105
Δa (inches 10⁻³)

Fig.14

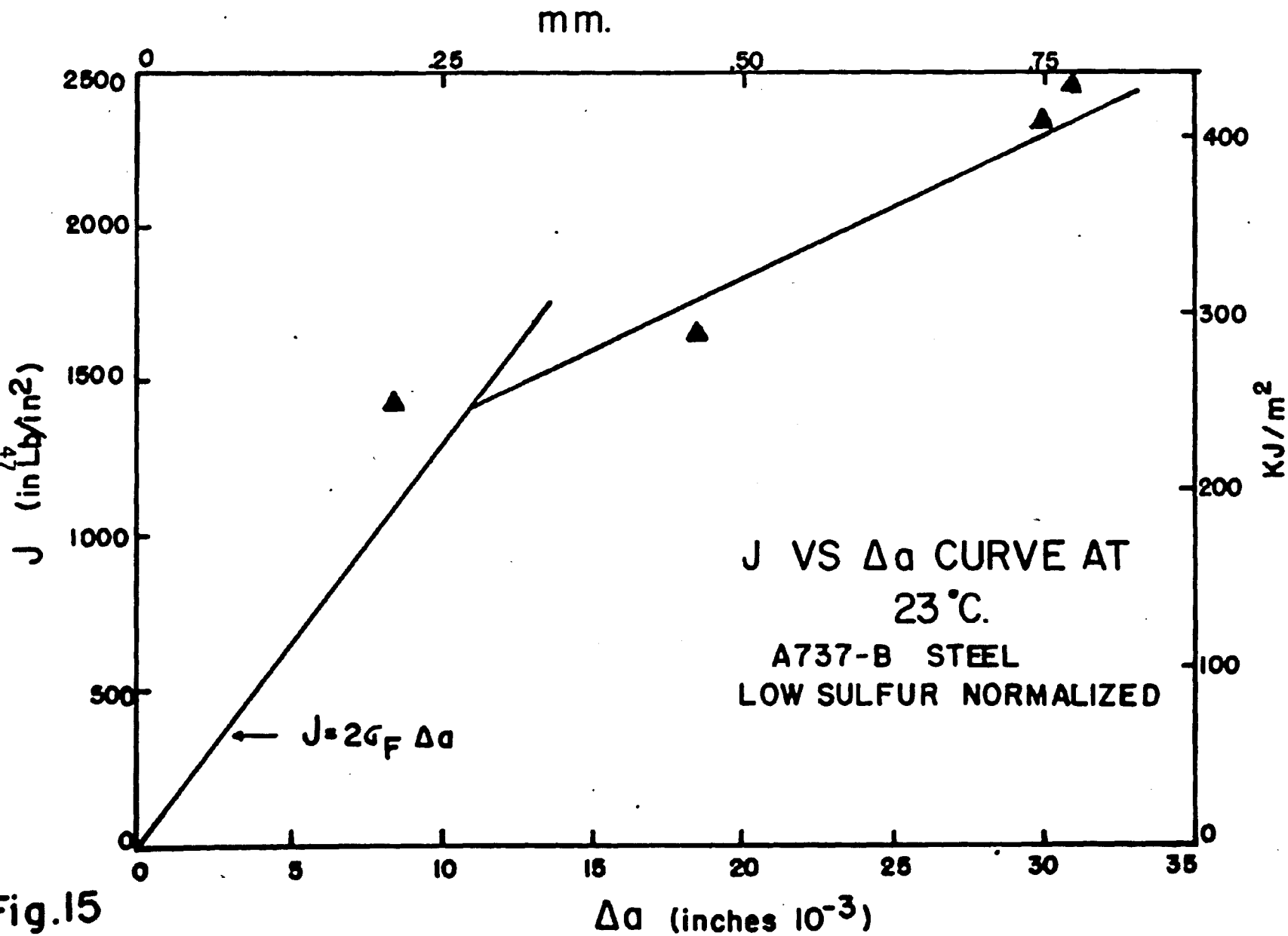
mm.
0
25
50
75
2500
2000
1500
1000
500
0
400
300
200
100
0
J (in Lb/in²)
KJ/m²
J VS Δa CURVE AT
23 °C.
A737-B STEEL
LOW SULFUR NORMALIZED
J=2σF Δa
0
5
10
15
20
25
30
35
Δa (inches 10⁻³)

