Mechanical Properties and Weldability of Commercially Produced Copper-Nickel Alloy Steel

Tests show that the 110,000-psi yield strength grade exhibits satisfactory weldability and good low-temperature properties

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ABSTRACT. The evaluation of two commercially produced heats of a new low-alloy quenched and tempered steel containing about 1% Cu and 3¾% Ni is reported. This evaluation was based on tensile, impact, nil-ductility transition temperature, explosion-bulge performance, dilatometric and isothermal transformation data as well as weldability studies. The steel was shown to possess an excellent combination of tensile and low-temperature impact properties. The low-temperature toughness was verified by nil-ductility transition temperature and explosion-bulge tests. Transverse properties were found to be in very good agreement with those in the longitudinal direction.

A satisfactory resistance to weld heat-affected zone cracking was shown by the steel at a nominal yield strength of 110,000 psi. In steel at this strength level, welded joints displayed satisfactory tensile and bend properties and a high standard of performance in explosion-bulge tests. The alloy has potential in applications requiring welded high strength steel.

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Introduction

An investigation was undertaken to determine the feasibility of replacing existing mild steel or wrought iron channel-marker buoy chains with lighter but stronger low-alloy steel chains. A major problem of pitting in salt water was largely overcome with the development of a steel containing about 1% Cu and 3¾% Ni. The development of this steel has been previously reported, and showed it to have a very good combination of tensile and impact properties in addition to its enhanced pitting resistance in salt water. In order to evaluate this alloy for other applications, two commercial heats were ordered. In the first heat (C-1), plates ⅝-in. and 1⅛-in. thick were made, and in the second heat (C-2), ¾-in., 1⅛-in., and 2-in. thick plates were produced. Analyses of the heats are listed in Table 1.

Table 1 — Composition of Heats C-1 and C-2

	Composition, wt %	
	Heat C-1	Heat C-2
Carbon	0.16	0.13
Manganese	0.78	0.73
Silicon	0.28	0.27
Sulphur	0.007	0.222
Phosphorus	0.004	0.013
Copper	1.11	1.08
Nickel	3.78	3.83

Melting and Fabrication

The heats were produced in a 10-ton basic electric furnace. No problems were encountered with the heats; standard melt practice was followed throughout.

The manufacturer reported that the sheet bar required only the normal amount of conditioning. Rolling was carried out at 1120C (2050F) without difficulty. All pieces were stock piled, then buried in vermiculite. It was mentioned that scale was quite heavy, and it may be this might cause some problems if the alloy were to be produced commercially.

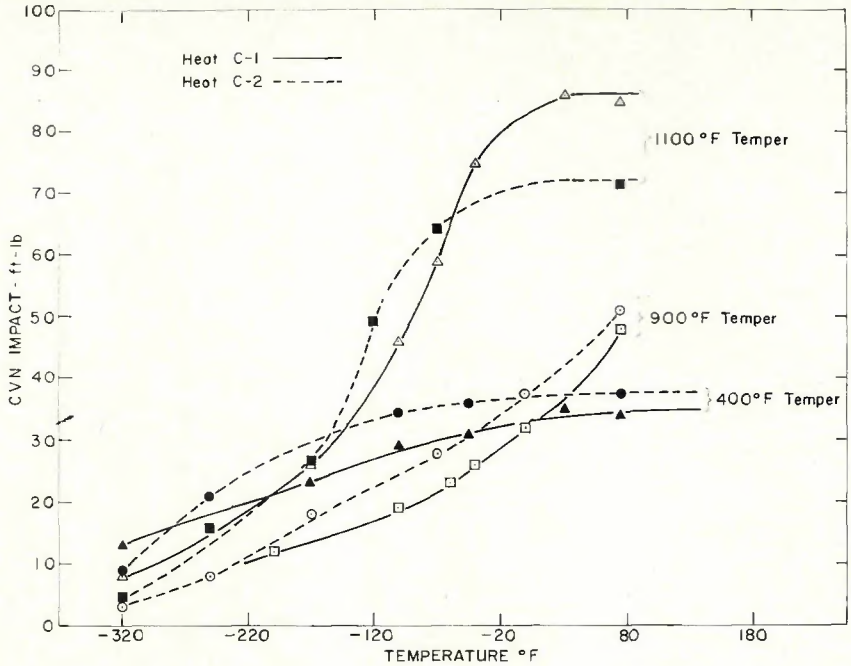


Fig. 1—Charpy V-notch (CVN) impact properties for two commercial heats of copper-nickel steel after water quenching from 900C (1650F) and tempering at indicated temperatures. (1-in. plate)

Table 2 — Tensile Properties of 1-in. Plate from Heats C-1 and C-2

	Heat No.	Tensile Property after Water Quench & Temper at 205C (400F)	480C (900F)	595C (1100F)
Tensile strength, kpsi	C-1	194.1	153.2	122.3
	C-2	187.3	142.8	121.5
Yield strength, kpsi (0.2% offset)	C-1	158.8	149.2	114.5
	C-2	155.3	137.3	111.5
% Elongation	C-1	12.5	16.5	21.2
	C-2	13.6	17.6	22.4
% Reduction in area	C 1	40.7	55.1	63.1
	C-2	37.5	59.4	64.5

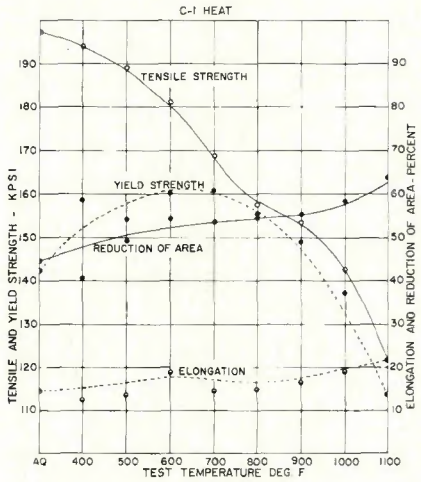


Fig. 2—Effect of tempering temperature on the tensile properties of heat C-1 after water quenching from 900C (1650F). (AQ = as quenched in water)

Tensile and Impact Tests

The tensile properties of the 1-in. thick plate for both heats are listed in Table 2 for the steels after water quenching from 900C (1650F) and tempering at 205, 480 and 595C (400, 900 and 1100F). The Charpy V-notch (CVN) impact properties for these same conditions are shown in Fig. 1 for the various test temperatures indicated. Figure 2 illustrates the effect of tempering temperature after water quenching from 900C (1650F) on the tensile properties of Heat C-1, 1-in. plate. The effect of tempering the same water-quenched plate on the impact properties at test temperatures of ambient, -73C (-100F) and -130C (-200F) is shown in Fig. 3.

