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Canada Centre for Mineral and Energy Technology
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COMPARISON OF NOTCH-DUCTILITY AND WELD-ABILITY OF THREE HIGH-STRENGTH STRUCTURAL STEELS

W.P. Campbell

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COMPARISON OF NOTCH-DUCTILITY AND WELDABILITY OF THREE HIGH-STRENGTH STRUCTURAL STEELS

by

W. P. Campbell*

1. ABSTRACT

A comparative study was made of the tensile, Charpy V-notch, and drop-weight properties of prime plate and welds in commercially produced T-1 and CHT-100 steels and in an experimental Cu-Ni steel which was produced commercially but with further laboratory processing. Comparison was also made of the cold-cracking behaviour of weld heat-affected zones in the three steels and of the behaviour of welds in explosion-bulge tests. Confirmatory crack-starter explosion-bulge tests were made on the Cu-Ni prime plate.

Prime plate tensile properties exceeding those of ASTM specification A517 were met by the three steels, and transverse weld tensile strengths exceeded the prime plate strengths. The highest prime plate Charpy V-notch ductility was developed by the Cu-Ni steel and the lowest by the CHT-100 steel. This relative rating was confirmed by the drop-weight results. Charpy V-notch properties of welds in each steel equalled or exceeded those of the corresponding plate. The drop-weight results, also for weld centre-line locations, were generally supportive of the Charpy

*Research Scientist, Physical Metallurgy Research Laboratories CANMET, Department of Energy, Mines and Resources, Ottawa, Canada

V-notch results for welds, although considerable difficulty was experienced with anomalous or secondary cracking in the crack-starter bead of many drop-weight specimens. This anomalous cracking was investigated to determine its cause and possible remedy.

Welds in T-1 and Cu-Ni steels showed consistently good performance in the explosion-bulge tests at temperatures down to -32°C (-25°F), but welds in CHT-100 steel demonstrated inconsistent performance ranging from good to poor at temperatures up to -1°C (30°F). The crack-starter explosion-bulge tests on Cu-Ni steel confirmed earlier results of a crack-arrest temperature at or close to -46°C (-51°F).

In the comparative heat-affected zone cold-cracking studies, the three steels showed no tendency to crack in Controlled Thermal Severity tests, but all cracked severely in Y-groove butt weld restraint tests unless preheating was employed. The Cu-Ni and CHT-100 steels required a slightly higher preheat level than did the T-1 steel to eliminate cracking.

UNE COMPARAISON ENTRE LA RESILIENCE DE TROIS ACIERS DE CONSTRUCTION TRES RESISTANTS

par

W.P. Campbell*

1. SOMMAIRE

Une étude comparative a été effectuée entre les différents essais de résistance à la traction, de résilience sur éprouvette Charpy et des propriétés de dynamique de chute d'une plaque-mère et de soudures exécutées sur des aciers T-1 et CHT-100 produits industriellement et sur un acier de Cu-Ni expérimental produit également en industrie mais subséquenment traité en laboratoire L'auteur a de plus comparé le comportement à la fissuration à froid de la zone thermiquement affectée des soudures de ce trois aciers avec le comportement des soudures pendant des essais de renflement par explosion. Des essais de renflement par explosion sur éprouvette rechargée et entaillée effectués sur la plaque-mère de Cu-Ni ont confirmé les précédents tests.

Les propriétes de résistance à la traction de la plaque-mère ont dépassé les spécifications A517 déterminées par l'ASTM dans le cas des trois aciers, et la résistance de la soudure en traction transversale a été meilleure que celles de la plaque-mère. Le taux le plus élevé de résilience sur éprouvette Charpy de la plaque-mère a été atteint par l'acier de Cu-Ni et le plus bas par l'acier CHT-100. Les résultats obtenus des essais de dynamique de chute ont confirmé ces données. Les propriétés d'éprouvette Charpy à entaille en V des soudures de chacun des aciers se sont avérées les mêmes ou meilleures que celles de la plaque correspondante. Les résultats

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*Chercheur scientifique, Laboratoires de recherche en métallurgie physique, CANMET' Ministère de l'Energie, des Mines et des Ressources, Ottawa, Canada.

obtenus de la dynamique de chute, de même que ceux pour les centres des soudures, correspondaient habituellement à ceux obtenus en résilience sur éprouvette Charpy pour les soudures, bien qu'il y ait eu fissuration due aux anomalies dans le cordon d'amorçage de la fissuration de plusieurs échantillons en dynamique de chute. Cette fissuration due aux anomalies a été étudiée afin d'en découvrir la cause et possiblement d'y trouver une solution.

Les soudures faites sur les aciers T-1 et Cu-Ni résistaient assez bien pendant les essais de renflement par explosion à des températures aussi basses que -32°C (-25°F), tandis que la résistance de l'acier CHT-100 variait selon les degrés de température qui s'est échelonnée jusqu'à -1°C (30°F). Les essais de renflement par explosion sur éprouvette rechargée et entaillée effectués avec l'acier de Cu-Ni ont confirmé les résultats ntérieurs obtenus à une température d'arrêt de fissuration de ou d'environ -46°C (-51°F).

Les trois aciers en question n'ont démontré aucune tendance à la fissuration lors des essais de sévérité thermique contrôlée qui ont eu lieu pendant les études comparatives de fissuration à froid d'une zone thermiquement affectée, mais de sévères fissurations ont pris place pendant les essais de soudure en bout bridé sur joint en Y sans préchauffage. Les aciers de Cu-Ni et CHT-100 ont dû être préchauffés à une température un peu plus élevée que l'acier T-1 afin d'empêcher la fissuration.

CONTENTS

2. INTRODUCTION

The development and provision of scientific data contributing to the integrity of structural steels and of steel structures has been designated as a necessary function in fulfilling the responsibilities of CANMET within the utilization activity of its Minerals and Energy program.

In earlier work at the Physical Metallurgy Research Laboratories (PMRL), a steel containing about 1% Cu and 3 3/4% Ni had been formulated and tested for potential application in mooring chains for marine service [1]. The properties found in this earlier work indicated that a steel of this composition, in the quenched and tempered condition, could have potential in structural applications requiring a high-strength steel. Consequently, a study was made on plate from commercially produced heats (C1 and C2) to provide data on mechanical properties and weldability [2]. Good notch-ductility of prime plate and welded plate and good weldability were indicated at a yield strength level of about 110 ksi (758 MPa).

The Department of National Defence then requested that a more specific study be made to compare the Cu-Ni steel with two commercially available steels which either have been used, or could be used, in marine service in the Canadian Navy. These latter steels were T-1 (United States Steel Corporation) conforming to Grade F of ASTM A517[3] and CHT-100 (Canadian Heat Treaters Limited) conforming to Grade C of this specification. These are quenched and tempered steels having a minimum specified yield strength of 100 ksi (690 MPa). Some applications of this type of steel have been in masts, launching doors, and landing decks for helicopters on destroyers [4].

As part of the study of the three steels, specimens of prime plate and welded plate were prepared, and these were tested for environmental cracking susceptibility under the direction of G.J. Biefer. The results of this phase of the study are found in his report [4].

The current report covers the balance of the study which was intended primarily to provide a comparison of the notch-ductility of the three steels and of welded joints in them. For many military and industrial applications of steels of this type, a high level of notch-ductility is essential to ensure adequate service, particularly under low-temperature conditions of operation. The report also summarizes studies made to compare the heat-affected zone (HAZ) cold-cracking behaviour of the steels as this can have a significant effect upon the ease and cost of producing reliable welded joints.

3. EXPERIMENTAL DETAILS AND RESULTS

3.1 Materials

3.1.1 Steel plate

The T-1 steel was purchased from United States Steel Corporation as four plates each 1 x 48 x 60 in. (25 x 1219 x 1524 mm) all from the same heat. The CHT-100 was purchased from Canadian Heat Treaters Limited as nine plates, each 1 x 40 x 60 in. (25 x 1016 x 1524 mm) and all cut from one large plate. Certified data from the suppliers are given in Tables 1 and 2, in comparison with specification requirements and with confirmatory tests carried out at CANMET. The T-1 steel was said to have received a standard heat treatment and the CHT-100 was stated to have been heated to 941°C (1725°F), water spray quenched, and tempered at 635°C (1175°F).

The Cu-Ni steel was produced commercially in a 10-ton (9070 kg) basic electric furnace with standard melt practices being followed. The manufacturer reported that the sheet bar required only a normal amount of conditioning. Rolling by the manufacturer to thicknesses of 3/4, 1 1/8, and 2 in. (19, 29 and 51 mm) was performed at 1120°C (2050°F) without difficulty. All pieces were stockpiled, then buried in vermiculite following rolling. The manufacturer reported that scale was quite heavy. Subsequently, smaller pieces of plate, as required, were batch heat-treated at PMRL by quenching from 900°C (1650°F) and tempering at 595°C (1100°F). Check analyses and tensile properties are summarized in Tables 1 and 2 respectively for steel from heat C2 which was employed for all tests discussed in this report except for three crack-starter explosion-bulge tests and some Controlled Thermal Severity weldability tests. Specimens for these tests were made from heat C1 which was shown to be similar in composition to heat C2 except for a higher carbon content of 0.16% and lower sulphur and phosphorus contents of 0.007% and 0.004% respectively [2]. Longitudinal tensile and Charpy specimens, machined from 1-in. (25 mm) plate, were also shown to develop similar properties in both heats.

The largest plates from heat C2, which were heat treated at PMRL for the work covered by the present report, measured approximately 1 1/8 x 10 x 20 in. (29 x 254 x 508 mm). These had to be straightened in a press to reduce distortion following heat treatment. On machining, several of these plates were found unsuitable for the explosion-bulge testing phase of the work as the combination of distortion and scale necessitated reducing the thickness too far below the desired value of 1 in. (25 mm). Consequently, these plates were replaced by additional plates rolled down in the PMRL mill from the 2-in. (50 mm) plate to 1 1/4-in. (32 mm) thickness. The additional 1/8-in. (3 mm) thickness was employed to ensure that distortion and scale would not prevent obtaining the desired thickness of 1 in. (25 mm) by machining following heat treatment. Also, some additional material was required for more 1-in. (25 mm) thick Y-groove weldability specimens and this was produced in a similar fashion.

3.1.2 Welding wire and electrode

All welds, except in the weldability tests, were made using 1/16-in. (1.6 mm) Linde 120 wire ordered to conform to MIL Type 120S-1 of specification MIL E-23765/2 (Ships) [5]. Table 3 compares CANMET analyses of the wire with the specification requirements.

Weldability specimens were welded with 5/32-in. (4 mm) CLA Atom Arc coated electrodes, ordered to conform to the E11018M classification of CSA Standard W48.3 [6]. Coating moisture determinations were made at intervals throughout the test program to ensure that the moisture content was always below 0.2%; the specified maximum for these electrodes.

3.2 Notch-ductility testing of prime plate

3.2.1 Charpy tests

Full-size Charpy V-notch impact specimens were prepared and tested. These were machined from the mid-thickness location in both longitudinal and transverse plate rolling directions, and notched in the plate thickness direction. Figures 1-5 show the transition curves based on testing at least two specimens at each temperature.

3.2.2 Drop-weight tests

Drop-weight tests were made on 1 x 3 1/2 x 14-in. (25 x 90 x 356-mm) specimens cut from the plates in the longitudinal rolling direction and, additionally, in the transverse direction from CHT-100 steel. The P-1 type specimens were prepared and tested in accordance with ASTM Specification E208 [7]. Crack-starter notches were made using a thin abrasive wheel. In several tests, anomalous cracking occurred transverse to the crack-starter bead at a point 3/8 to 1/2 in. (10 to 13 mm) from the crack-starter notch, in some cases extending to at least one edge of the specimen. In all cases, cracking had also occurred at the root of this notch. ASTM E208 provides no guidance respecting cracking that initiates away from the notch. The specification indicates that a test is valid if there is clear evidence of cracking at the root of the notch. If a crack extends to at least one edge of the specimen, this is to be taken as a "break" condition. In the current work, such a specimen was considered to have "broken", even though the cracking, which reached at least one edge of a specimen, did not extend from the notch. For purposes of record, Table 4 summarizes the drop-weight test data. ASTM E208 specifies that the Nil Ductility Transition (NDT) temperature is the highest temperature at which a "break" condition occurs, provided also that in two tests at a temperature 5.6°C (10°F) higher, a "break" condition does not occur.

Examination of a longitudinal section cut through the Hardex N crack-starter bead of a specimen which had not been drop-weight tested showed the presence of many weld cracks. This subject will be referred to later relative to drop-weight testing of welded specimens.

3.3 Weldability (cold-cracking) comparison

3.3.1 Y-groove restraint tests

Cold-cracking behaviour in welding the three steels was compared by means of a Y-groove specimen as illustrated in Fig. 6, except that in the more recent tests the configuration in the restraint weld regions was modified. This modification was that the bevel preparation on each side of the 1-in. (25 mm) thick plate extended only to one-third of the plate thickness leaving a central root face of 0.33 in. (8 mm). Without this wide root face, it was subsequently found that, in some of the earlier tests in this project, the root gap had not been in the range of 0.079 ± 0.004 in. (2.0 ± 0.1 mm) which had been recommended as the optimum for cracking evaluation [8]. Later tests in this project, and also in another project on a C-Mn steel [9], showed that the modified specimen provided a more reliable control of the root gap. All specimens in the high-strength steels were machined so that the test welds would be perpendicular to the direction of rolling.

In preparation of the specimens, the restraint welds were made either after preheating the assembly in a furnace to 121 to 177°C (250 to 350°F) or using a high level of arc energy input to reduce the possibility of cracking. The single-pass test weld was made either with the assembly at room temperature or immediately after preheating the assembly in a furnace to the plate temperature desired for a particular test. Two tests were made for each initial plate temperature. All welding was done manually with the 5/32-in. (4-mm) diam E11018M electrodes having moisture contents of 0.20% max. Arc energy input levels for the test welds were monitored by a recording wattmeter and were maintained very close to 42 kilojoules/in. (1.7 kilojoules/mm).

Representative transverse sections were removed with a liquid-cooled abrasive cut-off wheel from the test weld in each Y-groove assembly after more than 48 hr from completion of welding. These sections were examined for cracking with the aid of the wet, fluorescent magnetic particle inspection process. Some metallographic examination of polished and etched sections was performed where additional confirmation appeared necessary.

As a result of measurements made on all specimens to ensure that the root gap had been maintained within the recommended range, it was found that earlier tests made on the Cu-Ni steel at a plate temperature of 121°C (250°F) were invalidated because the root gap was only 0.06 in. (1.5 mm) [2]. No cracking had been found in these tests and it had been concluded that a preheat of 121°C (250°F) was adequate to prevent cracking. Consequently, new tests were made at 121 and 177°C (250 and 350°F) to supplement the previous tests at room temperature which were concluded to have been valid because the root gaps were confirmed to have been within the recommended range.

Table 5 summarizes valid comparative tests performed on the three steels. Figures 7 and 8, although from tests in a C-Mn steel [9], are reasonably illustrative of moderate and severe cracking, respectively, found in the tests summarized in Table 5. Metallographic examination confirmed that cracking in these tests initiated at or close to the junction of the root gap and the weld and extended upward in the HAZ. In sections judged to show severe cracking, frequently the crack had changed direction and propagated into the weld as illustrated in Fig. 8. In other cases, the crack remained entirely within the HAZ, or after deflecting into the weld from the HAZ, it then changed direction and travelled from the weld back into the HAZ. The path of severe cracking was observed to vary considerably, even in adjacent sections of the same test weld.

3.3.2 Controlled Thermal Severity tests

Controlled Thermal Severity (CTS) tests had been made previously [2] on the Cu-Ni steel and had shown no cracking tendency. These tests had been made using the CTS specimen shown in Fig. 9.