Fig.15

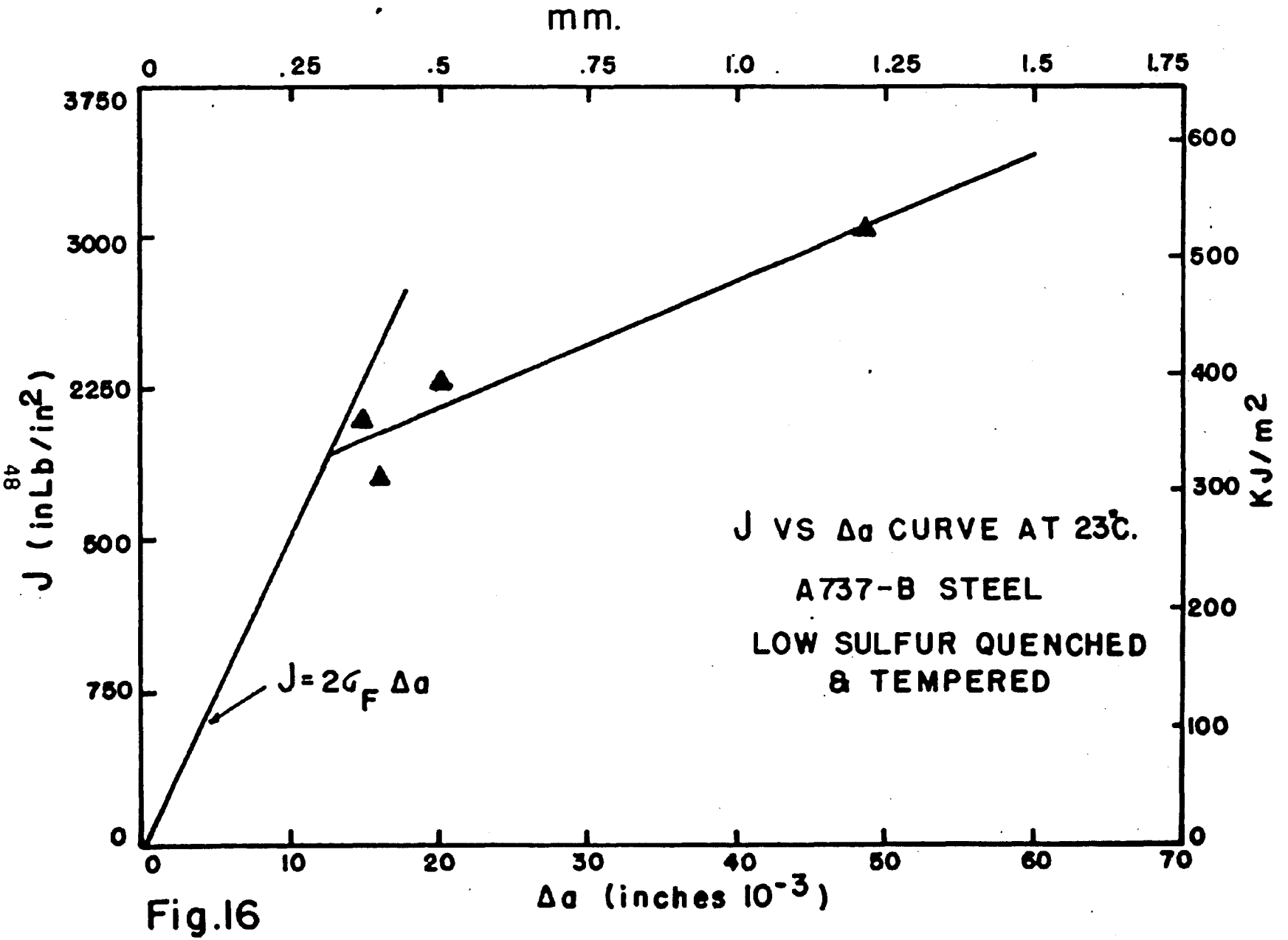
mm.
0
.25
.5
.75
1.0
1.25
1.5
1.75
3750
3000
2250
1500
750
0
J (inLb/in2)
48
600
500
400
300
200
100
0
KJ/m2
J VS Δa CURVE AT 23°C.
A737-B STEEL
LOW SULFUR QUENCHED
& TEMPERED
J=2σF Δa
0
10
20
30
40
50
60
70
Δa (inches 10-3)