Impact transition curves for the 1-in. plate from heat C-1 were also compared for the steel after water quenching and tempering at 595 and 205C (1100 and 400F) for specimens taken in the longitudinal and transverse directions, and the results are graphically displayed in Fig. 4. Longitudinal and transverse tensile bars were taken from the 2-in. plate of heat C-2 and tested after water quenching and tempering at 205C, 480C and 595C (400F, 900F and 1100F). These results are shown in Fig. 5.

Nil-Ductility Transition Temperature Tests

Tests were carried out in accordance with ASTM Specification E208[2] to determine the nil-ductility transition (NDT) temperature for heat C-1 after water quenching and tempering at 205 or 595C (400 or 1100F). The test bar used was 2 x 5 x ¾ in. For the 205C (400F) temper the NDT temperature was -143C (-225F) and for the 595C (1100F) temper the NDT temperature was -76C (-105F), showing that the higher-strength condition produced the lower NDT temperature.

An NDT temperature of -93C (-135F) for heat C-2 steel, quenched and tempered at 595C (1100F), was obtained using 3½ x 14 x 1-in. test bars.

Explosion-Bulge Tests

Explosion-bulge testing has been carried out on both prime and welded 1-in. plate from heat C-1. Samples were bulged on the die described[3] in NAVSHIPS 250-637-6 for Type 1 specimens. Explosion-bulge crack-arrest temperatures for prime plate with crack-starter beads were -47C (-52F) for plate water quenched and tempered at 595C (1100F), and -43C (-45F) for that water quenched and tempered at 205C (400F). These explosion-bulge crack-arrest temperatures are those temperatures at which cracks will not propagate beyond the plastically deformed region after two shots of 7-lb charges of pentolite, offset 15 in.

Two multiple-shot bulge tests, without crack-starter beads, were made on 1-in. thick plate tempered at 595C (1100F) and welded by the automatic gas metal-arc process. Double-Vee-groove welds were made in 8 or 9 passes employing argon-2% oxygen gas shielding, an electrode conforming to Type B88 of specification MIL-E19822,[4] no preheat, interpass temperatures of 20 to 150C (70 to 300F) and arc energy input levels of 41 to 43 kilojoules/in. The weldments were tested with weld reinforcements in place.

Two explosive shots were made on each specimen at -23C (-10F), resulting in thickness reductions of 10 to 11% near the apex of the bulge area

in the plates and without any evidence of cracking. On one specimen, an additional shot at -18C (0F) caused a further 3% thickness reduction with a slight indication of cracking along the edge of the weld. A further shot at this same temperature resulted in a total thickness reduction of 17% and a 4-in. long crack through the thickness along the edge of the weld and a short crack through the thickness and running across the weld. The other specimen withstood a third shot without cracking, at a temperature of -18C (0F), and developed a total thickness reduction of 12%. No further testing was done on this specimen.

Dilatometer and Isothermal Transformation Studies

Dilatometric data was obtained, using a Leitz dilatometer, at heating and cooling rates of 50 and 150C deg (90 and 270F deg) per hr for Ac , AC and Ar temperatures. It was found, however, that a cooling rate of 5C deg (9F deg) per hr was necessary to obtain a relatively accurate temperature for Ar In general, the transformation temperatures are as follows:

AC_1 — 700C (1290F)
AC_3 — 760C (1400F)
Ar_3 — 610C (1130F)
Ar_1 — 570C (1060F)

Isothermal transformation data have also been obtained for the alloy, and are shown in Figs. 6, 7 and 8. The bar used in these tests is shown in Fig. 9. Only the reduced section and a small portion of the bar on each side is heated. The reduced section can be cooled to 315C (600F) in about 4 sec from the austenitizing temperature of 870C (1600F). Transformation was traced by means of a dilatometric curve obtained on measurements across the reduced section. The instrument used was a thermal cycle simulator called a "Gleeble". The curves shown in Figs. 6 and 7 were obtained on bars austenitized for 30 sec at 870C (1600F). Figure 6 shows the results for as-rolled material, and Fig. 7 for heat-treated bars which were water quenched from 955C (1750F) and tempered at 595C (1100F). In Fig. 8, the data are shown for similarly heat-treated bars that were austenitized for 3 min at 870C (1600F). In general, the heat-treated bars did not start to transform at as high a temperature as the as-rolled bars. Also, the longer austenitizing time has shifted the curves down and to the right.

The curves are not entirely complete as the transformation at the higher temperatures is very sluggish, although it starts quite quickly.