In tests on steel from heat C2, both plates were 1 3/4 in. (44 mm) thick. Other tests had also been made on 1-in. (25-mm) steel from heat C1.

Two CTS tests were made under similar conditions to those for the Cu-Ni steel but employing only 1-in. (25-mm) plate, in both T-1 and CHT-100 steels. Arc energy input was controlled at very close to 32 kilojoules/in. (1.3 kilojoules/mm) and the CTS specimen was at room temperature prior to deposition of each of the two test welds. Examination for cracking, after more than 48 hr from completion of welding, was done as for the Y-groove specimens. No cracking was found.

3.4 Welding of other test specimens

Specimens for transverse tensile, Charpy, drop-weight and explosion-bulge comparison studies were welded by the automatic gas metal-arc process. Joint configuration consisted of a machined 60-deg double Vee groove with a $1/16^{+0}_{-1}/32$-in. ($1.6^{+0}_{-0.8}$-mm) root face. For transverse tensile specimens, the weld joint was perpendicular to the direction of rolling for T-1 and CHT-100 steel. For the Cu-Ni steel, specimens were prepared with both orientations. For explosion-bulge specimens, the weld was parallel to the direction of rolling due to the fact that the PMRL mill could not roll the Cu-Ni plates of 20 in. (254 mm) width. Consequently the same joint orientation was employed for explosion-bulge specimens in the other steels. For welds for Charpy and drop-weight tests notched at the weld centre-line, either orientation was employed, as convenient from the viewpoint of the dimensions of the plate at hand.

Typical welding parameters were 350 amp, 24 V, and 12 in./min (305 mm/min) travel speed with 1/2-in. (13-mm) electrode stickout and argon-2% O_2 gas shielding at 45 cfh (1.3 m^3/hr). The energy input was controlled within the range 39 to 45 kilojoules/in. (1.5 to 1.8 kilojoules/mm), with the aid of a recording wattmeter. A small root gap of 0.01 in. (0.25 mm) was normally employed. The two root beads in each assembly were made after the assembly had been preheated in a furnace to 149°C (300°F). Subsequent beads were deposited with the steel initially in the range 24 to 149°C (75 to 300°F). Bead sequence was such as to minimize distortion, and, as much as possible, the same sequence and number of beads were used. Typically, 9 or 10 beads were deposited in welding the 1-in. (25-mm) specimens. The underside of the first root bead was ground to bright metal prior to depositing the second root bead. Each bead was thoroughly wire brushed prior to depositing the next bead. All welds were radiographed to confirm soundness. Relatively little difficulty was encountered in meeting a high quality level with only slight occasional porosity. Some weld regions in earlier specimens contained porosity that was considered excessive, and these regions were excluded from further testing. No cracking or crack-like indications were observed.

A similar welding procedure was employed in producing joints in 1-in. (25-mm) T-1 and CHT-100 steels for all-weld metal tensile tests, except that 21 passes were made to fill each 45-deg single bevel joint having a 1/2-in. (13-mm) root gap landing on a 1/4 x 1-in. (6 x 25-mm) backing strip. The weld quality was determined to be satisfactory by radiographic examination.

3.5 Weld tensile tests

Table 6 summarizes the results of tensile tests, using 0.505-in. (12.8-mm) diam specimens centred at the mid-thickness of the joint, transverse to welds in each of the three steels. Also shown in this table are the results of all-weld metal tensile tests, using similar specimens, on welds made on the two commercially available steels.

3.6 Notch-ductility testing of welds

3.6.1 Weld Charpy tests

Full-size Charpy specimens, overlong and unnotched, were machined transverse to the welds with the longitudinal axis of each specimen being coincident with a plane 1/4 in. (6 mm) below the surface. After being lightly etched and scribed to locate the notch at the weld centreline and in the through-thickness direction, the specimens were notched and cut to length. Five specimens were tested at each of the following temperatures: approximately 20, -18, -40, -62, -84, and -107°C (approximately 70, 0, -40, -80, -120 and -160°F). An additional group of five specimens from the weld in the CHT-100 steel was tested at -62°C (-80°F). In determining the average absorbed energy at each test temperature, the extreme highest and lowest values were discarded according to normal procedure in many specifications when concerned with weld metal Charpy V-notch testing. Transition curves were determined for two welded specimens in each of the T-1 and Cu-Ni steels as shown in Fig. 10 and 11. Figure 12 shows the curve developed for the one specimen tested in the CHT-100 steel.

3.6.2 Weld drop-weight tests

Drop-weight specimens having dimensions conforming to Type P-1 of ASTM Specification E208 were prepared from representative welds in the three steels. The weld region in each specimen was etched to aid in positioning of the Hardex N crack-starter bead and of the crack-starter notch in this bead. The notch was specified to be in line with the weld centreline. Test data and results are given in Table 7.

With the first set of Cu-Ni weld specimens it was found that the crack-starter notch had been cut too deeply into the Hardex N deposit. Consequently, the deposit was ground off each specimen and new deposits were made and notched correctly. A second set of specimens from another weld in the Cu-Ni steel was subsequently prepared and tested in accordance with ASTM E208. The preparation and testing of the T-1 welded specimens and the first set of CHT-100 welded specimens were also in accordance with ASTM E208.

With the first set of CHT-100 welded specimens, and both sets of Cu-Ni welded specimens, anomalous transverse cracking occurred in the Hardex N bead in many tests. In several tests, this cracking propagated to the edge(s) of the specimen, and, as for the prime plate tests (see Table 4), such an occurrence was classed as a break. However, because the cracking was about 1/2 in.

(13 mm) away from the notch, the crack path was in the plate material rather than in the weld being tested (Fig. 13). In view of this experience, as well as the earlier experience with similar cracks when testing all three prime plate steels, it was decided to undertake some auxiliary studies to evaluate this anomalous behaviour.

The Canadian distributor of Hardex N electrodes was requested to advise if the electrode had a basic or low-hydrogen type coating. Information obtained was that the electrode coating was of the basic type and that the deposit composition was intended to be within the range given in Table 8. A deposit pad was made as per specification AWS A5.13-70(10) for two separate heats of Hardex N electrodes. Most or all of the drop-weight tests in the work covered by the current report were made with electrodes from heat B.

The behaviour of the electrode in welding and the coating appearance supported the statement that the electrode had a basic coating. It was thought by the writer that the extensive cracking in the Hardex N deposits might be related to an abnormally high level of moisture in such a coating. The electrodes were supplied in metal cans sealed with black plastic tape and this treatment could not be considered as fully adequate to prevent moisture pick-up. Further, once a can was opened, no special attention had been given to protect against moisture pick-up prior to subsequent use. ASTM E208-69 makes no reference to the possibility of cracking from excessive moisture levels in the coating.

Coating moisture determinations as per CSA W48.3-1968 [11] were made of sample electrodes taken directly from a newly opened can, and after baking for 1 hr at 316°C (600°F) or 1 hr at 427°C (800°F). In the latter cases, the electrode samples in glass vials were held in an oven at 177°C (350°F) until the moisture determinations were performed. The percentage moisture values thus obtained for these three conditions were 5.1, 0.44 and 0.1 respectively.

A deposit was made using electrodes baked for 1 hr at 427°C (800°F) on each of two drop-weight specimens in CHT-100 steel on the side of the plate opposite beads previously deposited with unbaked electrodes from the same heat. These previously deposited beads were made by the standard two-pass technique recommended by ASTM E208. The deposits with the baked electrodes were of the same length, and made under similar welding conditions but using a modified deposit technique. This was a single-pass deposit with the arc being broken at the end of the pass. A longitudinal section was then prepared from each drop-weight specimen to include both deposits. Numerous longitudinal cracks, and fewer cracks oriented more nearly perpendicular to the deposit fusion line, were observed in the deposits made with the unbaked electrodes and using the standard two-pass technique. There appeared to be more of the latter type of cracking in the first bead deposited, in the region closest to the termination of the second bead. In both of the single-pass deposits made with the baked electrodes, longitudinal cracks were found, but these were both shorter and fewer in number than in the deposits made with unbaked electrodes. There were only slight traces of cracking oriented more nearly perpendicular to the fusion line. However, the deposition characteristics of the electrodes baked at either 316°C (600°F) or 427°C (800°F) were unsatisfactory, as sporadic and extremely severe porosity was experienced.

The behaviour of the baked electrodes cast doubt upon the claim that the coatings were of the basic type. Consequently, an X-ray diffraction analysis was made on a coating sample. The major and minor constituents reported were rutile and anatase, both being TiO_2. There was a possibility of some iron being present, but due to coincidence of two of the major lines for anatase, this was not certain. Semi-quantitative spectrochemical analyses indicated Ti, Fe, and Si as principal constituents. Neither analyses indicated the presence of Ca or calcium compounds in any significant quantities as would be expected for a basic low-hydrogen type coating. The supplier subsequently advised that the coatings were not, in fact, basic coatings.

Electrodes from heat B (Table 8), and taken from a newly opened can, were used in a comparative study to confirm that the modified crack-starter technique could produce equivalent results to the standard technique when tested on smaller P-2 type specimens as prescribed in specification ASTM E208. These specimens were 3/4 x 2 x 5 in. (19 x 51 x 127 mm) machined from Stelcoloy S steel conforming to Grade 50A of CSA specification G40.21-1973 [12]. With both crack-starter techniques, the same NDT of -29°C (-20°F) was determined for the plate and there were no surface indications of cracking away from the notch. Three specimens for each crack-starter technique were also tested at 27°C (80°F), i.e., 56°C (100°F) above the plate NDT. All showed cracking at the root of the notch, thus confirming that the electrode and both deposition techniques were acceptable according to the requirements of ASTM E208. Two longitudinal sections from specimens tested at 27°C (80°F), and representative of each of the two specimen groups, were examined metallographically for cracking. All specimens showed some longitudinal cracks but considerably fewer in number than found in sections examined from the larger P-1 type specimens used in testing the three high-strength steels. A few cracks, more nearly perpendicular to the weld fusion line, were found in one of the deposits made by the standard technique. As in sections examined previously from the larger P-1 type specimens, it was observed that three of the four P-2 type specimens showed a tendency for the crack from the notch to be deflected slightly by inter-sections with longitudinal cracks in its path.

P-1 type specimens, having crack-starter beads deposited by the modified technique, were employed for further testing of CHT-100 welds. However, failures continued to occur by extension of cracks sufficiently far from the notch so that the fracture path was outside of the weld. A "no-break" condition was found at a test temperature of -46°C (-50°F) but at temperatures of -51 and -62°C (-60 and -80°F) cracking occurred away from the notch to cause "break" conditions.

Work by Australian researchers indicated that the tendency for anomalous or secondary cracking with Hardex N crack-starter electrodes could be reduced by a further modification of the deposition technique[13]. The crater at the end of the single-run deposit was eliminated on the specimen by placing a small piece of steel at the end of the groove in the copper template used as a guide in depositing the crack-starter bead. The template was cut so that the steel run-off piece butted against the open end of the groove. The deposit was made in the same manner as with the modified technique except that the deposit was terminated on the run-off piece. The latter was then ground off and some grinding was also done near and at the end of the deposit to provide a smoother transition. The test specimens employed were those that had been beaded previously using the modified technique but with these previously made crack-starter beads ground off. The deposits made in conjunction with the run-off tabs were laid directly over the locations of the previous deposits. The results of drop-weight testing of four such specimens are given in Table 7, (see CHT-100 - second set). No anomalous cracking was experienced. However, three additional specimens were also tested from a weld made using conditions as described in section 3.4 but employing the manual metal-arc process and E11018M coated electrodes. These specimens had the same history of crack-starter bead deposition as the previous four specimens. At -46°C (-50°F), one specimen displayed a "no break" condition, but a crack developed in the crack-starter bead about 3/4 in. (19 mm) from the notch, without extending into the plate. At -51°C (-60°F), a second specimen was similar except that the crack extended almost to one edge. Both specimens showed crack development, without extension, at the root of the notch. Also, at -51°C (-60°F), a third specimen developed a "break" condition with a crack extending from the notch to one edge of the plate. This specimen showed no other cracks.

3.7 Explosion-bulge testing

3.7.1 Multiple-shot tests of weldments

Explosion-bulge specimens were made by butt welding two 1 x 10 x 20-in. (25 x 254 x 508-mm) plates along the 20-in. (508-mm) dimension. The weld reinforcement was left intact in the central 10-in. (254-mm) region of each weld, but was removed elsewhere flush with the plate surfaces. A gradual transition was made between the ground regions and the as-welded reinforcement. The thickness of the plate in each specimen was measured at a point 1 1/2 in. (38 mm) from the edge of the weld, and otherwise centrally located on the specimen surface, using an ultrasonic thickness testing unit having a digital read-out. This was done shortly before each test plate was placed in the cooling baths at the test site.

Testing was conducted at the site, shown in Fig. 14, on the demolition range of the Canadian Forces Base, Petawawa, Ontario. Each specimen was cooled to the required test temperature in one of the three cooling baths placed on one side of the thick concrete wall, and then rapidly positioned on the die assembly seated on the concrete footing on the opposite side of the wall (Fig. 15, 16). The explosive charge was held at a fixed distance above the specimen by means of a cardboard box (Fig. 17) and connected to a detonator inside an armoured personnel carrier located on the other side of the wall. After all personnel were safely inside the carrier, the charge was detonated.

Each cooling bath consisted of a sheet metal box, open on the top side, surrounded on the bottom and sides by 1-in. (25-mm) styrofoam insulation, and enclosed in a wooden box. A removable wooden cover shielded each bath from sun, rain, and bits of debris which resulted from the blasting on the other side of the wall. The baths were partially filled with alcohol (primarily 92% ethanol, 7% methanol) and cooled by adding dry ice. A back-up supply of dry ice was maintained at the base headquarters in a larger insulated chest. Bath temperatures were measured by accurate immersion thermometers.

The main part of the assembly (Fig. 16) consisted of a high-strength steel plate, 2 1/2 x 20 x 20 in. (64 x 508 x 508 mm) with a 12-in. (305-mm) diam hole. At the upper side of the hole, the plate had a radius of 2 in. (51 mm). Attached to the bottom of this plate, by studs, was another plate of similar dimensions, except that it was only 1/2 in. (13 mm) thick and had no radius at the edge of the hole. This smaller plate had been attached to make the die conform more closely to that described in recommended practices for explosion-bulge testing [14]. Two loose plates of similar dimensions but each 1 1/2 in. (38 mm) thick were placed below the die assembly. These in turn were placed on a solid 1-in. (25-mm) plate during the latter part of the testing to reduce damage to the concrete footings and to provide a more solid support.

The 7-lb (3.2-kg) cast pentolite charge was as described in the recommended practices and was supported by the cardboard box so that the bottom face of the charge was 14 1/2 in. (368 mm) above the top surface of the die. This dimension, termed the "stand-off distance", was slightly less than the 15-in. (381-mm) dimension recommended.

In earlier work at PMRL, studies were made to determine (a) the length of time required to cool a plate from room temperature down to the test temperature, and (b) the gain in temperature of the plate after removal from the alcohol-dry ice bath until an assumed firing time 1 1/2 min later, and thus the extent of undercooling of the plate required to compensate for this gain in temperature. It was estimated in the field testing that the plate could be removed from the bath, carried to the die, and positioned on it within about 45 sec. The remaining 45 sec would be required to place the cardboard box and explosive over the specimen, connect the detonation wires, ensure that all personnel were in a safe location, and fire the charge. A thermocouple was welded to the bottom of a hole drilled to the central point of a 1 x 20 x 20-in. (25 x 508 x 508-mm) plate. The plate, when in equilibrium with an ambient outside temperature of 17 to 21°C (62 to 70°F) was then placed in a bath of alcohol and dry ice which had been cooled, in separate tests, to a few degrees below each of four plate temperatures at which bulge testing might be undertaken. Bath temperatures were monitored by accurate immersion thermometers. As the plate cooled in the bath, plate temperatures were plotted by a recorder. The bath temperature was maintained close to its original temperature by adding or removing small amounts of dry ice. When the plate had reached equilibrium with the bath, the plate was removed and held on a wooden rack for 45 sec after removal and then held on the explosion-bulge die plate for a further 45 sec. The gain in plate temperature was recorded during the 1 1/2 min interval from removal. From these tests the data in Table 9 were developed.