Fig.16

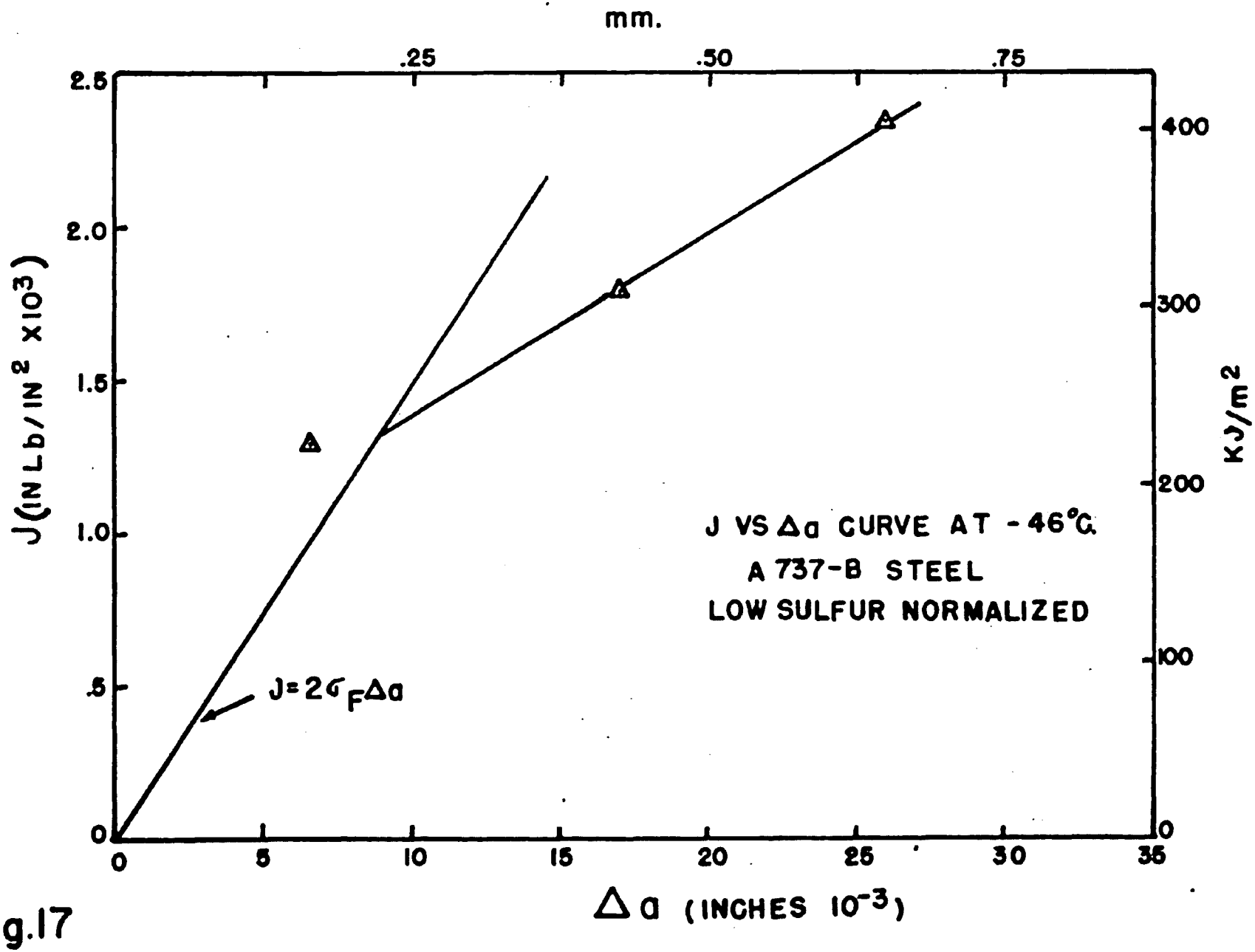
mm.
.25
.50
.75
2.5
2.0
1.5
1.0
.5
0
400
300
200
100
0
J (IN Lb/IN² X10³)
KJ/m²
J VS Δa CURVE AT -46°C.
A 737-B STEEL
LOW SULFUR NORMALIZED
J=2σFΔa
0
5
10
15
20
25
30
35
Δa (INCHES 10⁻³)

Fig.17

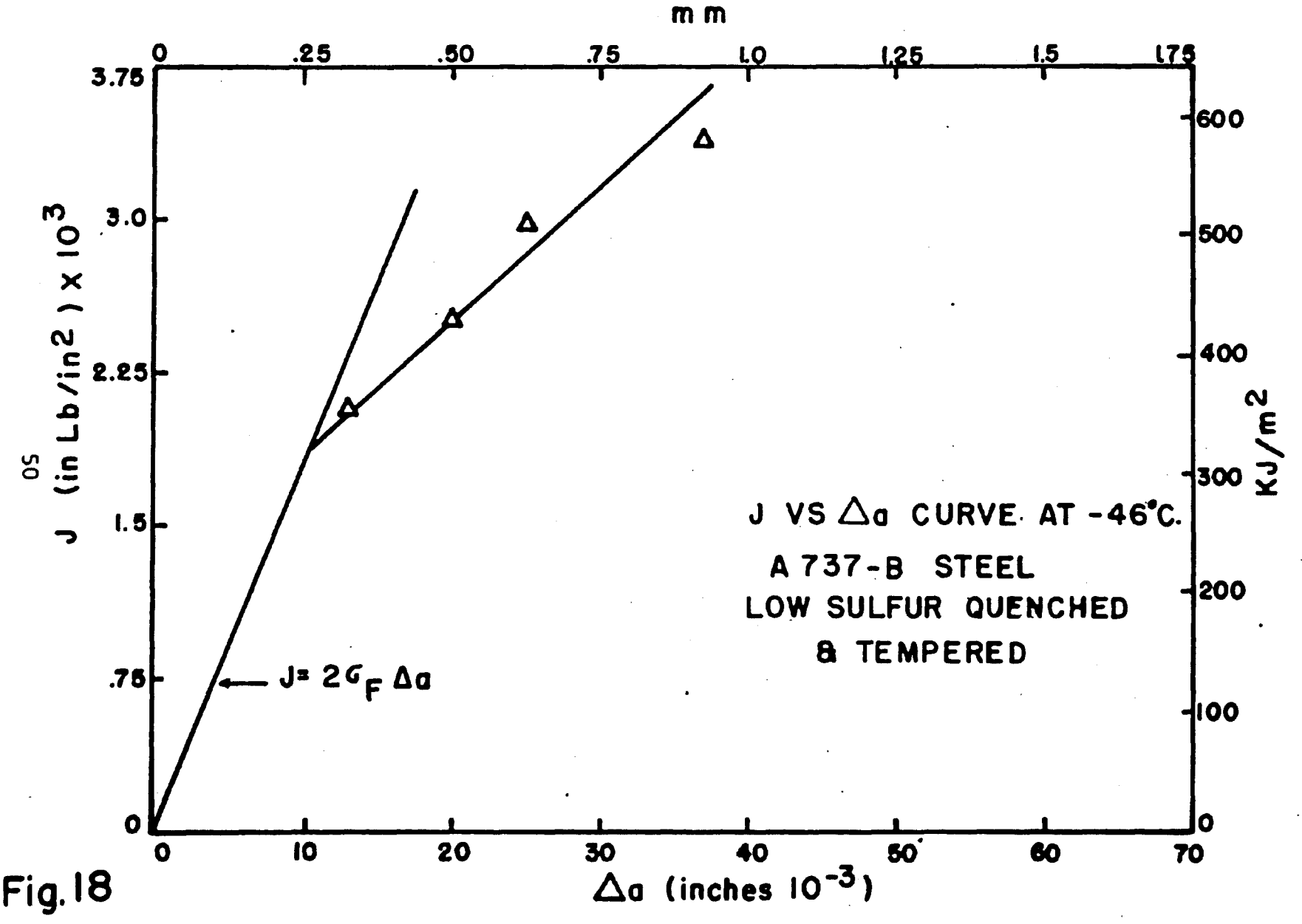
mm
0
.25
.50
.75
1.0
1.25
1.5
1.75
3.75
3.0
2.25
1.5
.75
0
J (in Lb/in2) X 10^3
KJ/m2
600
500
400
300
200
100
0
10
20
30
40
50
60
70
Δa (inches 10^-3)
J VS Δa CURVE AT -46°C.
A 737-B STEEL
LOW SULFUR QUENCHED
& TEMPERED
J= 2σF Δa