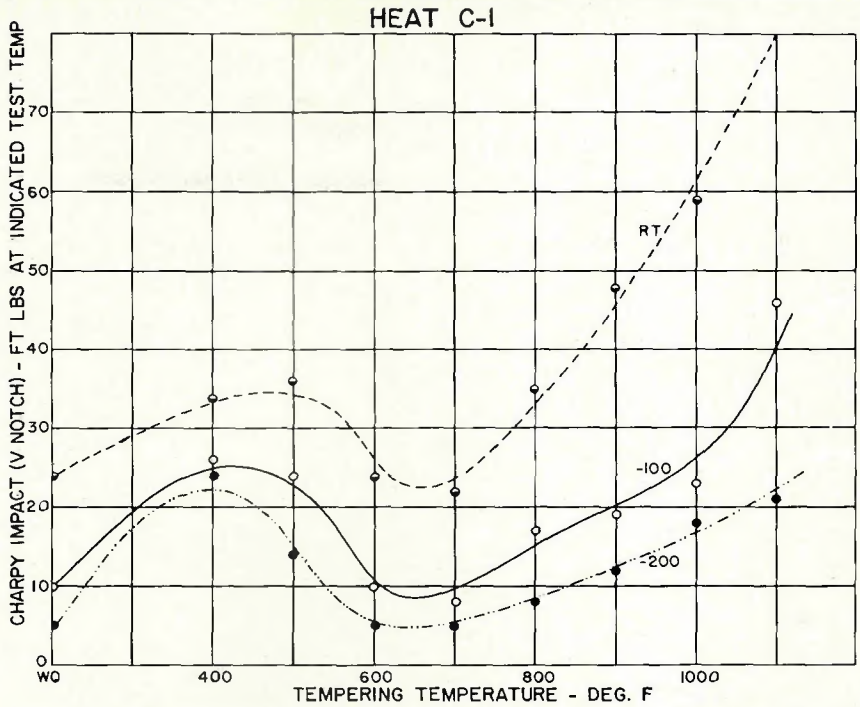


Fig. 3—Effect of tempering temperature on the impact properties of heat C-1 after water quenching from 900C (1650F) for test temperatures of ambient, -73C and -130C (-100F and -200F)

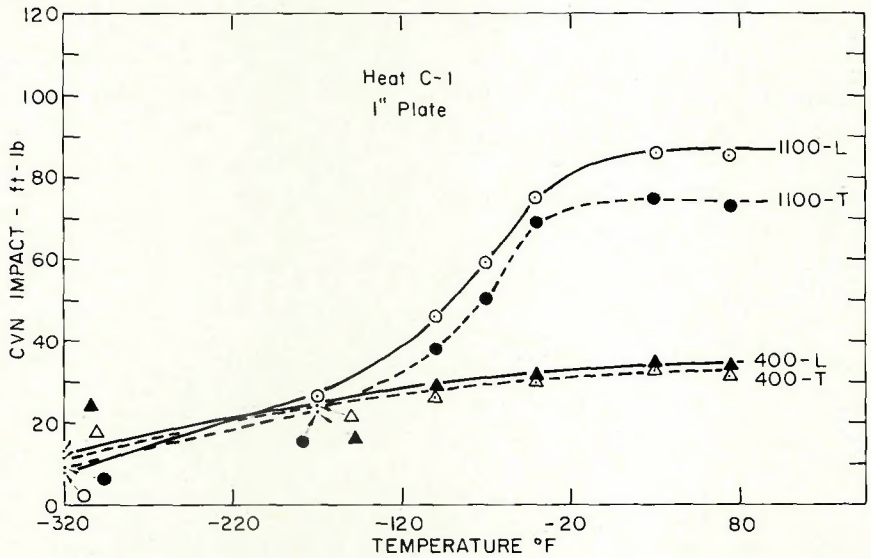


Fig. 4—CVN impact transition curves for specimens taken from both longitudinal and transverse directions of 1-in. plate after water quenching and tempering at either 205C (400F) or 595C (1100F)

Table 3 — Chemical Composition of HY-80 Steel Used in Comparative Welding Studies

Element	Composition for HY-80 plate ½-in. thick (cruciform tests)	1¾-in. thick (CTS tests)
C	0.14	0.15
Mn	0.26	0.26
P	0.011	0.012
S	0.026	0.021
Si	0.25	0.25
Ni	2.15	2.98
Cr	1.15	1.83
Mo	0.26	0.39
Cu	—	—

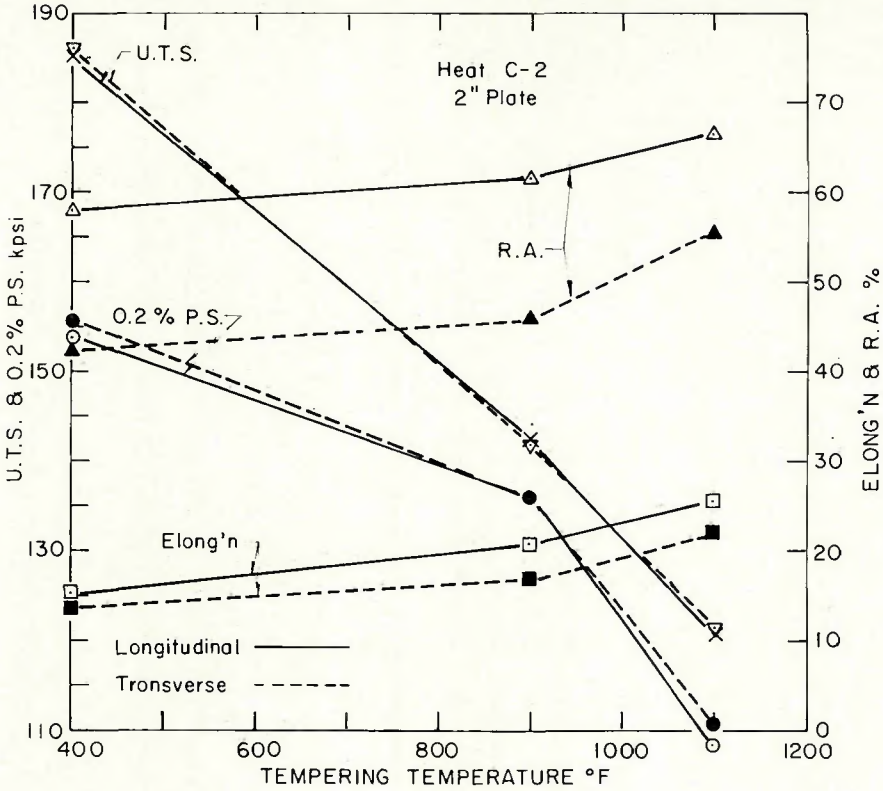


Fig. 5—Transverse and longitudinal tensile properties of specimens taken from 2-in. plate, heat C-2, after water quenching and tempering at 205, 480 and 595C (400, 900 and 1100F)