It was decided to standardize on a plate cooling time of 25 min, at least for testing at -32°C (-25°F). With three cooling baths in operation, it was thought that this cooling time would permit sufficient time between shots for recording of data and preparing for the next shot. Also, additional cooling time would ensure that plates at higher temperatures than 21°C (70°F) (i.e., the maximum ambient and initial plate temperatures in the simulated tests) would be adequately cooled to the test temperature.

A cooling time of 25 min would result in considerable time saving compared with a time of 90 min, which was recommended in procedures for bulge testing [14]. These recommendations were based on the use of a refrigerating chamber which apparently necessitates longer cooling times due to slower heat extraction by the air surrounding the plate.

In the testing at the Petawawa site, a plate was placed in a bath at, or close to, the bath temperature indicated in Table 9. Control of bath temperature normally required addition of some dry ice to compensate for heat transfer from the warmer plate just after it had been placed in the bath. The amount added depended on the desired test temperature and on whether the plate was being prepared for its first shot and was thus originally at the ambient temperature of the air, sometimes warmed further by sun heating, or had been cooled and subjected to an explosive shot. In the latter case, the plate temperature increased only slightly during the interval between removal from the bath to re-insertion in it, despite the blasting operation. The bath temperature was then maintained within ±1°C (±2°F) of the desired control temperature by adding or removing pieces of dry ice as required. A plate was judged to be ready for testing when it had been in a bath maintained within this temperature range for at least the minimum selected holding time given in Table 9 for each plate testing temperature. If the temperature of the bath varied from this temperature range, the temperature was readjusted by adding or removing dry ice, as required, and restarting the timing cycle for that plate. A log of bath temperatures was maintained by measuring the temperature about every five minutes and marking these values with a grease crayon on a plastic sheet attached to the cover of the bath. This was a practical solution to the problem of keeping track of each plate even in rainy weather.

After each shot, the test plate was examined for cracking. If cracking had not propagated to the "hold-down" regions of the test plate i.e., the portions of the plate which were clamped flat against the surface of the die by the explosive force and thus were not subjected to bulging, or if cracking had not extended completely through the plate or weld thickness, then an additional shot was made until either of these conditions occurred or the total plate thickness reduction reached a level of at least 10%. After each shot, provided that neither of these two cracking conditions had occurred, the thickness of the plate was measured with the ultrasonic thickness tester at the point 1 1/2 in. (38 mm) from the edge of the weld where thickness was determined prior to the first shot. The height of the bulge was also measured.

After the crew developed experience with the test routine, no difficulty was encountered, except in adverse weather, in making the necessary measurements after each shot and in preparing plates for testing by cooling for the minimum time periods as given in Table 9. There was no difficulty in ensuring that firing occurred 1 1/2 min after removal of a plate from the bath even under adverse weather conditions. A total of 87 shots were made in less than 4 days of testing despite adverse weather conditions approximately 50% of the time.

Some difficulty was experienced in the use of the ultrasonic thickness tester especially during rainy periods. Erratic thickness readings were being obtained on the specimens despite the fact that the tester gave correct readings on the test block. It was concluded that a thin film of ice forming on the cold plate as measurements were being made was the reason for erratic readings. It was also possible that, in spite of precautions, rain which did get into the cooling baths may have contributed to the problem. No difficulty was experienced after commencing a practice of flushing the test surfaces prior to measurement, using a squeeze bottle with fresh alcohol.

Part way through the project it was realized that the absence of a solid steel protective plate between the die assembly and the concrete footings was becoming of significance. Under rainy conditions, bits of concrete were being forced up onto the cold plate surfaces to freeze in a thin film which interfered with subsequent thickness measurements. Also, the amount of solid, flat surfaces on the footing for further tests was being reduced at a rapid rate and somewhat erratic and/or reduced thickness reductions were becoming more evident, presumably as a result of variable support by the footing. Finally, distortion in the die assembly had become quite noticeable. Measurements showed that the die assembly had been deformed from a flat plane by about 3/8 in. (9 mm) at a central position. Consequently, all further tests were made with a solid 1-in. (25-mm) high-strength steel plate between the concrete and the die assembly. This improved the conditions but by the completion of the program the two loose die insert plates were cracked completely through on one side, and there was a crack about 1/2 in. (13 mm) in length on the radius portion of the die running up from the flame-cut edge of the hole.

Table 10 summarizes the test data and results, and Fig. 18 to 24 inclusive illustrate performance of various specimens.

In the CHT-100 weldments, visual examination of fractures, magnetic particle inspection of specimens CHT6 and CHT7 (Fig. 21 and 22 respectively), and examination of selected sections were carried out. In all specimens, visual examination showed that fracture had been initiated at or very close to the weld toe on one side of the weld but no specific point of origin was evident. There was no visible evidence of cracking on the other side of the weld, on the bulge face. The following summarizes additional observations for each specimen. In referring to the fracture, the part of the fracture closest to the bulge face will be considered as the lower part.

CHT1: In the bulge region, most of the fracture path in the lower half of the fracture appeared to be in the plate, at or close to the weld fusion line, as traces of the weld bead pattern were visible. On the upper half of the fracture, the path appeared to travel through the weld.

CHT3: Much of the fracture path associated with the weld was judged to be at or close to the outer boundary of the weld HAZ. Figure 25 is illustrative.

CHT6: The fracture had a similar appearance along the entire length, showing traces of the weld bead pattern over all but the upper one-half area of the fracture. Figure 26 illustrates sections from opposite sides of the fracture at the bulge apex. These sections confirm that much of the fracture path was at or very close to the fusion line and was not through the weld metal. In Fig. 26, except for the upper one-half portion, only weld or fused metal is to the left of the fracture and only HAZ metal is to the right of it. In the upper one-half portion, weld metal is evident on both sides of the fracture, thus explaining the absence of traces of weld bead pattern on the corresponding surfaces of the fracture faces. Magnetic particle examination on the bulge face of the specimen revealed no indication of cracking on the side of the weld away from the fracture, i.e., corresponding to the lower side of the weld in Fig. 21 or the lower left side in Fig. 26.

CHT7: The visual appearance of much of the fracture was similar to that of CHT6, but there were some regions where the fracture path was further from the weld, and thus either in the HAZ or the prime plate. Magnetic particle examination, as for sample CHT6, revealed no cracking on the other side of the weld.

CHT8: The fracture path, although initiating at one edge of the weld, was judged to be mainly in the prime plate, based on visual examination. The fracture surface showed linear plateau-like regions. Figure 27 confirms these visual observations. Where fracture had passed through the hold-down region (left side of Fig. 23), the visual appearance indicated that the fracture path was similar to that illustrated by Fig. 26.

CHT10: In the central 3-in. (76-mm) region, the visual appearance indicated that the fracture had extended from the weld toe through the plate outside the HAZ. On either side of this central region, the fracture was closer to the weld outline but without showing any traces of weld bead pattern. Thus the fracture path was judged to be either in the HAZ away from the weld fusion line, or in prime plate outside the HAZ.

Microhardness traverses, using a 10-kg load and a diamond pyramid indicator, were made across a transverse section removed from bulge specimen CHT1. Traverses were made on each side very close to the surfaces of the plate and also at a central plane. Hardness ranges were similar in the three traverses. The following Victers hardness values were determined:

Unaffected base metal	264 to 287
Heat-affected zone	283 to 367
Weld fusion zone	312 to 370.

The region with maximum hardness in the HAZ was very close to the weld fusion boundary.

3.7.2 Crack-starter tests on Cu-Ni prime plate

Previously, explosion-bulge crack-starter tests had been made on prime plate steel from heat C1[2]. It was desired to carry out tests on heat C2 during the opportunity presented by the explosion-bulge testing phase of the work. However, because only steel from heat C1 was available in the size required for prime plate tests, it was decided to conduct confirmatory tests using specimens from this heat.

Three crack-starter specimens were prepared, each being 1 x 20 x 20 in. (25 x 508 x 508 mm) with a Hardex N bead deposited parallel to the direction of rolling. The crack-starter bead was deposited and notched as in the preparation of the drop-weight specimens, using the standard two-pass technique. The Hardex N electrodes were from heat B, which was used predominantly for the drop-weight testing (Table 8).

Specimens were cooled to 4°C (7°F) below test temperatures of -65, -55 and -45°C (-85, -67 and -49°F). The steel support plate was placed beneath the die assembly and the concrete footing. Trial tests on CHT-100 plate showed a thickness reduction of about 3% using a 7-lb (3.2 kg) charge offset 14 1/2 in. (368 mm).

At -65°C (-85°F), the plate broke into several pieces on the first shot (Fig. 28). The primary fracture initiation was in the crack-starter bead about 1/4 in. (6 mm) from the notch.

At -55°C (-67°F), the crack-starter bead developed three transverse cracks which extended just to the edges of the deposit. One crack was at the notch, and each of the others were located about 1/2 in. (13 mm) from the notch. On the second shot, one of the cracks away from the notch propagated so that a piece was broken out of the bulge region (Fig. 29) and cracking also extended into, but not through, the hold-down regions. One crack ran about 1 in. (25 mm) just to the hold-down region from the closest point of the piece that was blown out. The other crack extended from the central region of the specimen, nearly in a vertical direction with reference to the position of the specimen in Fig. 29, and for about 1 in. (25 mm) into the hold-down region.

On the first shot at -45°C (-49°F), the specimen developed a crack 7 in. (179 mm) in length and confined within the bulge region (Fig. 30). This crack was started in the crack-starter bead about 1/4 in. (6 mm) from the notch. On the second shot, cracking propagated at three locations just to the hold-down region (Fig. 31). An additional crack, which did not extend into the plate, was observed in the crack-starter about 1/4 in. (6 mm) from the notch, but the root of the notch appeared to be uncracked.

4. DISCUSSION

The scale formed on the Cu-Ni steel during hot working and heat treatment was found to make grinding operations required in preparation of specimens somewhat more difficult than for the other two steels. The manufacturer of the Cu-Ni steel had indicated that the scale was quite heavy during conditioning, although rolling was apparently performed without difficulty.

As shown by Table 2, all of the steels met the tensile requirements of ASTM A517 which are specified only for specimens prepared in the longitudinal direction of rolling. For the 2-in. (51-mm) Cu-Ni steel, and for each of the T-1 and CHT-100 steels, similar tensile strengths and similar yield strengths were obtained for both longitudinal and transverse directions. For the other thicknesses of Cu-Ni steel, the strengths in the transverse direction were significantly lower than in the longitudinal direction. The reason for this was not established. However, it is noted that only in the testing of the 3/4-in. (19-mm) and 1 1/8-in. (29-mm) Cu-Ni plates were the properties in the transverse direction obtained by tests made at a later stage of the program and on different samples of the steel than those used to obtain the longitudinal values. It is possible that variations in heat treatment and/or in rolling operations, for samples prepared at different times, may explain the difference. However, Brinell hardness tests, made on various Cu-Ni specimens such as for Y-groove weldability, drop-weight and bulge testing, gave values in the range 229 to 241. Based on the relationship that the ultimate strength is approximately 500 X the Brinell hardness, the corresponding ultimate strengths were in the range 115 to 120 ksi (793 to 834 MPa). Thus, this does not suggest any major variations in properties due to variable heat treatment or rolling operations.

Referring to Table 6, it is noted that the deposited weld metal overmatched the prime plate in tensile and yield strengths. Microhardness traverses made on a transverse section from explosion-bulge specimen CHT1 confirmed the overmatching strength of the weld fusion zone and showed also that the HAZ overmatched the prime plate. Thus transverse weld tensile specimens failed outside of the weld region and provided further data on the ultimate and yield strengths of the prime plates as well as showing that the welded joints exceeded prime plate strengths. The values for T-1 and CHT-100 specimens were very similar to those given in Table 2 for prime plate tensile tests. For the Cu-Ni steel, some variability in tensile properties is again illustrated. For example, the ultimate and yield strengths in the longitudinal direction of plate rolling are lower for the plate used in the transverse weld tests than for the plate used in prime plate tensile tests. Ultimate and yield strengths, transverse to the direction of plate rolling, are in accord with the transverse properties given in Table 2 for 3/4-in. (19-mm) plate, and are somewhat higher than for the 1 1/8-in. (29-mm) plate and considerably lower than for the 2-in. (51-mm) plate.

The Charpy data in Fig. 3, 4 and 5 for the Cu-Ni steel also resulted from earlier tests conducted in the longitudinal direction only and subsequent transverse tests on different samples from the same heat of Cu-Ni steel. The transverse tensile tests for the 3/4 and 1 1/8-in. (19 and 29-mm) plates (Table 2) were made on these same samples. Considerable divergence is noted between the longitudinal and transverse Charpy transition curves in each plate thickness. There is fair agreement among the longitudinal curves and among the transverse curves, respectively. It should be noted also, in passing, that the only other Charpy data for the two plate rolling directions in Cu-Ni steel, obtained earlier for 1-in. (25-mm) heat C1 steel, showed properties for the longitudinal direction fairly similar to those obtained in the current study for all three plates of heat C2 steel, but with somewhat higher values in the transverse direction at temperatures above about -73°C (-100°F)[2]. Figures 3, 4 and 5 indicate that, even in the transverse direction, a Charpy impact value of about 30 ft lb (41 J) was obtained at -73°C (-100°F) for the three plate thicknesses in the Cu-Ni steel from heat C2. Other comparisons for all three steels may be made by reference to the appropriate figures or to the summary given in Table 11. For example, to compare with the above-mentioned temperature relating to 30 ft lb (41 J) in the transverse direction, corresponding temperatures were -1°C (+30°F) for CHT-100 steel and -46°C (-50°F) for T-1 steel. Or, in the longitudinal direction for 1-in. (25-mm) plates, the temperature corresponding to 30 ft lb (41 J) was -96°C (-140°F) for T-1 steel, -34°C (-30°F) for CHT-100 steel, and -107°C (-160°F) for Cu-Ni steel.

Similarly, comparison of the Charpy V-notch ductility of the welds (Fig. 10, 11 and 12) among themselves, or with the prime plates (Fig. 1, 2, 3, and 4), may be made by reference to these figures or to the summary in Table 11. For example, unlike the transition curves for the T-1 plate, the curves for T-1 welds did not tend to flatten as temperatures increased. Thus, the welds developed increasingly higher values than the plate above about -57°C (-70°F) in the longitudinal direction and above about -96°C (-140°F) in the transverse direction. For the CHT-100 steel, the weld developed significantly higher values than the plate at all test temperatures. For the 1-in. (25-mm) Cu-Ni steel, an average curve for the two test welds would tend to approximate the curve for the longitudinal direction, being somewhat inferior to the plate in this direction, but significantly superior to the plate in the transverse direction.

Contrary to original expectations, considerable difficulty was experienced in the drop-weight testing phase of the program. Most drop-weight testing previously at PMRL had employed the smaller P-2 type specimen and no difficulty had been reported with cracking initiating away from the crack-starter notch. In the current study, the larger P-1 type specimen was employed mainly because of a desire to employ the same specimen as used in a previous study by others on T-1 steel [15]. The anomalous cracking experienced in the prime plate studies was the first indication that such a condition could occur (Table 4). After some deliberation, following the first occurrences of this condition, it was decided to continue with the testing. Although such cracking was not mentioned in specification E208 and thus apparently had not been anticipated by the writers of the specification, there appeared to be no strong argument indicating that the propagation of an existing crack in the Hardex N bead into the plate, rather than initiation of a crack from the notch and propagation into the plate, should necessarily invalidate the test. The NDT temperatures given in Table 4 for the three prime plate steels are considered to be valid, despite the presence of some anomalous cracking. However, when tests were made on the first set of CHT-100 welds and the two sets of Cu-Ni welds, several "breaks" occurred sufficiently far from the notch location so that the results were invalid.