Fig. 18

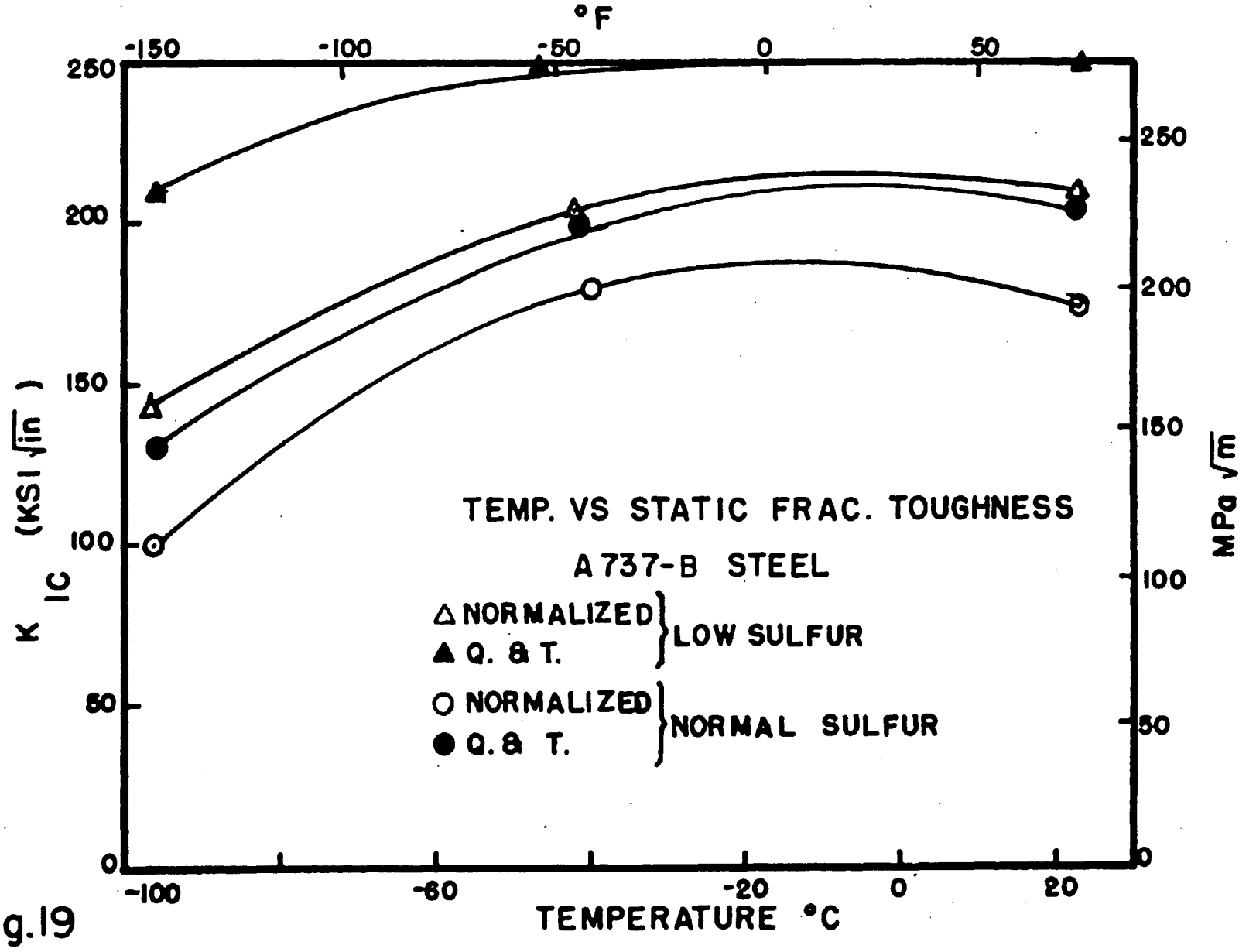
°F
-150
-100
-50
0
50
250
200
150
100
50
0
K IC (KSI √in)
MPa √m
TEMP. VS STATIC FRAC. TOUGHNESS
A 737-B STEEL
△ NORMALIZED
▲ Q. & T.
LOW SULFUR
○ NORMALIZED
● Q. & T.
NORMAL SULFUR
-100
-60
-20
0
20
TEMPERATURE °C