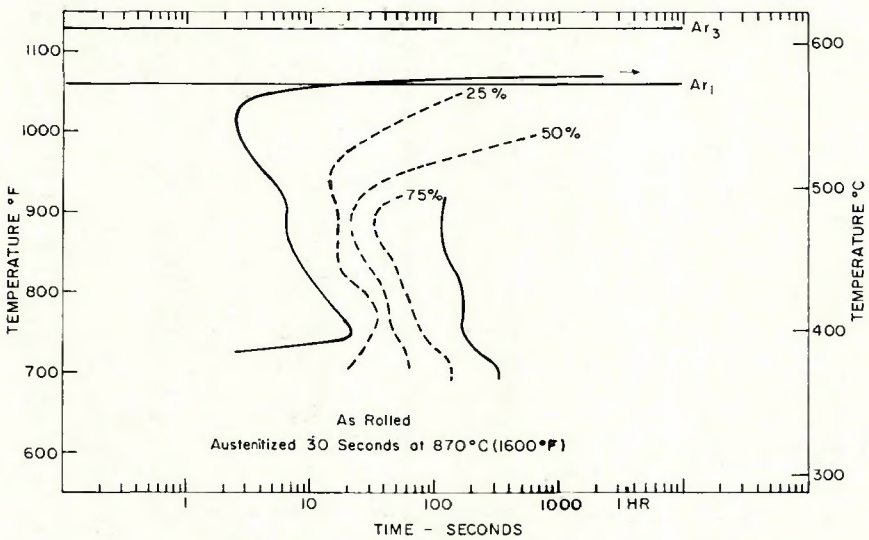


Fig. 6—Isothermal transformation curves for as-rolled specimens austenitized 30 sec prior to cooling

Heat-Affected Zone Cracking in Welding

Heat-affected zone cracking studies were made on heat C-1, water quenched and tempered at 595C (1100F). Fillet-weld type tests were made on this steel and both fillet-weld and butt-weld type tests were made on steel from heat C-2, which was similarly heat treated. Some comparative fillet-weld tests were also made on HY-80 steel (see Table 3).

Controlled thermal severity (CTS) tests were conducted using the assemblies shown in Fig. 10. Both assemblies provide "trithermal" heat flow conditions, that is, the heat from a test fillet weld is considered to flow away from it through one metallic path in the top plate and two paths in the bottom plate. The smaller assembly has one weld providing bithermal conditions; that is, heat is considered to flow away from this weld through one path in each of the two plates. CTS tests on 1-in. thick plate from heat C-1 were made with both specimens shown in Fig. 10. CTS tests (1¾-in. thick plate) were performed on both heat C-2 and HY-80 steel, employing the larger specimen. A root opening of 1/16-in. for the fillet welds was provided between top and bottom plates by means of a 1/16-in. steel shim plate. The presence of the opening was shown by previous investigators[5,6] to increase significantly the tendency for cracking. Because actual joints in structures cannot be made with assurance of very tight fit-up, it is logical to incorporate this opening in fillet weld, heat-affected-zone cracking specimens.

Cruciform heat-affected zone cracking tests were made on ½-in. thick heat C-1 steel using the smaller specimen whose configuration and dimensions are shown in Fig. 11. Tests on ½-in. thick heat C-2 steel and HY-80 steel were made only with the larger specimen described in Fig. 11. The four test fillet welds were deposited in consecutive sequence around each assembly as shown.

Y-groove butt weld restraint cracking tests were made on 1-in. plate from heat C-2. Figure 12 illustrates the Y-groove specimen. It is claimed[7] that the intensity of restraint and the cooling rate of welds in actual structures can be reproduced in this type of specimen. This is said to be accomplished by varying thickness and initial plate temperature in the case of cooling rate, and by varying thickness and/or the depth of slots cut into the plate in the case of restraint. The present tests were made without slots in the specimen and thus under only one condition of restraint. Intensity of restraint is said[7] to be 1650 kg/mm·mm for the unslotted 1-in. thick specimen. The restraint in the Y-groove test is defined as the force, acting transverse to a 1-mm length of the unwelded joint, required to reduce elastically the root opening of the joint by 1 mm, and the notation kg/mm·mm must be interpreted in this sense.

All welding was done manually with covered electrodes conforming to either E11018M or E12018M classifications. Precautions were taken to ensure that flux covering moisture contents were less than 0.2%.

Arc energy input levels for tests with the CTS and the larger cruciform assemblies were in the range 32 to 34 kilojoules/in. A few CTS

tests were made with values of 41 to 45 kilojoules/in. in order to evaluate the effect of higher heat inputs upon cracking. Arc energy input levels of 19 to 22 kilojoules/in. were employed in welding the smaller cruciform assemblies and levels of 39 to 45 kilojoules/in. were employed for the Y-groove restraint specimens. A level of about 42 kilojoules/in. was selected as a standard condition by the Japanese investigators for the Y-groove test.[7]

Each assembly was at room temperature prior to the deposition of each test weld except in some Y-groove tests where preheating was employed. A time interval of 2 hr was maintained between deposition of test welds in cruciform or CTS tests.

After at least 48 hr had elapsed from completion of welding, several representative transverse sections were removed from each test weld and examined for cracking. Most of the examination was performed by the wet, fluorescent magnetic particle inspection process with some microscopic examination of polished and etched sections being done to provide confirmation.