The development of a fracture away from the notch was seen to be related to the presence of extensive cracking in the crack-starter bead (Fig. 13). The Hardex N deposit composition for the electrodes used for most or all of the tests in the current program, was within the manufacturer's intended range except for the manganese content which was somewhat higher (Heat B, Table 8). On the basis of carbon-equivalent = $\%C + \frac{\%Mn}{6}$ the value for the weld deposit was 0.64% versus a maximum of 0.63% according to the manufacturer's intended range when both carbon and manganese have peak values. Thus, it was concluded that the deposit composition of heat B electrodes would be considered as normally acceptable, although representing the hardest and hence most crack-sensitive deposit permitted by the composition limits intended. It is noted that heat A electrodes (Table 8) had a carbon-equivalent of 0.54% and hence should be somewhat less susceptible to cracking. It is believed that cold-cracking rather than hot-cracking was involved because of the reduction in the cracking when the electrodes were baked to reduce the moisture content of the coating and thus to reduce or eliminate the influence of hydrogen. Also, the absence of failures away from the notch, when the smaller Type P-2 specimens were employed both in the current program and in others conducted at PMRL, suggests that a slower cooling rate tended to inhibit cold-cracking in the crack-starter bead of the Type P-2 specimens as compared with the larger Type P-1 specimens. Metallographic examination of deposits made under the same conditions with the heat B electrodes indicated that, although some cracking was present in the smaller Type P-2 specimens, it was much less than in deposits made on the larger Type P-1 specimens.

The cracks that initiated fractures away from the notch were seen to be oriented in the columnar growth direction of the Hardex N deposit. Also, there appeared to be more cracking near the termination of the second pass when the standard two-pass technique was employed. In Australian studies, it had been concluded that elimination of the intersection of the two passes and of any weld termination directly on the test specimen, by means of a single-pass deposit and a run-off tab, would eliminate anomalous cracking [13]. The limited number of tests employing this technique in the current project did indicate a lessening of anomalous cracking. However, it was not completely eliminated. Also, recent studies, aimed at selecting suitable Australian-produced electrodes to replace Hardex N, showed that anomalous or secondary cracking occurred with three of the five electrodes examined, despite the use of the single-pass deposit and a run-off tab [16].

It appears that the maximum carbon-equivalent for Hardex N, made possible by the manufacturer's intended range (Table 8), is satisfactory for use with the smaller drop-weight specimen but too high for use with the larger specimen. It is probable that an electrode producing this deposit composition, but having a basic or low-hydrogen coating and maintained so as to provide relatively low-hydrogen levels in the arc atmosphere, would produce virtually crack-free deposits and would avoid anomalous cracking even with the standard two-pass technique. Enquiries made to Canadian suppliers for such an electrode have to date had negative results.

Despite the difficulties encountered due to cracking away from the notch, and although the problem has not been fully resolved, the data in Table 7 are considered to provide reasonably adequate indications of the NDT temperatures for welds in the three steels. It is acknowledged that only for welds in T-1 steel was the NDT temperature obtained without any unusual occurrences or procedures. For the CHT-100 steel, in the first set, "no break" conditions occurred at -51°C (-60°F) and at -46°C (-50°F), but all other specimens in the set developed fractures in the prime plate to at least one edge of the specimen, i.e., "break" conditions, and thus prevented determination of the NDT temperature of the welds. In the second set, it is recalled that these specimens were first prepared with the crack-starter bead deposited in a single pass but without a run-off tab. When other specimens in this set showed transverse cracking away from the notch on drop-weight testing, the crack-starter bead was ground off each of the four untested specimens and a new single-pass bead was deposited directly over the location of the previous bead, but employing a run-off tab to eliminate any weld crater on the test specimen. On testing, the specimens at -46°C (-50°F) did not show "break" conditions, and one at -51°C (-60°F) showed a "break" condition without any secondary cracking initiating away from the notch. The NDT temperature was concluded to be about -51°C (-60°F). It is thought that the additional reheating of the upper region of the weld being tested, caused by the re-deposition of the single-pass crack-starter bead, would not modify significantly the crack-propagating behaviour of this region from that which would result from the standard deposit procedure involving two passes intersecting at the notch location. Support for this view is provided by the fact that ASTM E208 permits additional deposition of metal at the central crater location of the two-pass crack-starter bead when the initial welding has not provided sufficient weld height to permit proper notching. Following the same reasoning, the Cu-Ni weld specimens in the first set, are considered to provide valid data. It will be recalled that these specimens were also re-beaded when it was found, earlier in the program, that the notch in the first crack-starter deposits had been made incorrectly. In the second set the specimens were prepared strictly to ASTM E208 requirements. By combining the results for the two sets of specimens, it can be concluded that the NDT temperature is of the order of -96°C (-140°F).

It must be noted that the longitudinal cracks observed in the Hardex N deposits may tend to influence crack extension through the deposit (Fig. 13). Longitudinal cracks that happen to be in the path of the advancing "through" crack, either extending from the root of the notch or from a nearly vertical crack elsewhere in the deposit, may deflect the fracture path. This would tend to inhibit extension of cracking into the specimen being tested and might therefore displace the NDT temperature somewhat below its correct value. The variability of this longitudinal cracking could also affect consistency of testing.

The weldability examination of the three steels showed a marked difference in the cracking tendency of the HAZ in single-pass, fillet-welded Controlled Thermal Severity (CTS) tests as compared to that in single-pass, butt-welded Y-groove restraint tests. No cracking occurred in any of the steels in the CTS tests. However, in the Y-groove tests severe cracking occurred in all three steels until a sufficiently high level of preheat was employed to prevent it. It should be noted that two factors in the Y-groove test were less severe than in the CTS test. The combined-plate thickness was less in the Y-groove test, i.e., 2 in. (51 mm) versus 3 in. (76 mm), or more in some of the Cu-Ni steel tests, and the energy input was higher, i.e., 42 kilojoules/in. (1.7 kilojoules/mm) versus 32 kilojoules/in. (1.3 kilojoules/mm) in the CTS tests. In previous work on a C-Mn steel, it was also found that Y-groove tests showed severe cracking whereas CTS tests showed none, despite thickness and energy input factors in the CTS test being such as to produce more crack-sensitive microstructures than in the Y-groove test [9]. It was concluded from that work that the level of stress developed at the root area was greater in the Y-groove specimen than in the CTS specimen and overshadowed the less severe factors in the Y-groove specimen.

In a separate study [17], the Cu-Ni steel was included in comparative Varestraint testing with several micro-alloy high-strength line-pipe steels to evaluate hot-cracking susceptibilities. The Cu-Ni steel was found to have a higher level of susceptibility than those other steels. However, the cracking found in the Y-groove testing of Cu-Ni steel in the current work was not excessive in comparison with that found in testing in the T-1 or CHT-100 steels. Also, such cracking was concluded to be cold-cracking rather than hot-cracking. The former would be expected to be eliminated by preheating, as was the case with all three steels. Further, no indication of hot-cracking was found in any of the butt welds made in the 1-in. (25-mm) Cu-Ni plate. It is possible that an increase in hot-cracking susceptibility might appear in more highly restrained joints, as in fact the butt welds were not restrained by any hold-down device. However, it is thought that any marked tendency for hot-cracking in the HAZ would have been shown by the 1-in. (25-mm) Y-groove testing.

Resulting from a discussion with Dr. P. Puzak, then of the U.S. Naval Research Laboratory, Annapolis, Maryland, attainment of a plate thickness reduction of 10% in the explosion-bulge test was considered to demonstrate fully satisfactory performance and a high level of notch ductility of the weldment.

According to the recommended procedures intended for evaluation of HY-80 steel weldments, four specimens should be tested at -18°C (0°F) [14]. In the current program, it was considered desirable to test specimens also at -32°C (-25°F). Referring to Table 10, for T-1 and Cu-Ni steels, two welded specimens in each steel showed no cracking of any significance while being bulged to at least 10% thickness reduction at -32°C (-25°F), e.g, Fig. 18 and 19. The performance at the lower temperature was taken as evidence that no cracking would occur while bulging to 10% thickness reduction if these specimens had been tested at -18°C (0°F). Consequently, only two additional tests in each steel were made at this temperature. These tests showed no significant cracking during bulging to over 10% thickness reduction.

Variable performance was demonstrated by the CHT-100 weldments. At -32°C (-25°F), one specimen was broken almost into two pieces (Fig. 20), while the other specimen withstood about 12% thickness reduction without cracking. Of four tests at -18°C (0°F), one developed 14% thickness reduction without cracking, another developed about 7% thickness reduction without cracking but suffered complete fracture on the next shot (Fig. 22), and the two other specimens failed after only slight thickness reduction on the first or second shot (Fig. 21 and 23). At -1°C (30°F), one specimen achieved about 13% thickness reduction without failure, but another specimen developed almost complete separation following about 5% thickness reduction without cracking on the previous shot (Fig. 24).

All failures in CHT-100 specimens were initiated at the weld toes. Apart from this, there was no clear indication of any specific failure mode or area of weakness common to all failed specimens. For example, specimens CHT6 and CHT8 both failed after very little bulging and thickness reduction at the same test temperature (Table 10). Specimen CHT6 developed a fracture, toward the tension side of the bulge, at or very close to much of the weld fusion boundary (Fig. 26). Specimen CHT8 showed fracture propagation initially through the HAZ well away from the fusion boundary and then, through the unaffected plate metal for most of the fracture path (Fig. 27). This figure also indicates some tendency for secondary fractures along planes parallel to the plate surface. At higher magnification, these planes were seen to correspond to inclusion stringers. However, this did not appear to be a dominant factor in determining the main fracture path.

The erratic performance of the CHT-100 bulge specimens was due, most probably, to somewhat greater notch acuity being present at fracture initiation points at the toes of welds in specimens which failed prematurely as compared with specimens which developed at least 10% thickness reduction without cracking, in conjunction with the lower notch-ductility of this steel. Charpy and drop-weight tests on prime CHT-100 plate showed that the notch-ductility was lower than that of the other two steels, or of the weld fusion zones in all three steels. Similar tests were not performed on the weld HAZ. However, as fractures in the CHT-100 bulge specimens tended to propagate in both the HAZ or in the unaffected plate, it is reasonable to assume that the propagation behaviour at least, was fairly similar in both regions.

The explosion-bulge crack-starter tests on prime Cu-Ni plate showed similar behaviour to that obtained in earlier studies on steel from this same heat [2]. It was found that cracking extended just to the hold-down region of the specimen on the second shot made at -45°C (-49°F). This was judged to be at or very close to the crack-arrest temperature, i.e., the temperature at which cracking would not propagate beyond the plastically deformed bulge region after two shots of 7-lb (3.2-kg) charges of pentolite offset 14 1/2 in. (368 mm). In earlier tests, which were performed similarly except for a 15-in. (381-mm) offset, the crack-arrest temperature was concluded to be -47°C (-52°F).

It is noted that the behaviour of the Hardex N crack-starter bead was similar to that encountered frequently in the drop-weight testing. In all test plates, the primary fractures into the plate were extensions from transverse cracking in the crack-starter bead 1/4 to 1/2 in. (6 to 13 mm) from the notch.

5. CONCLUSIONS

1) Tensile properties exceeding the minimum specified by ASTM A517 were demonstrated by the three steels. The Cu-Ni steel showed greater variability, due most probably to the batch nature of processing of plates in this steel only.

2) Welds having tensile strengths exceeding those of the prime plates can be made without difficulty in each steel.

3) Controlled Thermal Severity tests, employing a single-pass fillet weld deposited at low energy input, indicated no tendency for HAZ cold-cracking in any of the steels welded with properly controlled low-hydrogen electrodes and without preheating. The Y-groove butt-weld restraint tests, employing a single root pass made with similar electrodes but at higher energy input, showed severe HAZ cracking in each of the steels. Cracking could be eliminated in each steel by preheating. The T-1 steel required a lower preheating temperature to stop cracking than the CHT-100 and Cu-Ni steels. The latter two steels responded similarly at the same preheat temperatures. Thus the T-1 steel had slightly less susceptibility to cold cracking.

4) No evidence was found to support indications in separate Varestraint studies that the Cu-Ni steel would be susceptible to hot-cracking during welding.

5) Charpy V-notch testing indicated that in both longitudinal and transverse directions, the Cu-Ni steel had a higher level of notch-ductility, the T-1 steel was intermediate, and the CHT-100 steel had a lower level of notch ductility.

6) No difficulty was experienced in producing welds in each steel having Charpy V-notch properties at a central location which equalled or exceeded those of the corresponding prime plate. The greatest divergences between weld properties and longitudinal plate properties were shown with the T-1 steel where weld values became increasingly higher at temperatures above about -57°C (-70°F), and with the CHT-100 steel where weld values were consistently much higher at all temperatures.

7) Drop-weight testing rated the notch-ductility of the steels in the same relative order as by the Charpy V-notch comparison. Nil-ductility transition (NDT) temperatures were -99, -73 and -40°C (-146, -100 and -40°F) for Cu-Ni, T-1 and CHT-100 steels respectively.

8) Although hampered by anomalous crack initiation in drop-weight testing of welds in the three steels, reasonably accurate estimates of NDT temperatures are believed to be -96, -57 and -51°C (-140, -70 and -60°F) for weld central positions in Cu-Ni, T-1 and CHT-100 steels, respectively.

9) Anomalous or secondary crack initiation in the Hardex N crack-starter bead of drop-weight tests, appeared to be related to the deposit composition having a maximum carbon-equivalent, to the use of the largest standard drop-weight specimen, and to the high hydrogen-producing potential of the crack-starter electrode coating.

10) The use of a single-pass crack-starter deposit and avoiding a weld termination on the specimen, as recommended by Australian researchers, was only partially effective in preventing anomalous cracking in drop-weight testing with the largest standard specimen.

11) The problem of anomalous cracking in deposits having a maximum carbon-equivalent level with the largest standard drop-weight specimen should be eliminated by employing the technique recommended by Australian researchers in conjunction with crack-starter electrodes having properly maintained low-hydrogen type coatings.

12) Consistently good performance in explosion-bulge tests, at temperatures down to at least -32°C (-25°F), can be expected for welded joints in T-1 and Cu-Ni steels.

13) Inconsistent performance, ranging from good to inferior, can be expected in explosion-bulge tests at temperatures in the range -32 to -1°C (-25 to 30°F) for welded joints in CHT-100 steel.

14) Poor explosion-bulge performance of some CHT-100 welded joints is believed to be related to the lower notch-ductility of the prime plate and HAZ relative to that of the other two steels. In the CHT-100 welded joints, it is probable that there is lower tolerance for notches or slight defects at the edges of the welds and thus fracture can be initiated from a notch or slight defect which would have no effect in welded joints in the other steels.

15) The performance of Cu-Ni steel prime plate in crack-starter explosion-bulge tests was confirmed despite anomalous cracking in the crack-starter deposit. The crack-arrest temperature, for tests involving two explosive shots of 7 lb (3.2 kg) of pentolite offset 14 1/2 to 15 in. (368 to 382 mm), is at or very close to -46°C (-51°F).