Fig.19

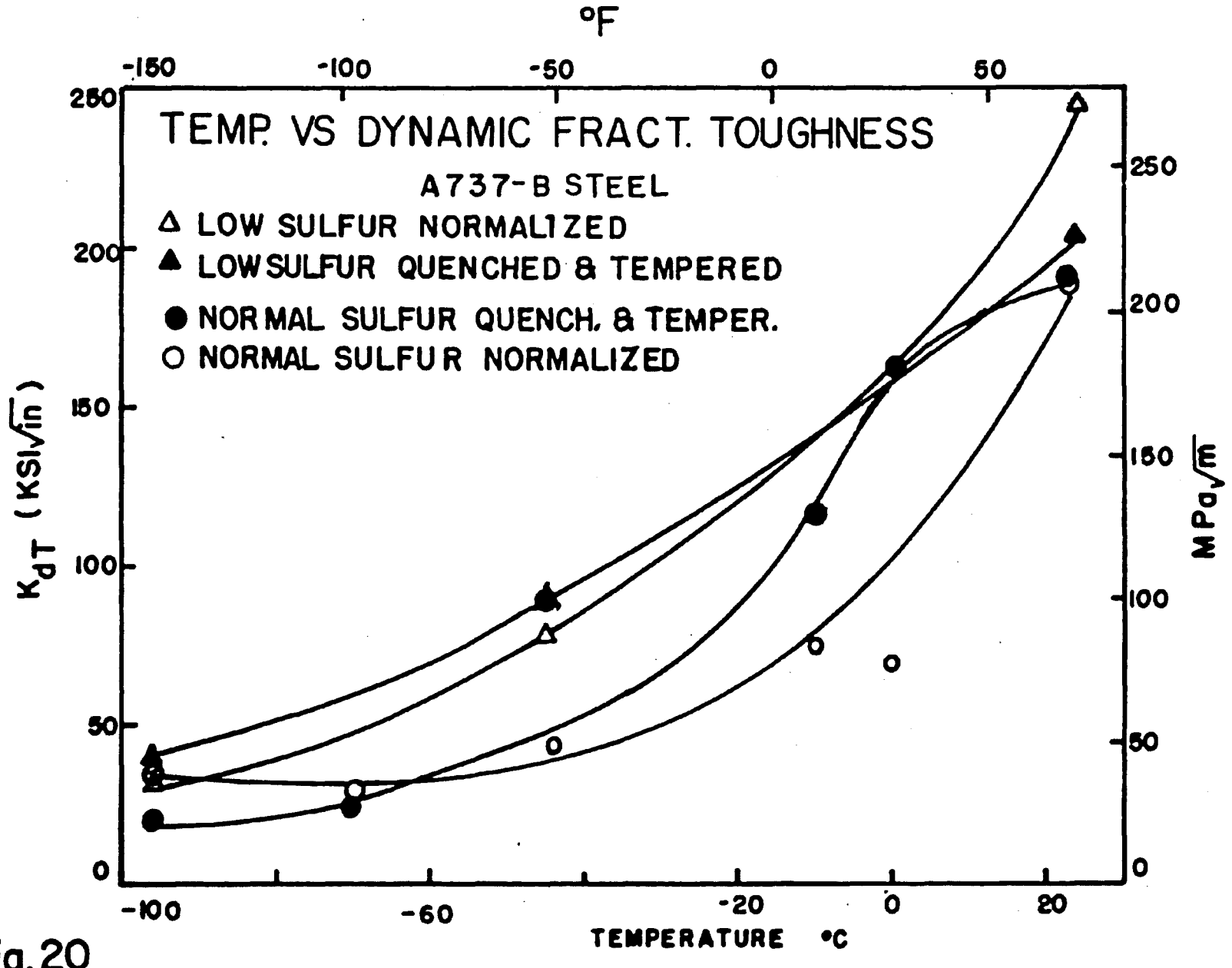
°F
-150
-100
-50
0
50
TEMP. VS DYNAMIC FRACT. TOUGHNESS
A737-B STEEL
△ LOW SULFUR NORMALIZED
▲ LOW SULFUR QUENCHED & TEMPERED
● NORMAL SULFUR QUENCH. & TEMPER.
○ NORMAL SULFUR NORMALIZED
250
200
150
100
50
0
K_{dT} (KSI$\sqrt{in}$)
MPa$\sqrt{m}$
-100
-60
-20
0
20
TEMPERATURE °C