No cracking occurred in CTS or small cruciform tests on heat C-1 steel welded with E11018M electrodes, but sporadic heat-affected zone cracking occurred in CTS tests on this steel when welded with E12018M electrodes at energy input levels up to 45 kilojoules/in. HY-80 steel and heat C-2 steel were uncracked in the large cruciform or CTS specimens welded with E12018M electrodes.

Y-groove restraint tests on steel from heat C-2 showed significant weld and heat-affected zone cracking in specimens welded with E11018M electrodes without preheating or with a preheat of 93C (200F), and in specimens welded with E12018M electrodes without preheating. Preheating at 121C (250F) was effective in preventing cracking in specimens welded with E11018M electrodes.

Mechanical Properties of Welded Joints

A butt joint in ½-in. plate, which was machined from the ⅝-in. plate rolled from heat C-1 and tempered at 595C (1100F), was welded to permit transverse tensile and bend properties to be determined. The welding procedure was similar to that employed for welding the explosion-bulge plates, except for the deposition of only six weld passes.

Results of tensile tests of flat specimens, transverse to the weld, were:

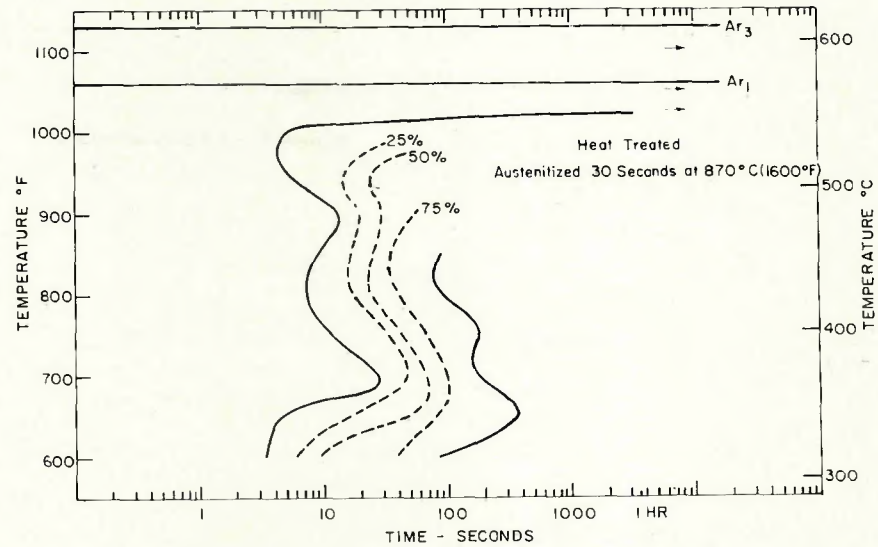


Fig. 7—Isothermal transformation curves for heat-treated specimens, austenitized 30 sec prior to cooling

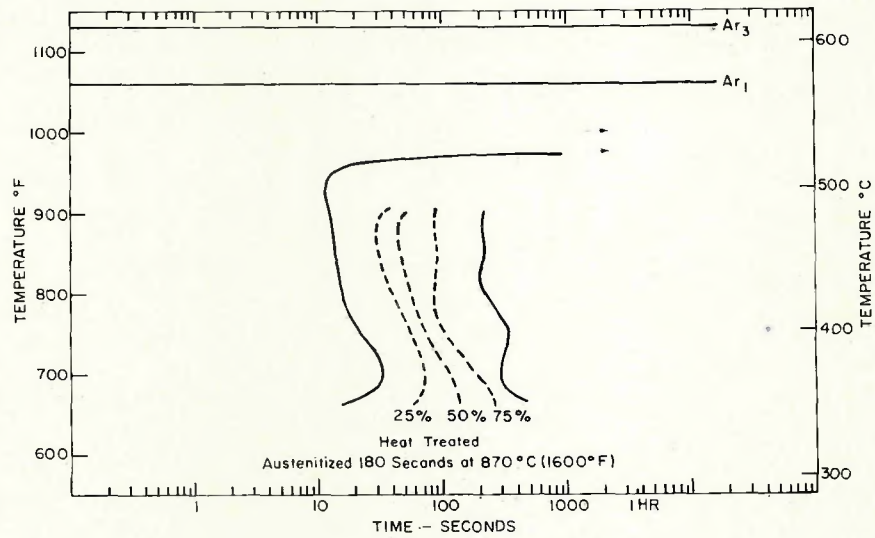


Fig. 8—Isothermal transformation curves for heat-treated specimens austenitized 180 sec prior to cooling

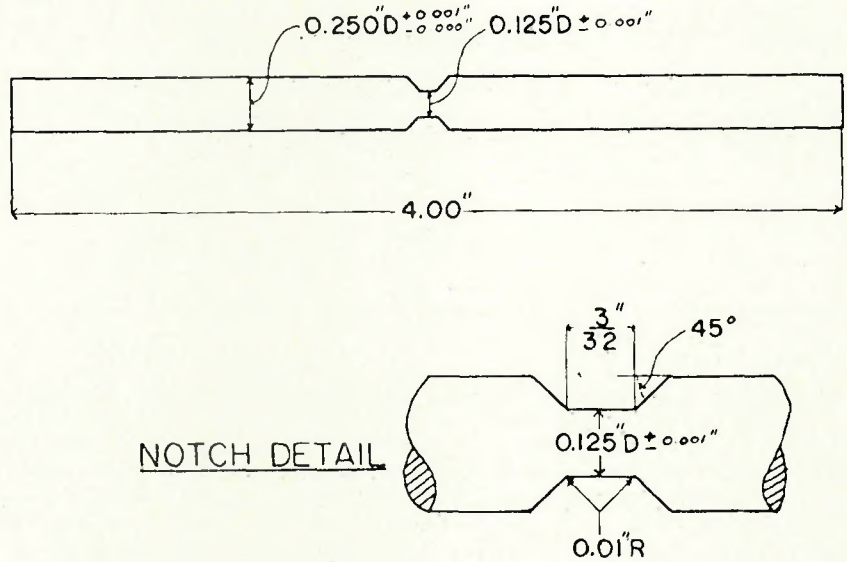


Fig. 9—Sketch of bar used to determine isothermal transformation curves shown in Figs. 6, 7 and 8