6. ACKNOWLEDGEMENTS

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Cu-Ni prime plate properties. All gas metal-arc welding was conducted by G. Sylvestre, Welding Section, PMRL. Manual metal-arc welding, required in the weldability and drop-weight testing, was performed by L.O. Joy, Welding Section, PMRL. M.J. Nolan, formerly of the Welding Section, PMRL, helped co-ordinate preparation of specimens. K. Winterton, Head, Welding Section, PMRL, provided useful advice. R.V. Narraway, Welding Section, PMRL, assisted in the preparation of Charpy, drop-weight, and explosion-bulge specimens, conducted drop-weight tests, aided directly in planning, conducting and evaluating the bulge testing work, and conducted all metallographic and much of the photographic work involved in the program. J.A. Darling, Canadian Explosives Laboratory, CANMET, provided assistance and advice relative to the explosive-bulge testing work, and arranged for a suitable test site. Finally, the explosion-bulge-testing work could not have been performed without the excellent co-operation of officers and men of the Canadian Forces Base, Petawawa, Ontario.

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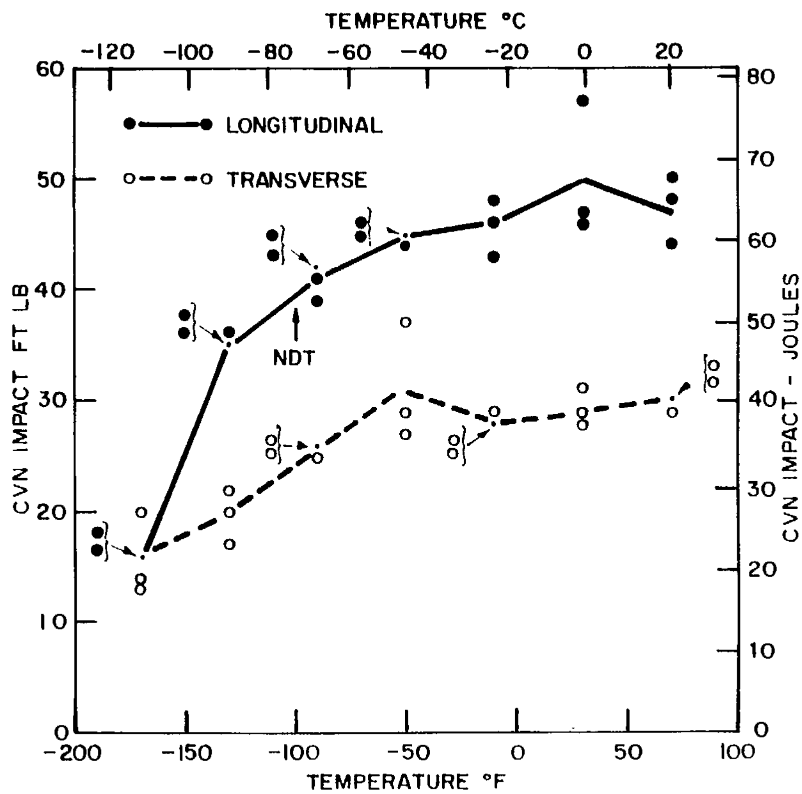


Fig. 1. Charpy V-notch properties - 1-in.(25-mm) T-1 prime plate.

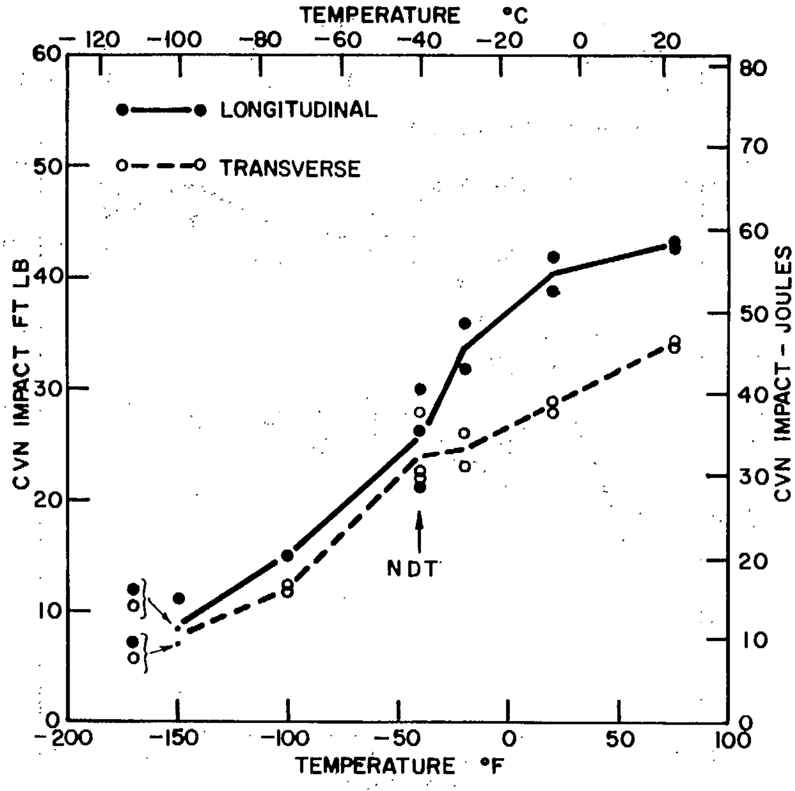


Fig. 2. Charpy V-notch properties - 1-in. (25-mm) CHT-100 prime plate.

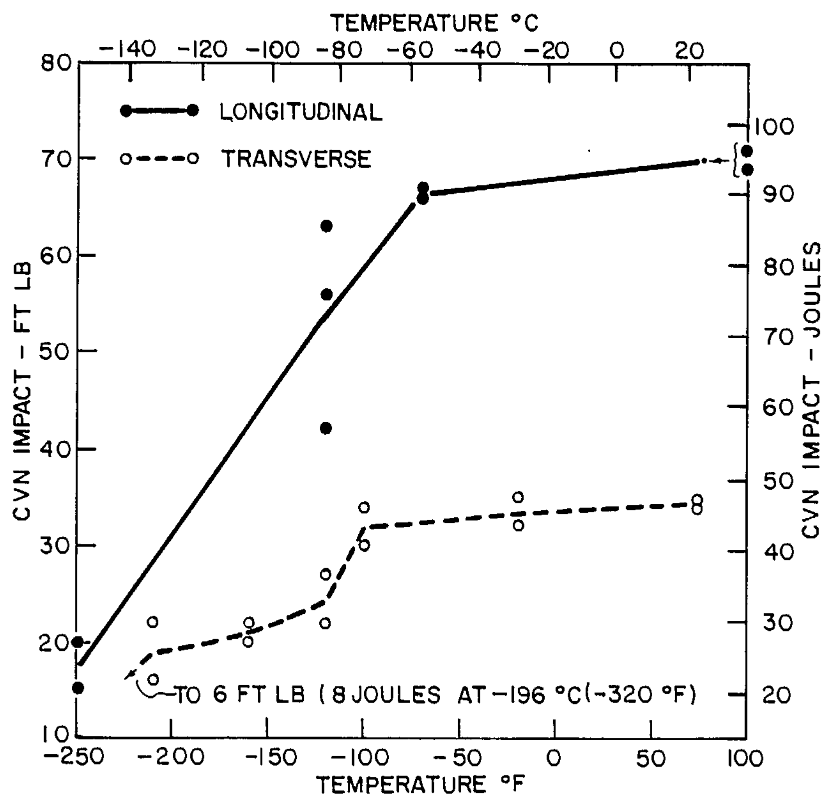


Fig. 3. Charpy V-notch properties - 3/4-in. (19-mm) Cu-Ni prime plate.

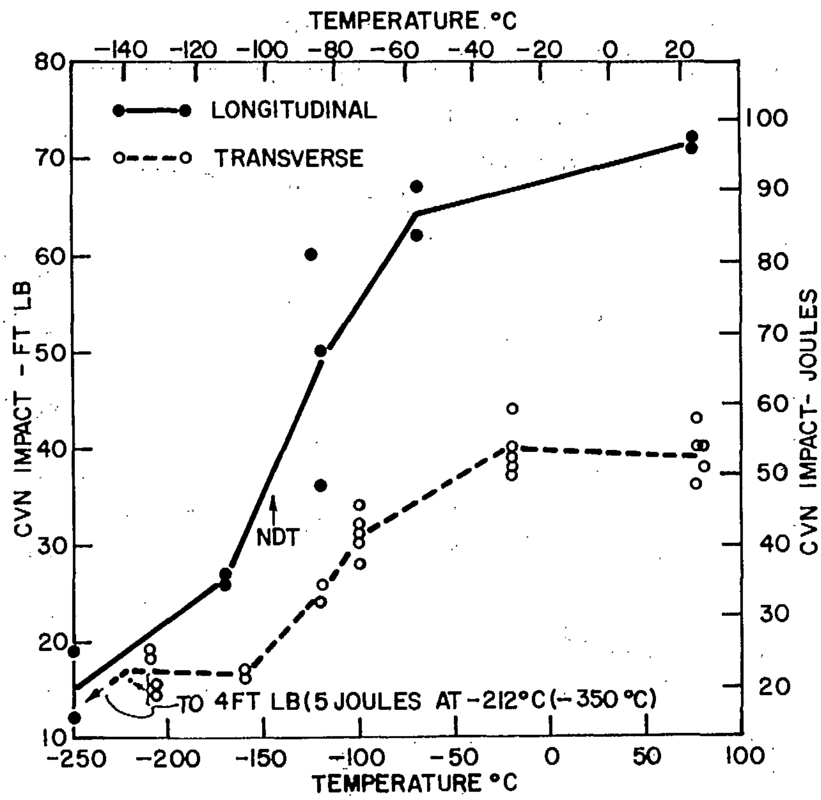


Fig. 4. Charpy V-notch properties - 1 1/8-in. (29-mm) Cu-Ni prime plate.

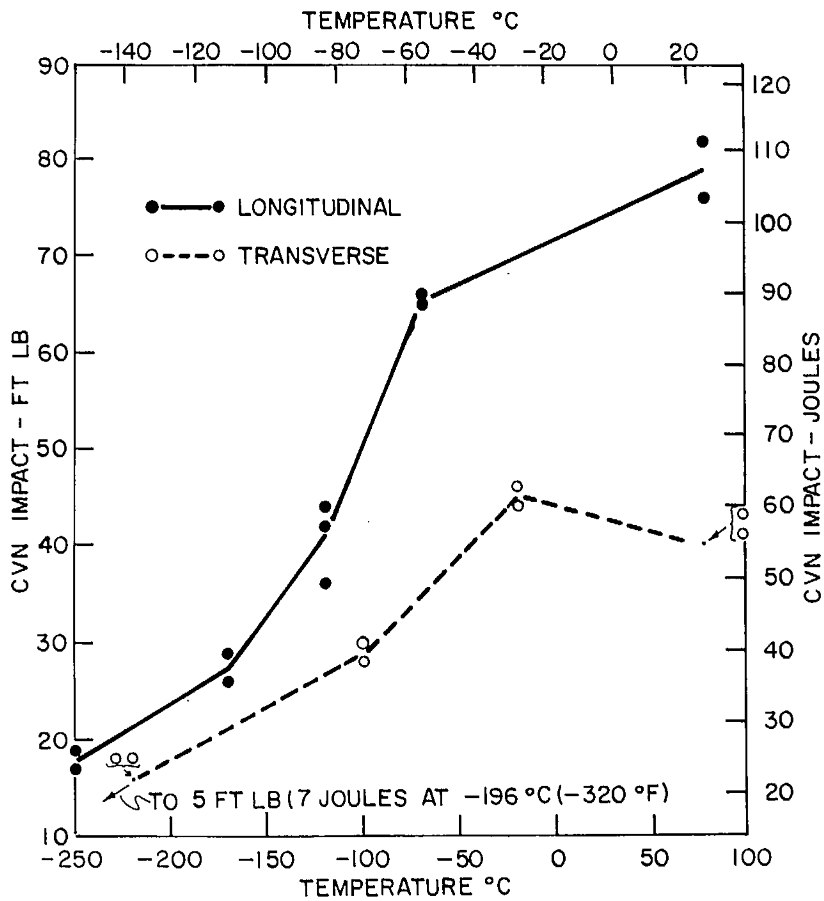


Fig. 5. Charpy V-notch properties - 2-in. (51-mm) Cu-Ni prime plate.

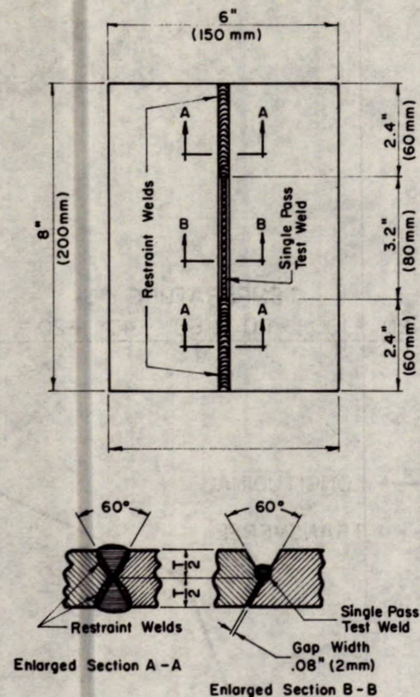


Fig. 6. Y-groove weldability specimen.

Fig. 7. Moderate cracking in Y-groove test.

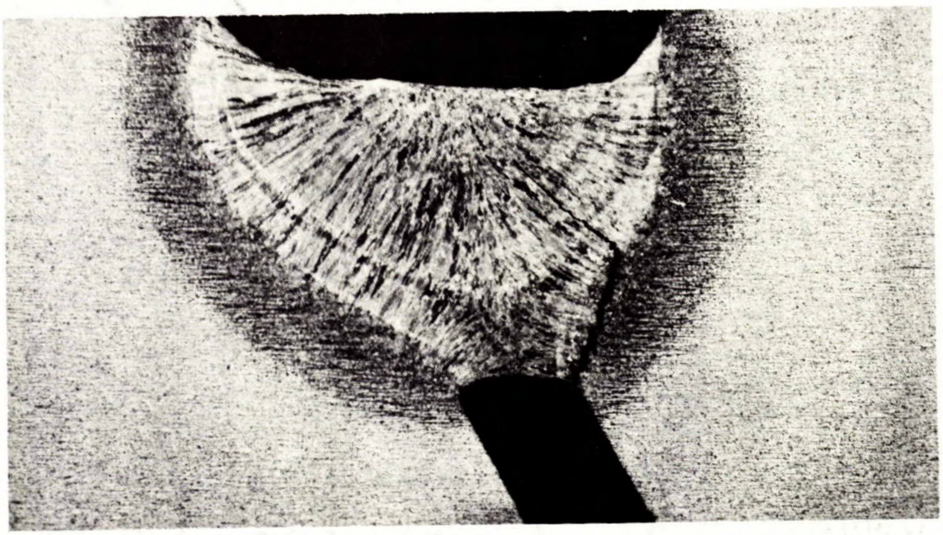


Fig. 8. Severe cracking in Y-groove test.

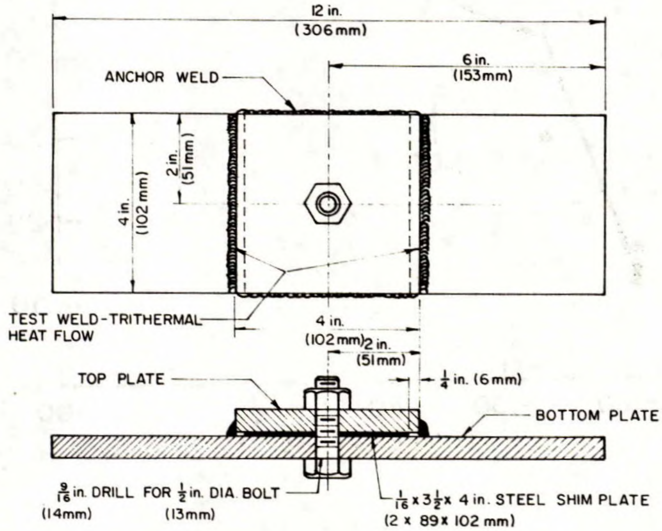


Fig. 9. Controlled Thermal Severity (CTS) weldability specimen.