Fig. 20

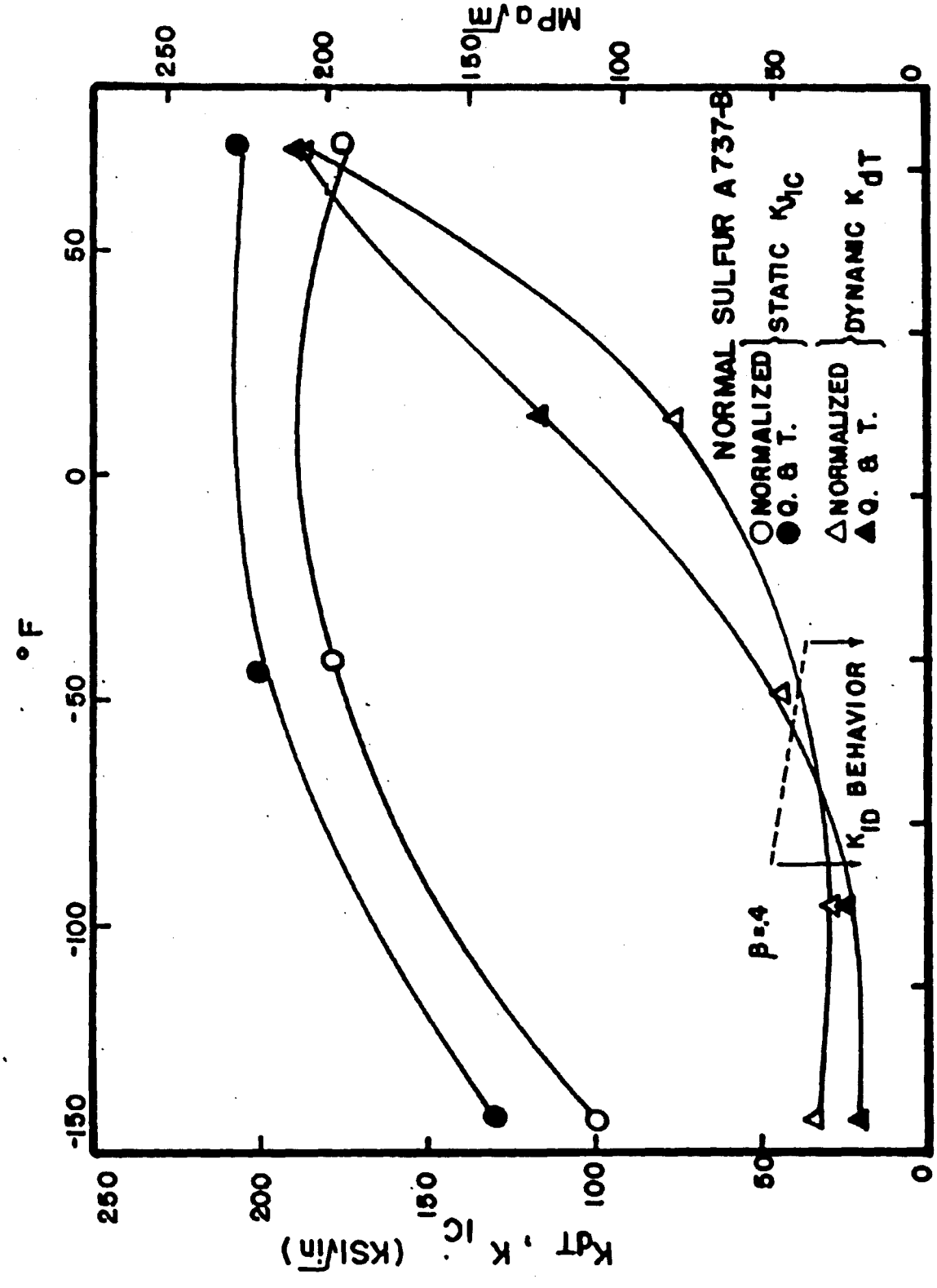
NORMAL SULFUR A737-B
NORMALIZED Q. & T.
STATIC K_{IC}
NORMALIZED Q. & T.
DYNAMIC K_{dT}
K_{ID} BEHAVIOR
β=4
K_{dT} , K_{IC} (KSI√in)
MPa√m
°F
TEMPERATURE °C