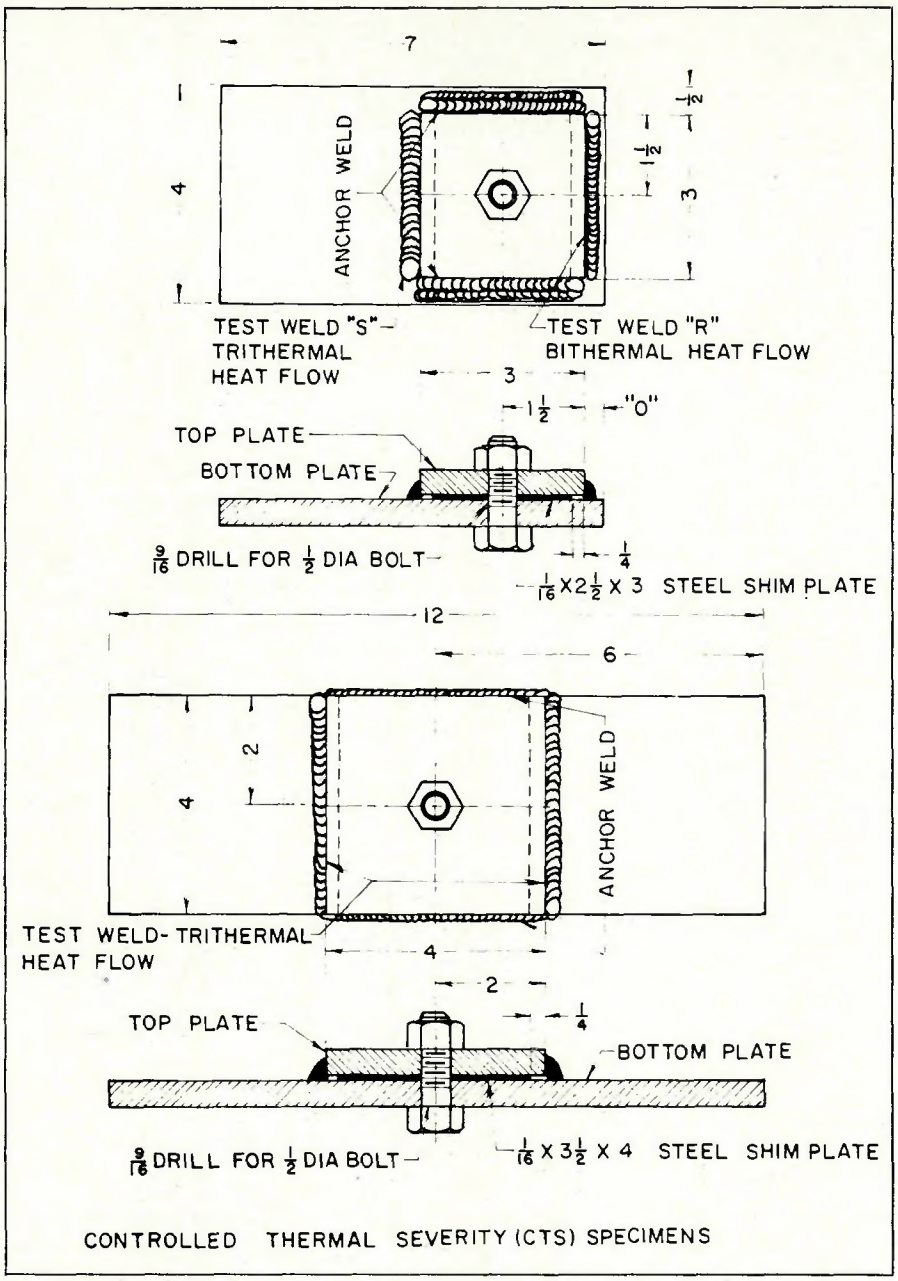


Fig. 10—Details of controlled thermal severity (CTS) tests employed in weldability studies. (Dimension "O" equals fillet weld leg length plus 1/16 in.)

Table 4 — Summary of CVN Impact Strength at Different YS Levels

YS, kpsi (0.2% offset)	Impact strength ft-lb at -57C (-70F)
155-160	30-35
137-150	20-25
111-115	59-65

127,000 psi tensile strength, 122,000 psi 0.2% yield strength, and 7.8% elongation in 8 in.

All fractures were in the weld. These results compare favorably with the tensile properties of the prime plate except that the elongation was lower in the welded specimens. Examination of the broken samples indicated that the weld deposit had deformed to a greater extent than the adjacent plate.

Bend test specimens, 3/8-in. in thickness, and both transverse to and parallel to the weld, were bent 180 degrees around a 2½-in.-dia forming tool without cracking.

Transverse tensile, bend, and hardness tests were also made on a welded joint in 1-in. thick steel from heat C-1 tempered at 205C (400F). A double-Vee-groove weld was made by the automatic gas metal-arc process with a shielding gas mixture of argon-2% oxygen and an electrode which had been developed commercially for welding of HY-130 steel. Preheat and interpass temperatures of 93 to 121C (200 to 250F) were maintained. Arc energy input levels were 45 kilojoules/in. for the root pass and 41 kilojoules/in. for the six other passes. Transverse tensile properties were:

148,000 psi tensile strength, 132,000 psi 0.2% yield strength, 10.3% elongation in 2 in. and 2.7% elongation in 8 in.