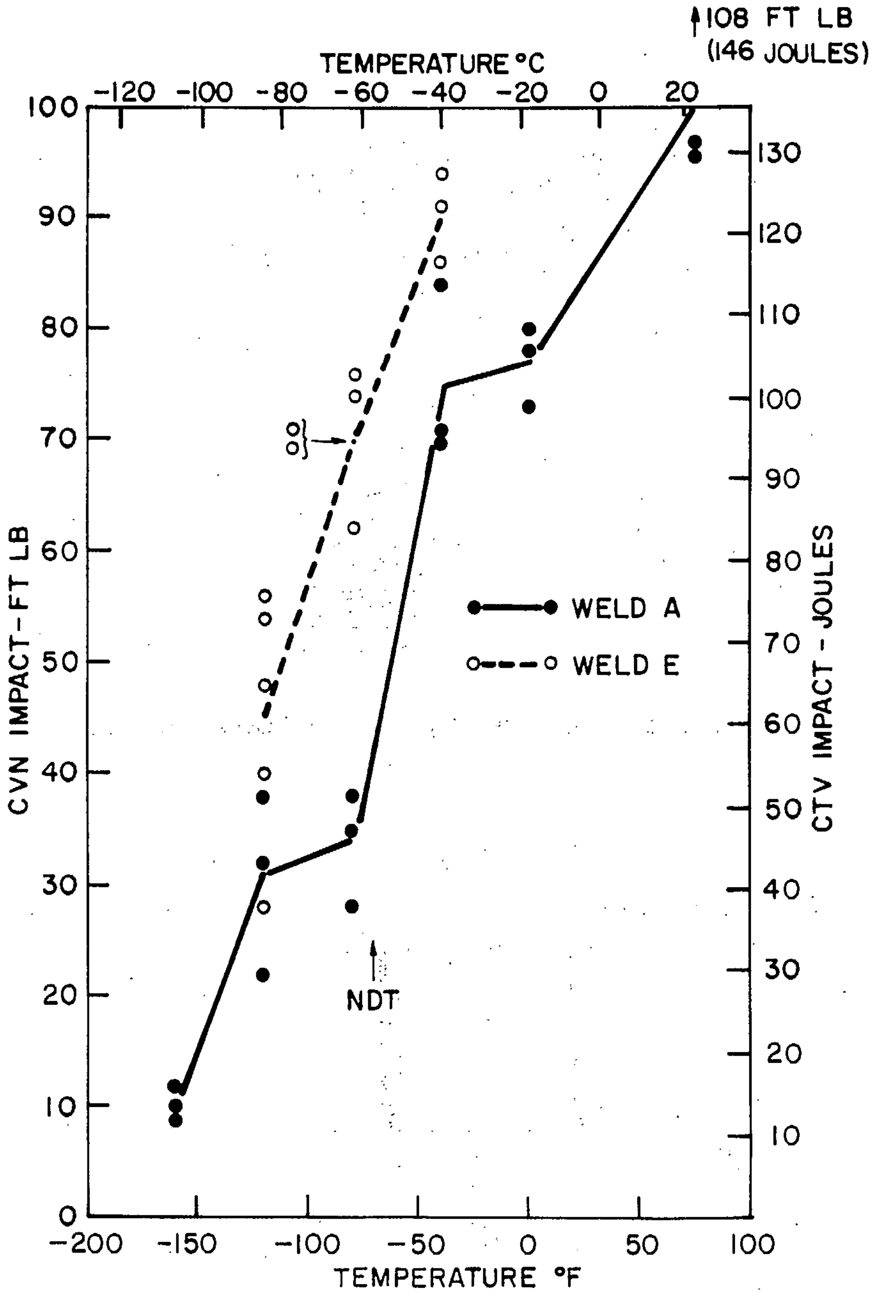


Fig. 10. Charpy V-notch properties - welds in 1-in. (25-mm) T-1 plates.

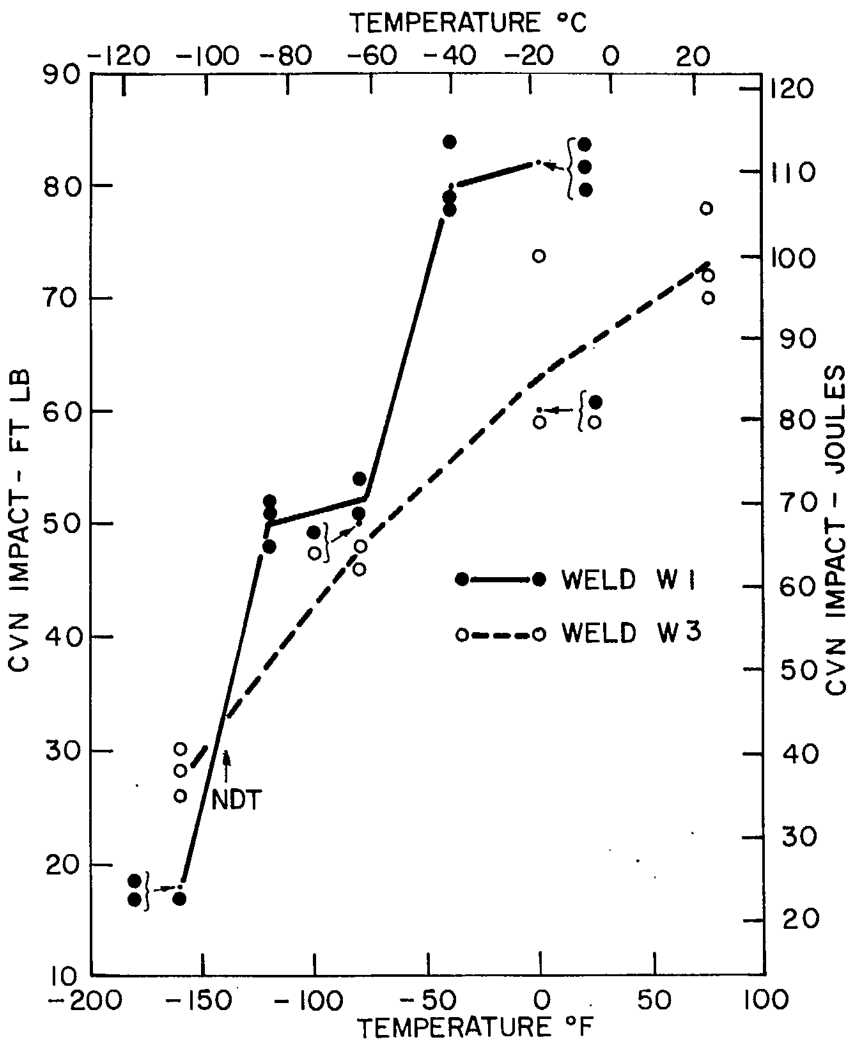


Fig. 11. Charpy V-notch properties - welds in 1-in. (25-mm) Cu-Ni plates.

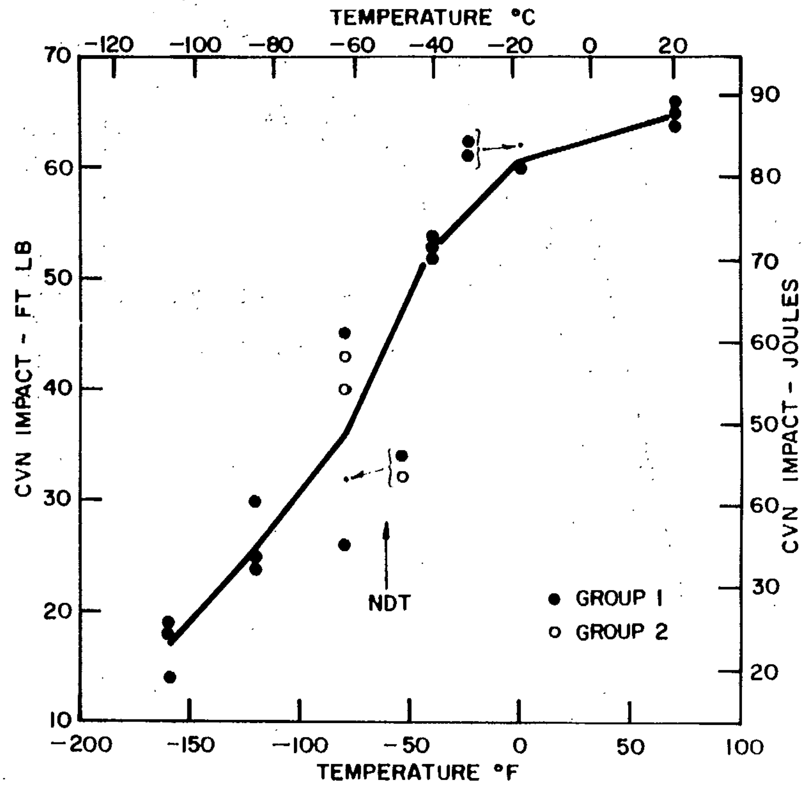


Fig. 12. Charpy V-notch properties - weld in 1-in. (25-mm) CHT-100 plate.

Fig. 13. Illustrating anomalous behaviour in drop-weight test of a specimen from a CHT-100 weld.

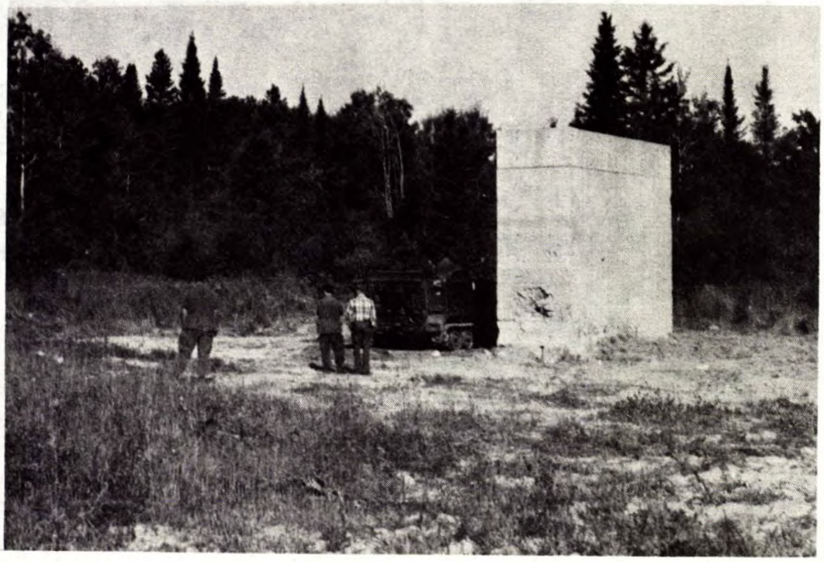


Fig. 14. General view of location used for explosion-bulge testing.

Fig. 15. Cooling baths located on one side of concrete wall.

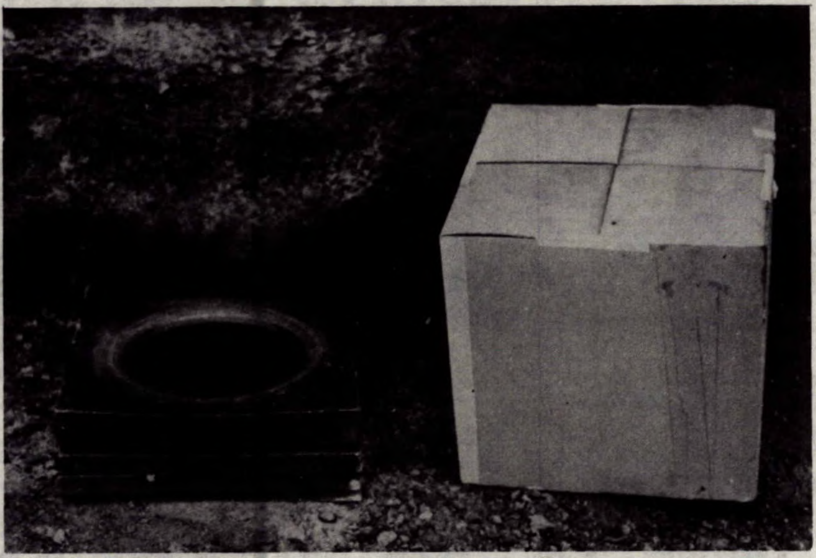


Fig. 16. Die plate, insert plates and support plate.

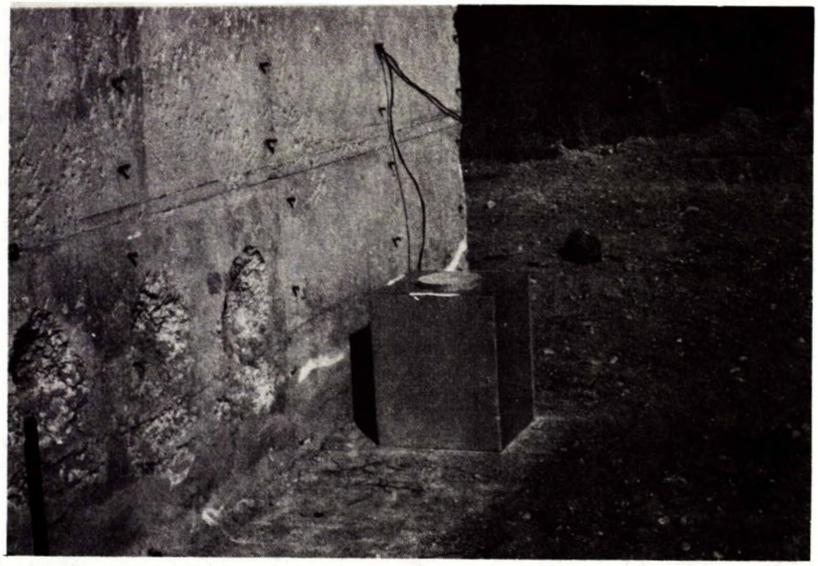


Fig. 17. Explosive supported on cardboard box, ready to fire.

Fig. 18. T-1 steel weldment T1XJ after 5 shots at -32°C(-25°F). No cracking after 4 shots and 9% thickness reduction. On the fifth shot, two cracks, each about 3/4 in. (19 mm) long, developed on the surface, at a total thickness reduction of 10-11%. See also Fig. 19.

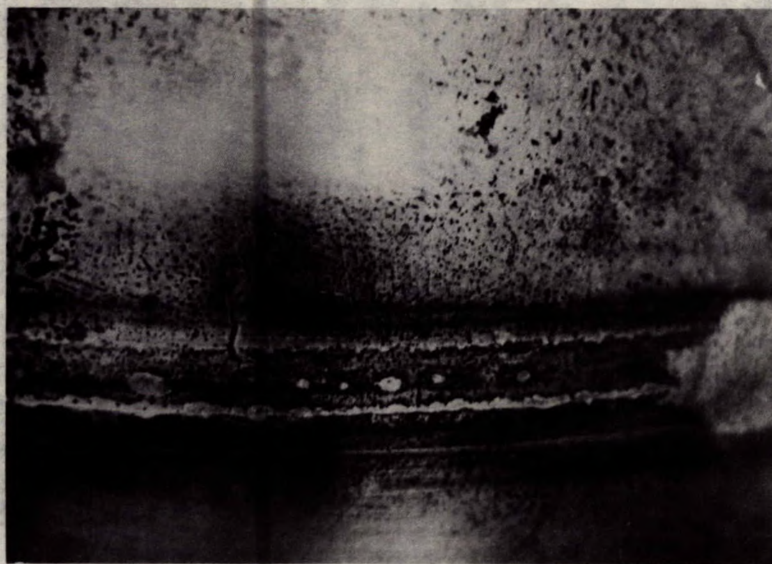


Fig. 19. As for Fig. 18, showing two small cracks developed on the fifth shot. These were not "through" cracks.