Fig.21

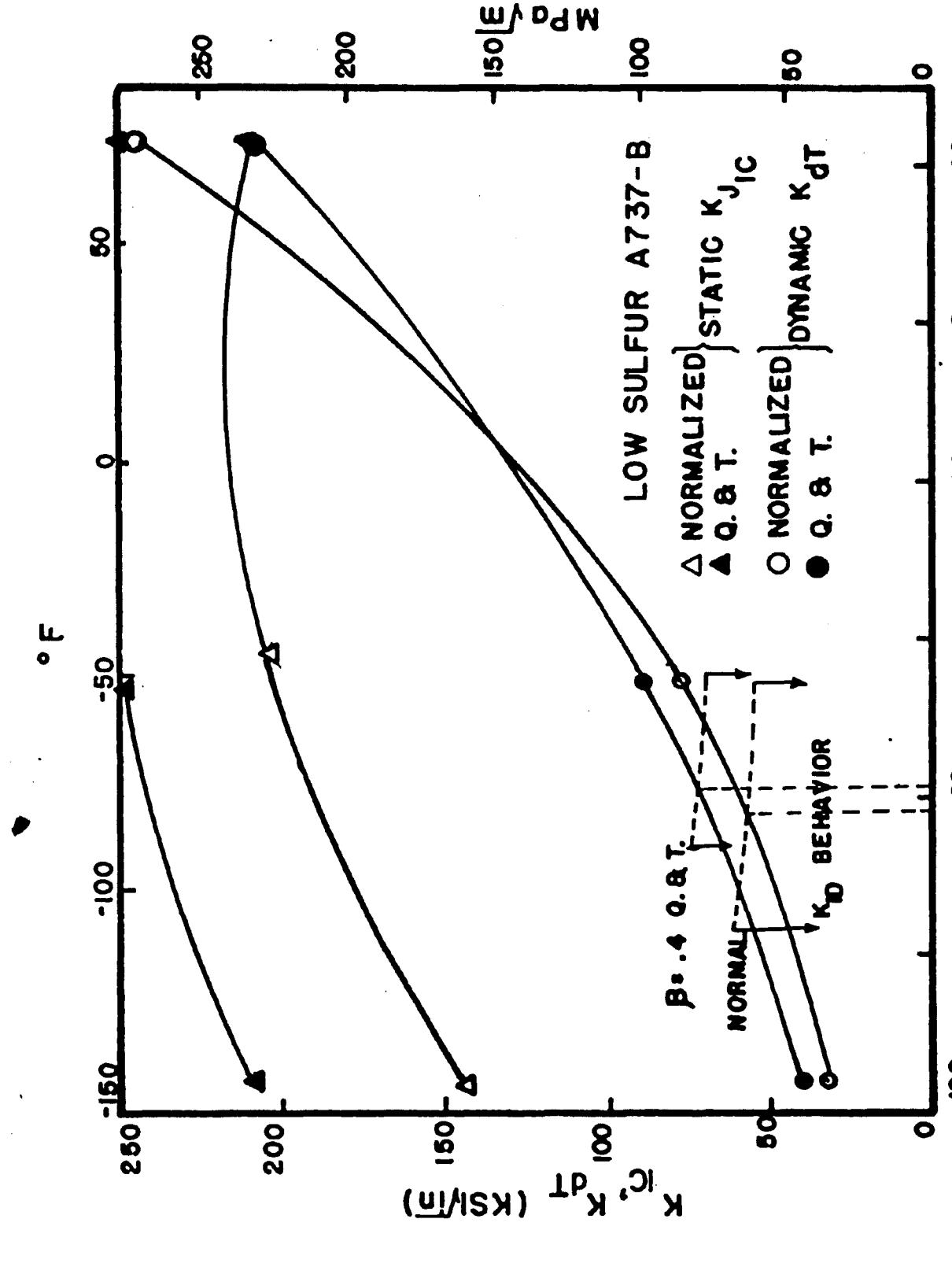
LOW SULFUR A737-B
△ NORMALIZED } STATIC $K_{J_{IC}}$
▲ Q. & T.
○ NORMALIZED } DYNAMIC K_{dT}
● Q. & T.
K_D BEHAVIOR
NORMAL
β = .4 Q. & T.
K_{IC}, K_{dT} (KSI√in)
MPa√m
°F
TEMPERATURE °C

Fig. 22

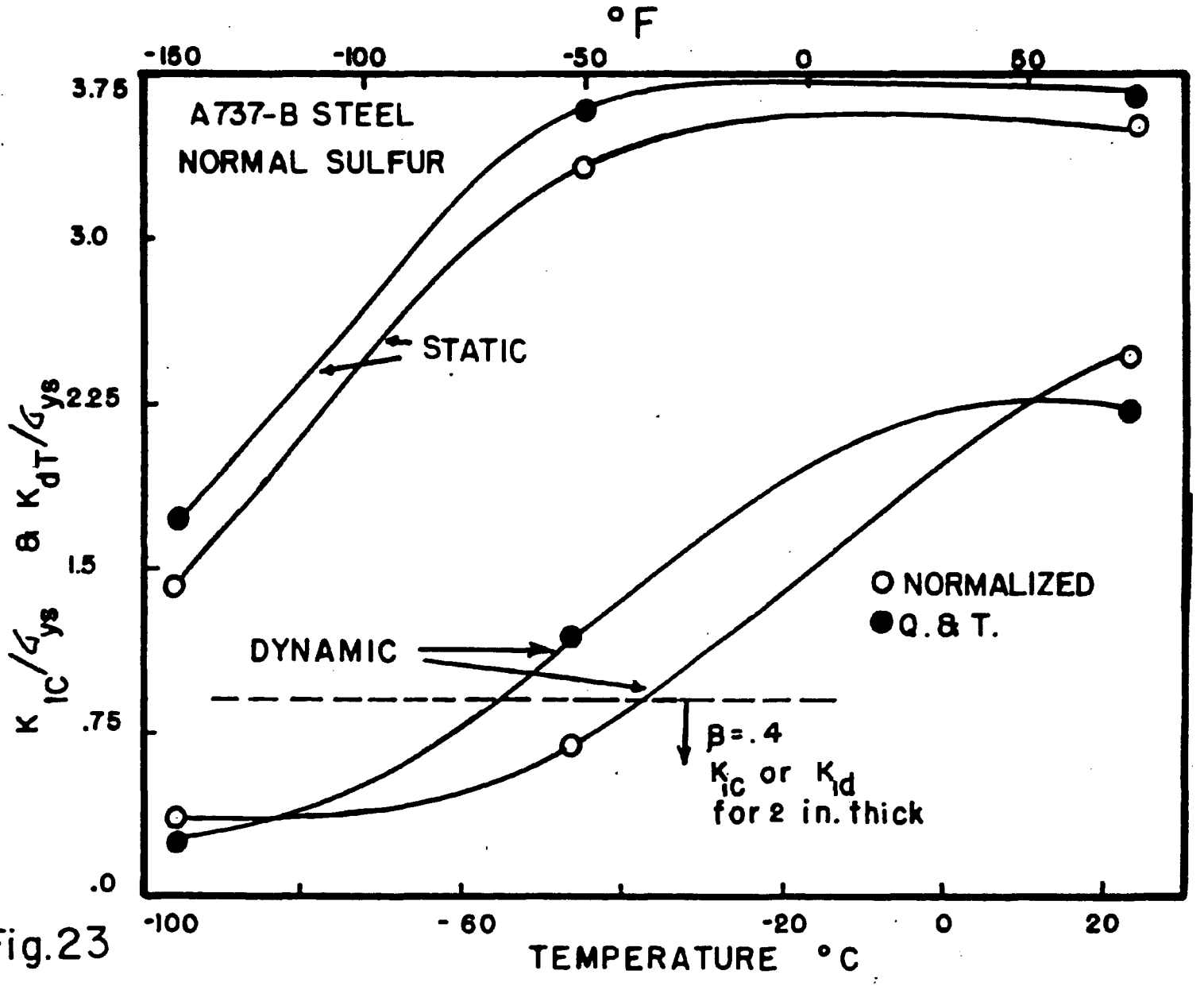
°F
-150
-100
-50
0
50
3.75
3.0
2.25
1.5
.75
.0
A737-B STEEL
NORMAL SULFUR
STATIC
DYNAMIC
O NORMALIZED
● Q. & T.
β=.4
K_{IC} or K_{Id}
for 2 in. thick
K_{IC}/σ_{ys} & K_{dT}/σ_{ys}
-100
-60
-20
0
20
TEMPERATURE °C