Fractures occurred through the weld metal or the heat-affected zones with almost all reduction occurring in these regions. Transverse bend specimens, which had the 3/8-in. thickness centered on the 1-in. plate thickness and which were bent around a 2½-in.-diam forming tool, also showed excessive deformation in the weld and heat-affected zones. Severe cracking occurred in these regions after one specimen was bent 90 degrees and the other 20 degrees. Hardness testing showed considerable variation in hardness at different locations in the joint. For example, fused zone hardnesses were about 40 Rc in the last bead deposited and 35 Rc in an earlier bead. Heat-affected zone values were about 39 Rc adjacent to the last bead deposited and 29 Rc adjacent to an earlier bead. Hardness values increased from 29 to 40 Rc over a distance extending from the outer boundary of the visible heat-affected zone to a point about 3/8 in. farther away from this boundary where the as-tempered hardness of the plate, about 41 Rc, was regained.

Discussion

The slight differences in tensile and impact properties, shown in Table 2 and Fig. 1 respectively, between the two heats is most probably a result of the lower carbon content of heat C-2. The largest differences for the two heats are in the tensile and yield strengths of the steel tempered at 480C (900F). The Cu-Ni steel displays excellent combinations of yield strength and low-temperature impact properties.

Table 4 summarizes the CVN impact strength determined for the steel at the different yield strengths investigated. The lowest impact strength occurs at a yield strength of 137,000–150,000 psi, when the steel is tempered at 480C (900F). This may be due to the initial precipitation of copper, which would occur at around this temperature, the age-hardening temperature.

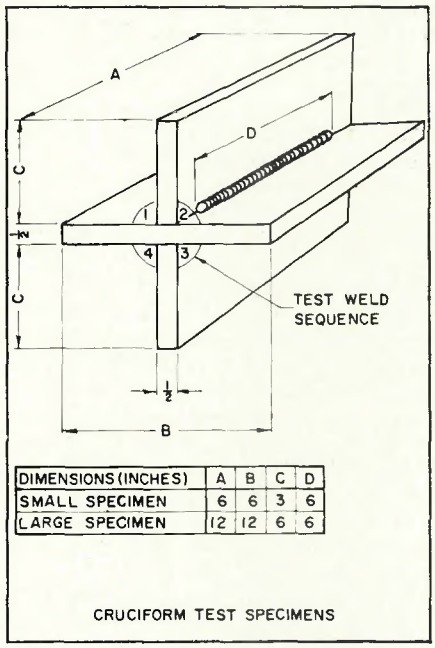
Figures 2 and 3 show an embrittlement of the quenched steel when tempered in the 315 to 425C (600 to 800 F) region. This is shown by an increase in the yield strength, and a decrease in the impact strength in this tempering region. It is probably akin to the "blue brittleness" phenomenon found in most ferritic steels.

The surprising results of the NDT temperature determinations, where the highest strength condition exhibited superior NDT temperature data, might be explained by a variation in grain size which could occur as a result of the different tempering temperature used, but, in the author's opinion, is more readily explained by this brittleness trough. As stipulated in the ASTM Specification[2], specimens tempered at low temperatures are to be heat treated after deposition of the crack-starter weld, whereas those tempered at high temperatures cannot be heat treated at this time because the crack-starter weld would be softened at the high tempering temperatures. After deposition of the crack-starter weld, the heat-affected zone (HAZ) would be expected to contain some embrittled regions as a result of exposure during the welding operation to temperatures in the range of 315 to 425C (600 to 800F). Thus, the steel in the high strength condition, containing no HAZ and hence no zones of embrittlement, would be expected to have a lower NDT temperature than the steel in the lower strength condition, containing a HAZ with some embrittled regions.

Although the total reduction in forging and rolling was not excessive in the production of the plate (ingot size was about 18 in. square), Figs. 4 and 5 indicate that the steel also possesses excellent impact and tensile properties in the transverse direction. Some deterioration in the tensile ductility of the 2-in. plate in the transverse direction was found, but this was not serious.

The performance of the welded explosion-bulge specimens, made from plate quenched and tempered at 595C (1100F), compares favorably with that of reported results[8] of similar tests at comparable temperatures on 1-in. thick, submerged-arc welded or shielded metal-arc welded specimens in commercial plate conforming to ASTM A517 Grade F steel. The performance of these commercial weldments were rated[8] as "good" for the submerged-arc welded specimens and "excellent" for the shielded metal-arc welded specimens. The performance of the Cu-Ni weldments was judged to be better than that for the submerged-arc welds and at least equivalent for the shielded metal-arc weldments in the ASTM A517 Grade F steel.

Referring to the isothermal transformation curves shown in Figs. 6, 7 and 8, the longer austenitizing time of 180 sec (Fig. 8) has resulted in a shift of the transformation to lower temperatures and to longer times. It is likely that the 30-sec austenitize was not long enough to achieve complete solution of all phases, so that existing sites were still present in the steel to more readily initiate transformation earlier and at a higher temperature. The M_S point for the steel has not been accurately determined, but indications are that it is relatively high, being of the order of 315C (600F). Metallographic examination has shown tempered martensite to be present after water quenching, and undoubtedly is due to auto-tempering as a result of the relatively high M_S point.