Fig. 20. CHT-100 steel weldment CHT1 after 4 shots at -32°C(-25°F). No cracking after 3 shots and 7% thickness reduction.

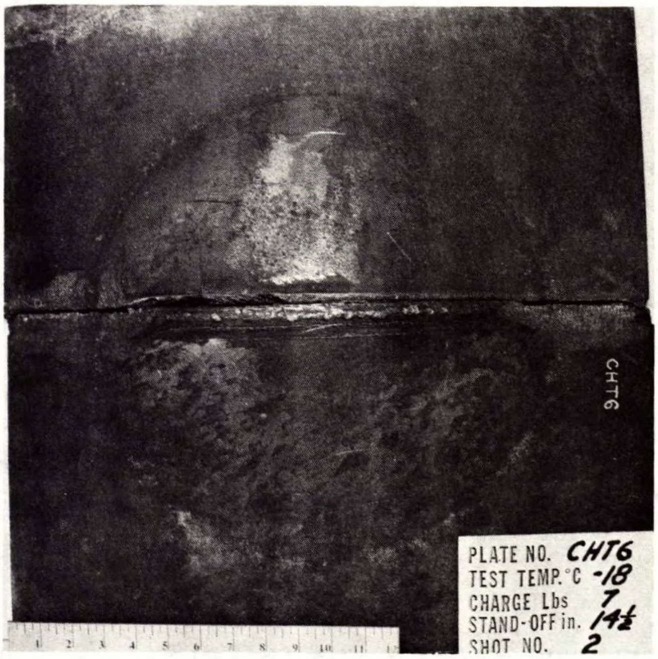


Fig. 21. CHT-100 steel weldment CHT6 after 2 shots at -18°C (0°F)
No cracking on first shot and 1% thickness reduction.

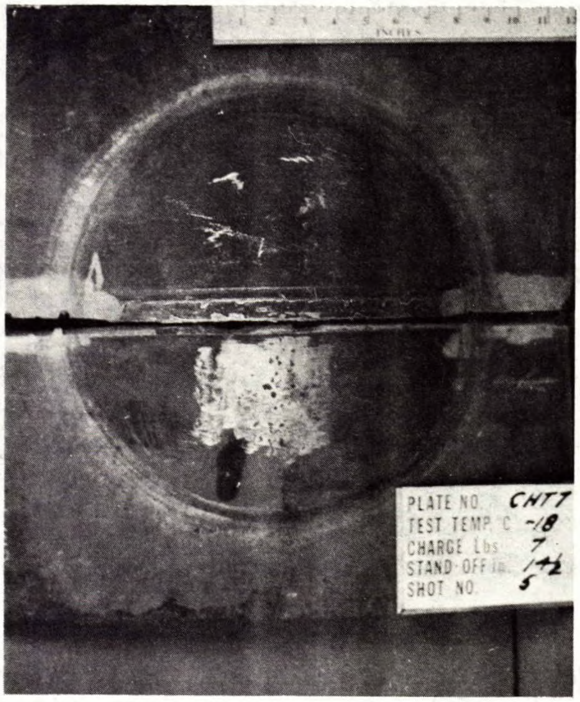


Fig. 22. CHT-100 steel weldment CHT7 after 5 shots at -18°C (0°F).
No cracking after 4 shots and 7% thickness reduction.

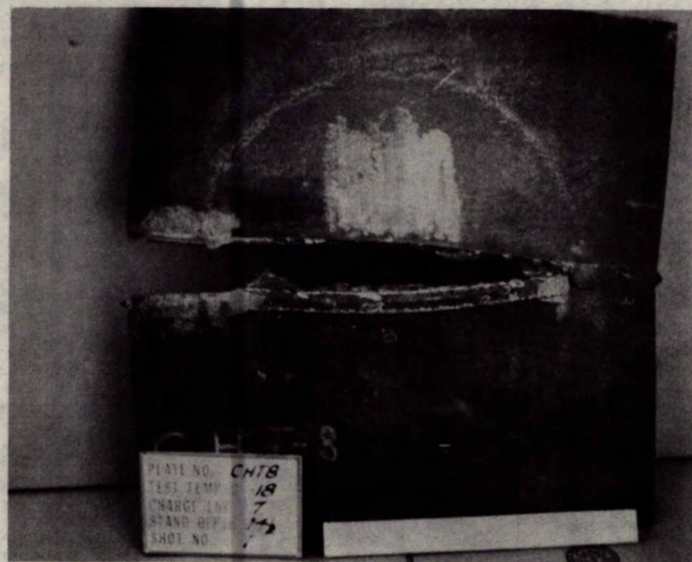


Fig. 23. CHT-100 steel weldment CHT8 after 1 shot at -18°C(0°F).

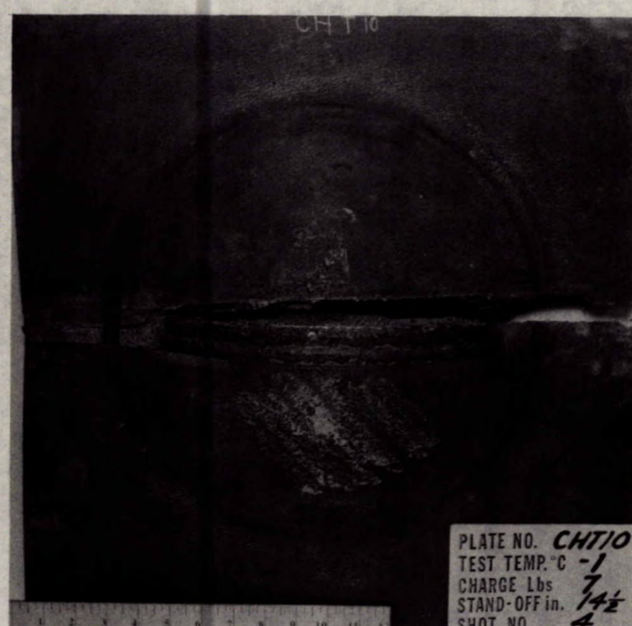
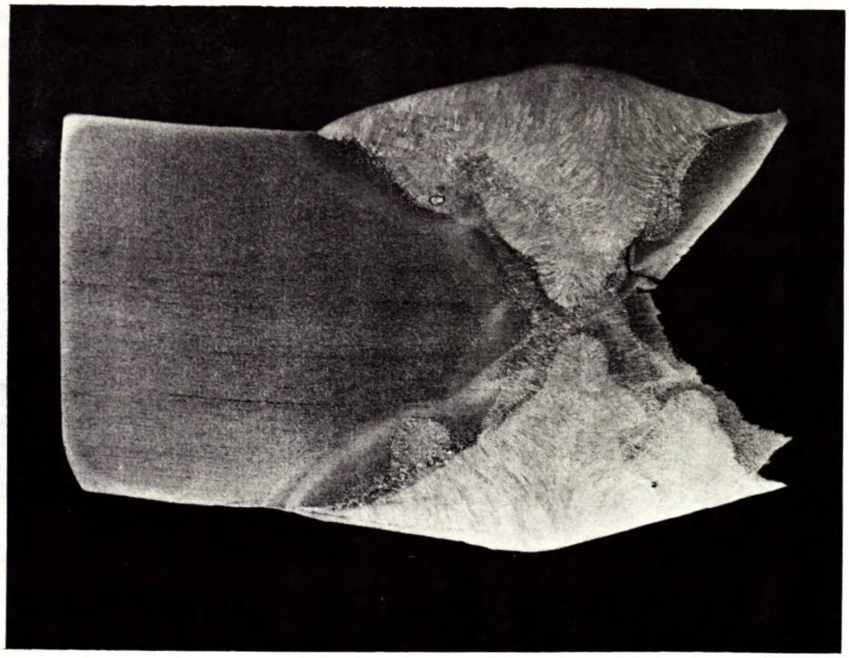


Fig. 24. CHT-100 steel weldment CHT10 after 4 shots at -1°C(30°F). No cracking after 3 shots and 5% thickness reduction.

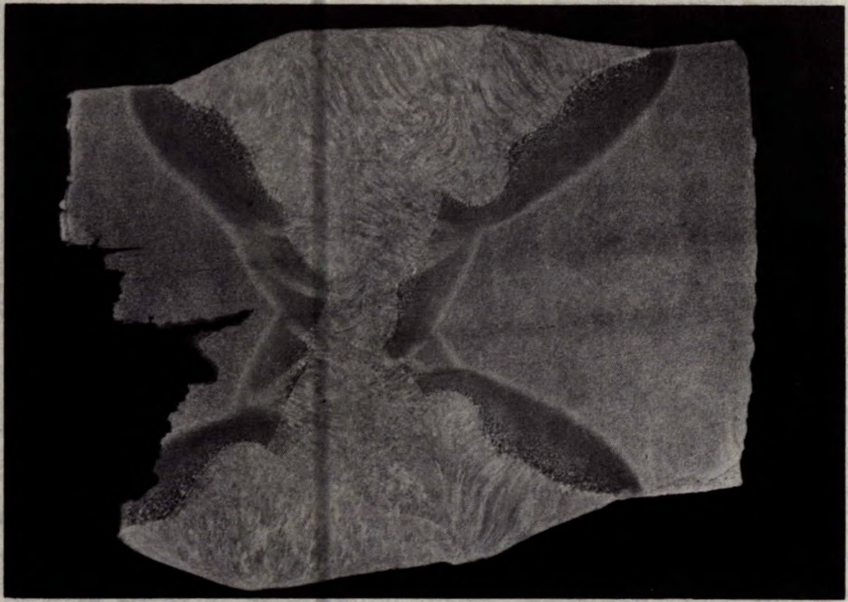


X 2.4 Nital etch

Fig. 25. Transverse section from central region of fracture in specimen CHT3, with bulge side at bottom.

X 2.6 Nital etch

Fig. 26. Transverse sections from apex of bulge in specimen CHT6.



X 2.5 Nital etch

Fig. 27. Transverse section near apex of bulge in specimen CHT8.

Fig. 28. Explosion-bulge crack-starter test on Cu-Ni plate after 1 shot at -65°C (-85°F).

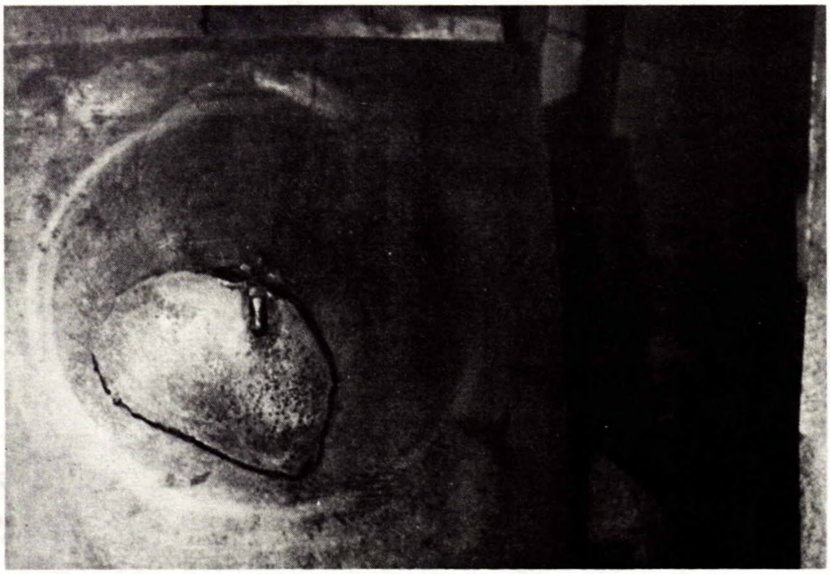


Fig. 29. Explosion-bulge crack-starter test on Cu-Ni plate after 2 shots at -55°C (-67°F).

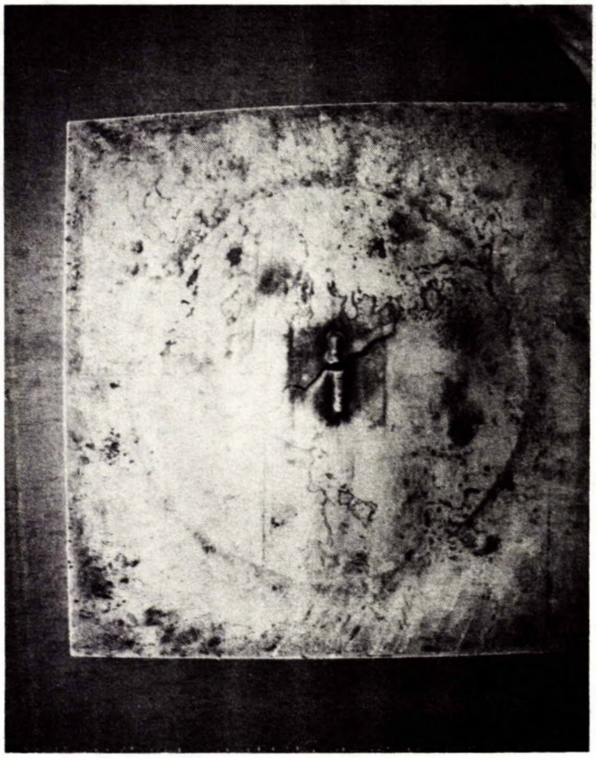


Fig. 30. Explosion-bulge crack-starter test on Cu-Ni plate after 1 shot at -45°C (-49°F).

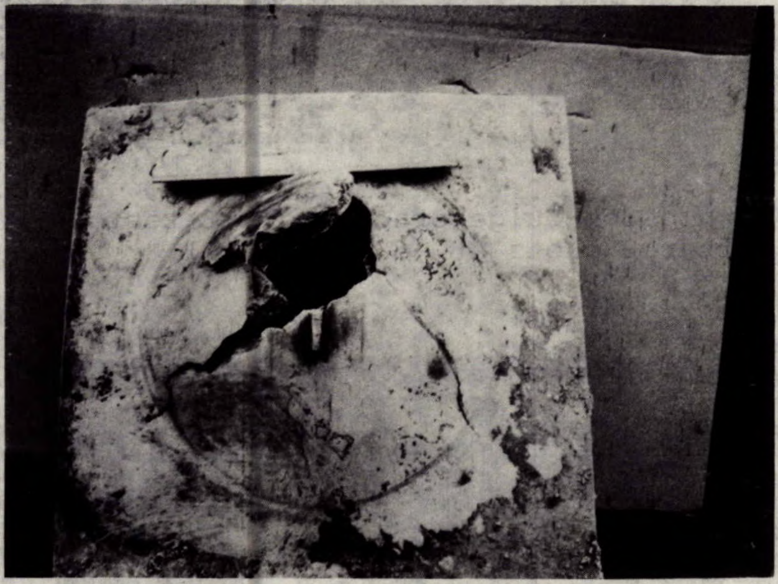


Fig. 31. Same specimen and test temperature as for Fig. 30 but after additional shot.