Fig.23

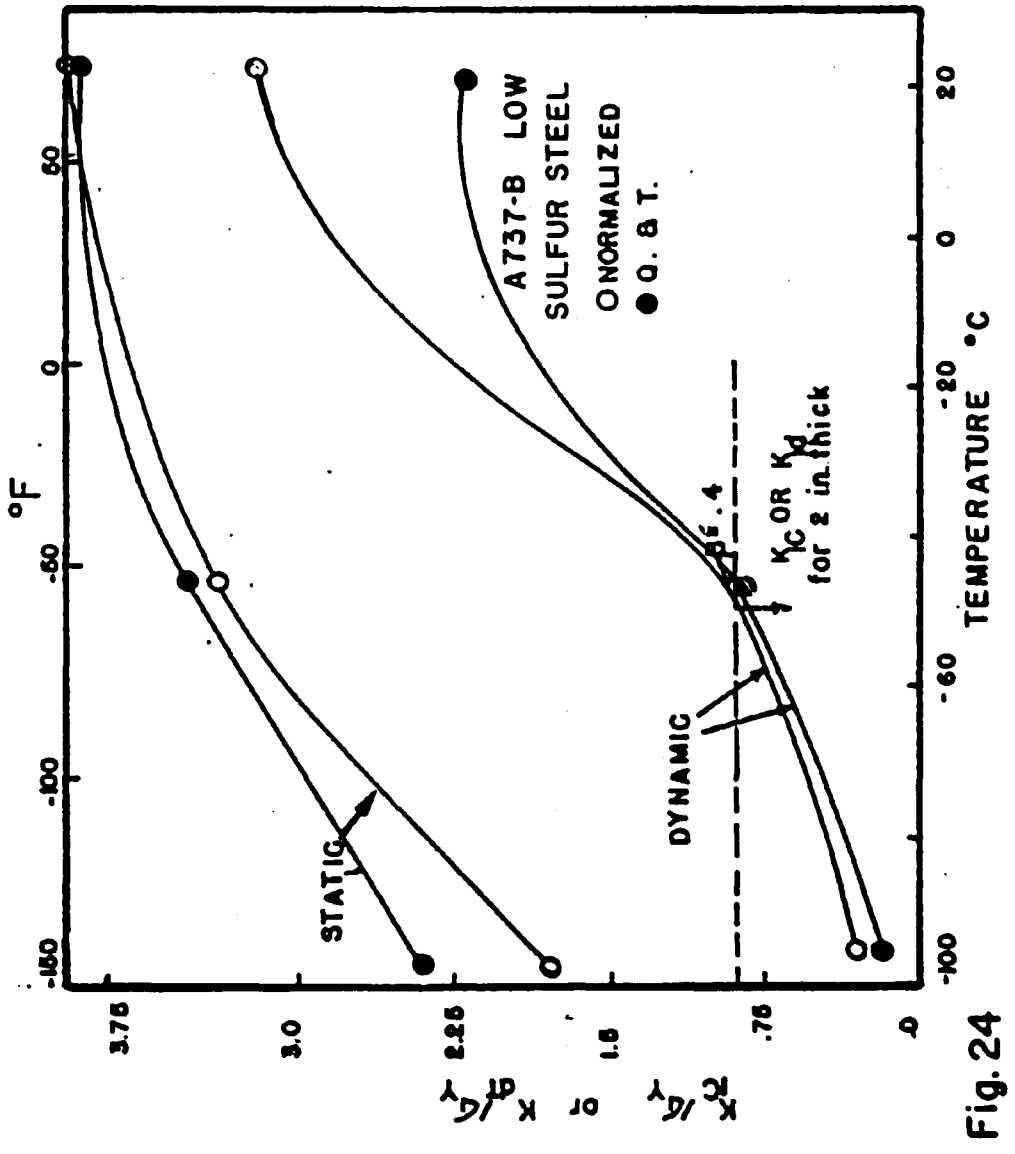
A737-B LOW
SULFUR STEEL
ONORMALIZED
● Q. & T.
STATIC
DYNAMIC
K_C OR K_d
for 2 in. thick
°F
TEMPERATURE °C
$K_C/\sqrt{a_Y}$ or $K_{dT}/\sqrt{a_Y}$

Fig. 24

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VITA

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