DIMENSIONS (INCHES)	A	B	C	D
SMALL SPECIMEN	6	6	3	6
LARGE SPECIMEN	12	12	6	6

Fig. 11—Cruciform, heat-affected-zone, cracking test specimen

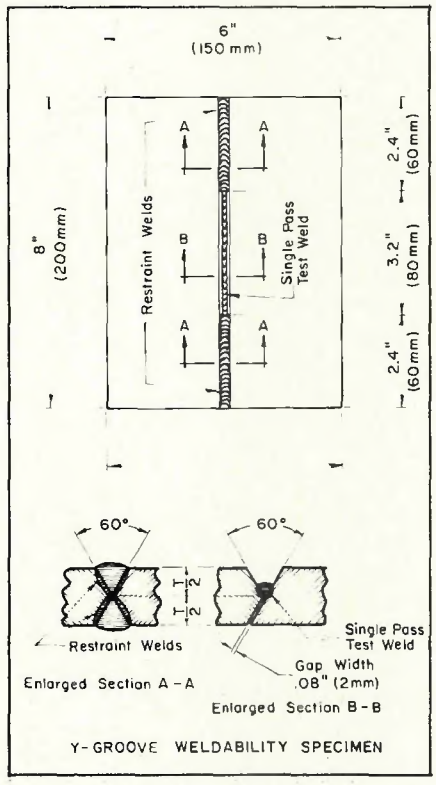


Fig. 12—Y-Groove restraint cracking specimen

Encouraging results were obtained in heat-affected zone cold-cracking tests completed to date on steel tempered at 595C (1100F). These studies indicate that the steel has a resistance to cold-cracking equivalent to that of other steels in approximately the same or even lower strength range. For example, on the basis of the CTS and cruciform tests, no difference in cracking tendency was observed between Cu-Ni steel from heat C-2 and the commercially produced HY-80 steel. Both steels were uncracked in these tests. Comparison CTS tests with steels conforming to specification ASTM A517 are planned.

Steel from heat C-1 showed sporadic but significant cracking in CTS tests welded with E12018M electrodes, whereas similar tests on heat C-2 steel were uncracked. This is attributed to the higher carbon content of heat C-1 (0.16% vs 0.13% for C-2). Thus, the slightly lower carbon content of heat C-2 is preferable for improved weldability.

Although cracking occurred in CTS tests on heat C-1 steel when welded with E12018M electrodes, no cracking occurred in similar tests with the lower-strength E11018M electrodes. This may be due to a lower stress in the weld heat-affected zone with the E11018M electrodes as compared to the stress produced with the higher-strength E12018M electrodes.

The behavior of heat C-2 steel in the Y-groove tests was in general agreement with that predicted in a report[7] of cracking studies on Japanese high-strength steels tested by the same method, although the nickel and copper contents of the Cu-Ni steel exceeded the limits in which the Japanese data was claimed to apply. Further Y-groove studies are being made to compare weldability of the Cu-Ni steel with commercially produced steels conforming to the ASTM 517 specification. Partially completed studies indicate that a commercially produced steel, conforming to ASTM 517 Grade F, behaves similarly to the heat C-2 steel in the Y-groove test. This test appears to be more severe than either

the CTS or cruciform tests and is believed to more closely approximate the restraint levels of joints in welded construction.

For steel tempered at 595C (1100F), ultimate tensile and yield strength values equivalent to the steel properties were obtained readily in gas metal-arc welded specimens in ½-in. plate. Satisfactory ductility was also shown by transverse tensile and bend tests from the same weldment. These results are in conformance with the requirements of Section IX "Welding Qualifications" of the ASME Boiler and Pressure Vessel Code. It was evident from tensile, bend and hardness tests on a joint in 1-in. plate welded by the gas metal-arc process, that steel tempered at 205C (400F) could not be arc welded practically without considerable impairment in mechanical properties. With such a low-tempering temperature being required to achieve the higher-strength properties, it is practically impossible to avoid overtempering and, hence, loss of strength in the weld region.

Conclusions

1. Commercially produced heats of a steel containing about 1% Cu and 3¾% Ni have been shown to possess an excellent combination of strength and low-temperature toughness. At a nominal yield strength of 110,000 psi, CVN impact strengths above 45 ft lb at -73C (-100F) were recorded. This low-temperature toughness was also verified by NDT temperature and explosion-bulge tests.

2. Tests to date showed little effect of directionality on the tensile and impact properties. Transverse tensile ductility was slightly lower in 2-in. thick plate.

3. Satisfactory resistance to weld heat-affected zone cracking was shown by the steel having a carbon level of 0.13% and a nominal yield strength of 110,000 psi.

4. Satisfactory tensile and bend properties were exhibited by specimens from welded joints fabricated from steel having a nominal yield strength of 110,000 psi. Inferior properties were shown by specimens from joints in steel having a nominal yield strength of 155,000 psi.

5. A high standard of performance was shown by explosion-bulge tests on weldments fabricated from 1-in. thick plates which had been heat treated to a nominal yield strength of 110,000 psi.

6. A steel containing about 1% Cu, 3¾% Ni and 0.13% C, at a nominal yield strength of 110,000 psi, has potential in special structural applications requiring welded high-strength steel. At a nominal yield strength of 155,000 psi, the steel has potential only in applications where welding is not required or in structures which can be subsequently heat treated.

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"Fatigue Behavior of Aluminum Alloy Weldments"

by W. W. Sanders, Jr.

The primary objective of this study, carried out for the Aluminum Alloys Committee of the Welding Research Council, was to conduct a literature search related to fatigue of aluminum weldments and to prepare an interpretive report on the work which has already been completed. In particular, this study includes:

- accumulation of all available fatigue data on welded aluminum
- analyses of these data
- preparation of a report indicating the present state of knowledge in the field
- recommendations for future research

This report presents a summary of this study, including: (1) descriptions of the methods of fatigue testing and analysis; (2) factors affecting fatigue strength of welded joints; (3) static and fatigue properties of unwelded aluminum; (4) a comprehensive survey and analysis of the behavior of butt-welded, fillet-welded and miscellaneous welded joints; and (5) a comprehensive bibliography on fatigue behavior of welded aluminum structures.

The results reported include tests of 21 different alloys with 40 different heat treatments and tempers. The alloys include two from the 2000 series, one from the 3000 series, eight from the 5000 series, three from the 6000 series, and seven from the 7000 series.

About 300 different reports and papers were reviewed and over 400 test series with about 5000 individual tests were analyzed. The data from the applicable studies were summarized so that an independent analysis of all data could be conducted.

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