TABLE 1. Composition of Steels - Weight Per Cent

Element	T-1			CHT-100			Cu-Ni (Heat C-2)		
							CANMET Check Analyses		
	Supplier Certified Heat Analyses	CANMET Check Analyses*	ASTM A517 Gr. F Product Analyses	Certified Heat Analyses	CANMET Check Analyses**	ASTM A517 Gr. C Product Analyses	3/4-in. (19 mm) Plate	1 1/8-in. (29 mm) Plate	2-in. (51 mm) Plate
Cu	0.18	0.16	0.08/0.22	0.16	0.17	0.08/0.22	0.13	0.14	0.12
Mn	0.90	0.86	0.55/1.05	1.50	1.60	1.05/1.55	0.73	0.72	0.72
P	0.012	0.007	0.035 max	0.006	0.008	0.035 max	0.013	0.013	0.015
S	0.022	0.016	0.040 max	0.031	0.030	0.040 max	0.022	0.021	0.018
Si	0.26	0.21	0.13/0.37	0.27	0.30	0.13/0.32	0.28	0.28	0.28
Ni	0.83	0.75	0.67/1.03	-	-	-	3.83	3.83	3.83
Cr	0.56	0.57	0.36/0.69	-	-	-	-	-	-
Mo	0.47	0.43	0.36/0.64	0.23	0.21	0.17/0.33	-	-	-
V	0.04	0.05	0.02/0.09	-	-	-	-	-	-
Cu	0.30	0.28	0.12/0.53	-	-	-	1.08	1.08	1.08
B	0.002	0.002	0.0005/0.006	0.002	0.002	0.001/0.005	-	-	-

*Analyses made on one of the four plates supplied.

**Average of analyses made on three of the plates supplied.

TABLE 2. Tensile Properties of Steels

	ASTM A517 Limits	T-1 Steel				CHT-100 Steel				Cu-Ni Steel					
		Supplier Certified Properties		CANMET Determined Properties		Supplier Certified Properties		CANMET Determined Properties		3/4-in. (19 mm) Plate		1 1/8-in. (29 mm) Plate		2-in. (51 mm) Plate	
		Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans	Long	Trans
UTS-ksi	115.0/135.0	126.9	124.8	129.6	129.6	121.4	-	123.1	122.2	121.8	114.8	121.5	108.6	121.5	121.3
-MPa	795/930	875	860	894	894	837		849	842	840	792	838	749	838	836
Y.S.(0.2% offset) -ksi	100.0 min	115.4	112.9	120.1	121.0	116.6	-	116.2	115.6	110.3	105.5	111.5	96.5	108.0	110.5
-MPa	690 min	796	778	828	834	804		801	797	760	727	769	665	745	762
Elong. in 2 in. or 50 mm, min %	16	19.2	18.0	20.0	17.5	19	-	19.3	17.3	23.6	23.2	22.4	25.2	25.7	22.0
R.A., min %	45	62.2	53.0	59.3	48.6	57	-	57.5	50.3	65.0	55.1	64.5	57.4	66.1	55.5

NOTE: For T-1, CHT-100 and 2-in. (51 mm) Cu-Ni plate, the properties were determined in both directions of rolling using specimens machined in each steel from adjacent plate regions. For the 3/4-in. (19 mm) and 1 1/8-in. (29 mm) Cu-Ni plate, the transverse tensile properties were determined, at a later period in the program, from different samples of the steel from the same heat and having the same specified heat treatment as that for which longitudinal data was obtained earlier.

TABLE 3. Welding Wire Composition - Weight Per Cent

Element	Specification Requirements*	CANMET Analyses
Carbon	0.10	0.09
Manganese	1.40/1.80	1.63
Phosphorus	0.01	0.006
Sulphur	0.01	0.009
Silicon	0.25/0.60	0.36
Nickel	2.00/2.80	2.44
Chromium	0.60	0.28
Molybdenum	0.30/0.65	0.45
Vanadium	0.03	< 0.01
Aluminum	0.10	< 0.01
Titanium	0.10	0.03
Zirconium	0.10	< 0.01

*Single values are maxima.

TABLE 4. Prime Plate Drop-Weight Tests

Steel	Test Temp. °C	Test Temp. °F	Results
T-1	-62	-80	No break.
	-68	-90	No break. Transverse cracking in bead 1/4-1/2 in. (6-13 mm) from notch.
	"	"	" " " " " " " " "
	"	"	No break.
	"	"	" "
	-73	-100	No break. Transverse cracking in bead 1/4 in. (6 mm) from notch.
	"	"	Break from transverse cracking in bead 1/4 in. (6 mm) from notch.
	"	"	No break.
	"	"	Break.
			NDT = -73°C (-100°F)
CHT-100 (longitudinal)	-34	-30	No break.
	"	"	" "
	-40	-40	Break.
	-46	-50	"
	"	"	"
	"	"	Break from transverse cracking in bead 1/2 in. (13 mm) from notch.
			NDT = -40°C (-40°F)
CHT-100 (transverse)	-34	-30	No break. Transverse cracking in bead 1/2 in. (13 mm) from notch.
	"	"	" " " " " " " " "
	-40	-40	Break from transverse cracking in bead 1/2 in. (13 mm) from notch.
	-46	-50	Break.
			NDT = -40°C (-40°F)
Cu-Ni	-84	-119	No break.
	"	"	" "
	-94	-137	" "
	"	"	" "
	-99	-146	Break from transverse cracking in bead 1/2 in. (13 mm) from notch.
	-103	-153	" " " " " " " " "
			NDT = -99°C (-146°F)

NOTE: In all specimens, a crack was clearly visible at the root of the notch in the crack-starter bead. Unless otherwise indicated, cracking was found only at or extending from this location.

TABLE 5. Y-Groove Weldability Tests

Steel	Type Specimen	Plate Temp. °C	Plate Temp. °F	Cracking
T1	Fig. 6	21	70	Severe
"	"	"	"	"
"	"	121	250	None
"	"	"	"	"
CHT-100	Modified	21	70	Severe
"	"	"	"	"
"	"	121	250	"
"	"	"	"	"
"	"	177	350	None
"	"	"	"	"
Cu-Ni	Fig. 6	21	70	Severe
"	"	"	"	"
"	Modified	121	250	Moderate
"	"	"	"	"
"	"	177	350	None
"	"	"	"	"

TABLE 6. Weld Tensile Tests

	Transverse to the Weld*				All-Weld Metal	
	T-1 Plate	CHT-100 Plate	Cu-Ni Plate		T-1 Plate	CHT-100 Plate
	Weld perpendicular to plate longitudinal direction		Weld perpendicular to plate longitudinal direction	Weld parallel to plate longitudinal direction		
UTS-ksi -MPa	129.2 891	122.7 846	115.5 796	113.7 784	141.0 972	140.6 969
Y.S.(0.2% offset) -ksi -MPa	119.8 826	114.6 790	104.3 719	104.7 722	135.5 934	135.0 931
Elong. in 2 in. (51 mm) min %	16.8	16.0	19.5	17.8	19.5	20.5
R.A., %	62.4	58.2	65.0	57.5	62.4	60.9

*All specimens broke outside of the weld zone.

TABLE 7. Weld Drop-Weight Tests*

Steel Welded	Test Temp. °C	°F	Test Results**
T-1	-51	-60	No break.
	"	"	" "
	-57	-70	Break.
	-68	-90	"
	"	"	"
	-73	-100	"
			NDT = -57°C (-70°F)
CHT-100 (1st set)	-46	-50	No break. Transverse cracking in bead 1/2 in. (13 mm) from notch.
	"	"	***
	-51	-60	***
	"	"	***
	"	"	No break.
	-57	-70	***
	-62	-80	***
			NDT indeterminate as "breaks" occurred beyond weld.
CHT-100 (2nd set)	-46	-50	No break.
	"	"	" "
	-51	-60	Break.
	"	"	No break.
			NDT = -51°C (-60°F)
Cu-Ni (1st set)	-76	-105	No break.
	-84	-119	" "
	-90	-130	No break. Transverse cracking in bead 3/8 in.(10 mm) from notch, extending only part way across specimen, but not to an edge.
	-96	-140	No break. Notch cracked at root, but no extension into weld.
	"	"	***
	"	"	Break.
	-104	-155	"
			NDT not fully determined, but probably lower than -90°C (-130°F).
Cu-Ni (2nd set)	-90	-130	No break. Transverse cracking in bead 1/2 in.(13 mm) from notch.
	-96	-140	" " " " " " " " "
	-107	-160	No break.
	-112	-170	" "
	-118	-180	Break.
			NDT not fully determined, but lower than -90°C (-130°F). Combining the results of the two sets, NDT = -96°C (-140°F).

*The "standard" two-pass technique was employed for making the crack-starter deposit for all except the 2nd set of CHT-100 specimens. For the latter, a single pass deposit was employed, with the crater termination being made on a run-off tab.

**Unless otherwise indicated, a crack was clearly visible at the root of the notch in the crack-starter bead. Also, unless otherwise indicated, cracking was found only at or extending from this location.

***Break from transverse cracking in bead 1/2 in.(13 mm) from notch. Failure outside weld, thus not a weld test.

TABLE 8. Hardex N Compositions - Weight Per Cent

	Manufacturer's Stated Intended Range	Heat A Electrodes	Heat B Electrodes
C	0.26/0.32	0.24	0.29
Mn	1.45/1.85	1.78	2.10
Si	0.65/0.85	0.86	0.86
Cr	0.80/1.10	0.91	1.03
Fe	Balance	Not tested	Not tested

TABLE 9. Cooling Plate Data for Bulge Test

Desired plate temp. at moment of firing		Controlled temp. of cooling bath ±1% C (±2% F)		Min time required to cool plate to bath temp.	Min time selected for holding test plates at bath temp.	Gain in plate temp. after 1½ min from removal from bath	
°C	°F	°C	°F	min	min	°C	°F
-1	30	-3	27	8	15	+2	+3
-18	0	-20	-4	10	20	+2	+4
-32	-25	-35	-31	15	25	+3	+6
-46	-50	-49	-57	15	25	+4	+7

TABLE 10. Multiple Shot Explosion-Bulge Tests

Specimen No.	Test Temp. °C	Test Temp. °F	Shot No.	Bulge Height after Each Shot in.	Bulge Height after Each Shot mm	% Thickness Reduction on Shot	Total % Thickness Reduction	Remarks
				T-1 Weldments				
T1XE	-32	-25	1	1 5/6	33	-**		No cracks.
			2	2 1/16	52	-**		" "
			3	2 7/16	62	-**		" "
			4	2 3/4	70	1.9		" "
			5	3 1/16	78	3.1	10.2	" "
T1XJ	-32	-25	1	1 9/16	40	1.7		No cracks.
			2	2 1/4	57	3.5		" "
			3	2 11/16	68	2.9		" "
			4	2 15/16	75	0.8		" "
			5	3 1/4	83	1.6	10.6	Two small cracks but not through thickness. (Figs. 18 and 19)
T1XG	-18	0	1	1 1/2	38	1.8		No cracks.
			2	2 3/16	56	3.5		" "
			3	2 1/2	64	2.3		" "
			4	3 3/8	86	3.6	10.5	" "
T1XH	-18	0	1	1 7/8	48	3.0		No cracks.
			2	2 3/16	56	2.6		" "
			3	2 5/8	67	1.9		" "
			4	-	-	2.5		" "
			5	3 1/8	80	0.9	10.4	" "
				CHT-100 Weldments				
CHT1	-32	-25	1	1 3/4	44	3.1		No cracks.
			2	2 1/4	57	2.0		" "
			3	2 15/16	75	2.4	7.3	" "
			4	-	-	-		Failure. (See Fig. 20)
CHT3	-32	-25	1	1 7/16	37	2.7		No cracks.
			2	2 3/16	56	2.1		" "
			3	2 9/16	65	2.7		" "
			4	2 7/8	73	2.8		" "
			5	-	-	2.3	12.0	" "
			6	-	-	-	-	Failure. Through-thickness cracks extend into hold-down along edge of weld and also at right angles to weld in plate.

(cont. on p. 66)

TABLE 10 (cont.)

Specimen No.	Test Temp.		Shot No.	Bulge Height after Each Shot		% Thickness Reduction on Shot	Total % Thickness Reduction	Remarks
	°C	°F		in.	mm			
CHT5	-18	0	1	1 7/8	48	1.9		No cracks.
			2	2	51	2.8		" "
			3	2 1/4	57	0.6		" "
			4	2 3/4	70	1.7		" "
			5	2 15/16	75	2.9		" "
			6	3 15/16	84	4.3	13.5	" "
CHT6	-18	0	1	1 5/8	41	1.1	1.1	No cracks.
			2	-	-	-	-	Failure (See Fig. 21).
CHT7	-18	0	1	1 3/4	44	2.1		No cracks.
			2	2 1/16	52	2.0		" "
			3	2 7/16	62	0.7		" "
			4	2 15/16	75	2.6	7.2	" "
			5	-	-	-	-	Failure (See Fig. 22).
CHT8	-18	0	1	-	-	-	-	Failure (See Fig. 23).
CHT9	-1	30	1	1 5/16	33	0.8		No cracks.
			2	2	51	2.5		" "
			3	2 5/8	67	1.7		" "
			4	2 7/8	73	4.5		" "
			5	3 1/4	83	4.0	12.9	" "
CHT10	-1	30	1	1 5/16	33	0.8		No cracks.
			2	-	-	2.1		" "
			3	2 11/16	68	2.8	4.8	" "
			4	-	-	-	-	Failure (See Fig. 24).
Cu-Ni Weldments								
CNXD	-32	-25	1	1 1/2	38	1.7		No cracks.
			2	2 3/16	56	3.1		" "
			3	2 9/16	65	2.4		" "
			4	3	76	2.2		" "
			5	3 3/8	86	3.0	12.0	" "

(concluded on p. 67)

TABLE 10 (concluded)

Specimen No.	Test Temp.		Shot No.	Bulge Height after Each Shot		% Thickness Reduction on Shot	Total % Thickness Reduction	Remarks
	°C	°F		in.	mm			
CNXG	-32	-25	1	1 9/16	40	3.2		No cracks.
			2	2 1/8	54	1.9		" "
			3	2 11/16	68	2.7		" "
			4	3 1/16	78	3.5		" "
			5	3 15/16	84	2.0	12.6	" "
CNXB	-18	0	1	1 5/16	32	0.8		No cracks.
			2	2 1/8	54	2.8		" "
			3	2 7/16	62	-**		" "
			4	2 13/16	71	2.6	10.4	" "
CNXC	-18	0	1	1 5/8	41	-**		No cracks.
			2	2 3/16	56	-**		" "
			3	2 1/2	64	-**		" "
			4	2 7/8	73	-**		" "
			5	3 3/16	81	1.8	10.3	" "

*Calculated from original and final thicknesses when no failure occurred or from original thickness and thickness after shot prior to the one causing failure.

**Thickness readings unreliable.

TABLE 11. Comparison of Charpy and Drop-Weight Data

Material	Lowest Charpy V-notch Temperature for Absorbed Energy - ft lb(J) of: 20 (27)		30 (41)		40 (54)		50 (68)		NDT Temp.		Charpy V-notch Energy at NDT*	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	ft lb	Joules
Ti-prime plate -												
longitudinal	-107	-160	-96	-140	-73	-100	-1	30	-73	-100	40	54
transverse	-90	-130	-46	-50	-	-	-	-	-	-	-	-
T-1 weld	-96	-140	-84	-120	-59	-75	-51 -79	-60 -110	-57	-70	44	60
CHT-100 prime plate -												
longitudinal	-57	-70	-34	-30	-7	20			-40	-40	26	35
transverse	-51	-60	-1	30	38	~100			-40	-40	24	33
CHT-100 weld	-101	-150	-73	-100	-57	-70	-46	-50	-51	-60	45	61
Cu-Ni prime plate** -												
longitudinal	-134	-210	-107	-160	-96	-140	-84	-120	-99	-146	38	52
transverse	-96	-140	-73	-100	-29	-20	-	-	-	-	-	-
Cu-Ni weld	-107	-160	-101	-150	-79 -90	-110 -130	-57 -84	-70 -120	-96	-140	33	45

*For the CHT-100 prime plate, the Charpy value was determined at the NDT temperature. For all other cases, an estimate of the value at the NDT temperature was made from the corresponding graphical data.

**1 1/8-in. (29-mm) plate.

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