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CHARPY V-NOTCH IMPACT STUDIES ON STRESS-RELIEVED MY130 WELDMENT--ETC(U)
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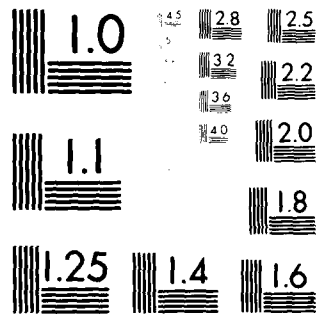
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Materials Report 79-G

CHARPY V-NOTCH IMPACT STUDIES ON STRESS-RELIEVED HY130 WELDMENTS

B.F. Peters

December 1979

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Materials Report 79-G

CHARPY V-NOTCH IMPACT STUDIES ON
STRESS-RELIEVED HY130 WELDMENTS.

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December 1979

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ABSTRACT

A Charpy V-notch impact testing study has been conducted on samples of HY130 steel (ESR and AMVD) and its weldments (MIL 140S MIG, and E12018 and E14018 stick).

The parent materials and MIG weldments do not suffer from an appreciable decrease in impact strength when subjected to stress-relief heat treatment followed by air cooling or furnace cooling. E14018 weldments suffer significantly when furnace cooled but not when air cooled from the stress-relief heat-treating temperatures.

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INTRODUCTION

HY130 steel has shown every indication of being a very suitable weldable high strength steel for advanced surface ships and, accordingly, has received considerable international attention.^{1,2} Because HY130 appeared in 1974 to be the prime candidate for future Canadian Forces hydrofoils and because at that time, much of the research data on this material was unavailable in Canada, a number of investigations were initiated in Canada* to establish the engineering properties of HY130 steel and its weldments.

Studies at the Defence Research Establishment Pacific (DREP) have shown that:

1. HY130 has excellent fracture toughness, with a K_{IC} parameter in excess of 140 ksi $\sqrt{\text{in}}$ (J.R. Matthews & G. West, Report in preparation).
2. HY130 is not subject to environmental crack initiation in plate or welded material.³
3. HY130 has very good environmental crack propagation resistance, with a K_{ISCC} parameter in excess of 100 ksi $\sqrt{\text{in}}$ for parent material and 80 ksi $\sqrt{\text{in}}$ for welded material, and a K_{IHac} parameter in excess of 85 ksi $\sqrt{\text{in}}$ for parent material and 50 ksi $\sqrt{\text{in}}$ for welded material.³
4. HY130 steel weldments have acceptable fatigue crack initiation properties. For welded and machined and ground specimens, simulating material that would be present in the highly stressed areas of a foil, the weldments have an endurance limit of 70,000 psi at $R = -1$ (a stress ratio more demanding than that expected for a hydrofoil).⁴

*Canadian DND work on HY130 steel was conducted at DREP, PMRL, DREA/DL, UBC Dept. of Metallurgy, Atlantic Industrial Research Institute and Nova Scotia Research Foundation Corporation.

Work has also been conducted at DREP to evaluate the effect of residual stresses, due to welding, on the properties of HY130 steel and its weldments. Residual stresses in HY130 steel have been shown to be high.⁵ To remove these residual stresses, stress-relief heat treatments are required. Some of these heat treatments are, however, known to affect deleteriously the engineering properties of high strength steels.⁶

Charpy V-notch impact testing has been applied to HY130 steel and its weldments at DREP over the last few years to assess the effects of a number of heat treatments on impact toughness. The purpose of this paper is to collate the numerous Charpy V-notch data obtained and reported in isolation, to report on more recent Charpy V-notch impact studies conducted on stress-relieved HY130 weldments and to judge whether the reductions in toughness associated with some of the heat treatments have engineering significance. It was also hoped to establish if there were any heat treatments that would reduce residual stresses without deleteriously affecting the properties of the steel.

These investigations involved the assessment of two types of parent material (Air Melt Vacuum Degassed, AMVD; and Electroslag Remelted, ESR) and three types of weldments (MIG wire, E14018 and E12018 stick electrodes).

A number of the initial Charpy V-notch studies in 1975 served as indicators to give direction to the DREP HY130 Program. Because of the very limited number of samples evaluated in some instances these results should not be taken as definitive properties of the materials evaluated.

In addition to establishing the Charpy impact values, the fracture appearances were evaluated for percent ductility. The work was supported with electron fractography and hardness tests.

EXPERIMENTAL PROCEDURES

A. Material and Specimen Preparation

Analysis showed that the two parent materials and the three weld types evaluated had the following compositions:

	<u>Composition in Percent</u>							
	<u>C</u>	<u>Ni</u>	<u>Mn</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>Si</u>	<u>S</u>
AMVD Parent	.1	5.3	.78	.59	.49	.06	.3	.012
ESR Parent	.1	5.4	.73	.59	.49	.06	.2	.003
E14018 Weld		3.5	.9	.55	.64			.005
E12018 Weld		2.3	1.6	.74	.37			.014
MIG Weld		2.1	1.9	.88	.54	<.01	0.3	.008

The MIG welding involved the use of an Argon - 2% oxygen shielding gas and 0.035 inch filler wire (MIL-140S) stored at 85°F. The parent metal plate was preheated at 250°F and welded with multiple passes (all weave) at 28V and 225A. A total of 10 passes was required to weld the one-inch plate.

Standard Charpy V-notch specimens machined from the parent and welded materials (the parent plate specimens were machined to evaluate the weaker transverse direction) were heat treated in a number of ways as follows:

1. Parent material was given a 1950°F heat treatment for $\frac{1}{2}$ hour to produce a grain structure similar in size to that of the heat affected zone near weldments, and then quenched in water. This material is referred to as SIM-HAZ.
2. Some of the specimens were given a stress-relieving heat treatment at various temperatures (850, 900, 950, 1000, 1100, 1150°F) for two hours and then furnace cooled. (Some of this heat treatment took place in a muffle furnace without protective atmosphere while other heat treatments were performed in a tube furnace in an argon atmosphere). Specimens were heat treated for various periods of time.
3. Some of the earlier work involved heat treating specimens at 1150°F for two hours and air cooling.

B. Testing and Evaluation

The impact studies were carried out on a standard Charpy V-notch impact tester using the 120 ft lb scale. Testing temperature (-18°F or -40°F) was attained by placing the specimens in a 40:60 ethyl alcohol-water solution and holding in a refrigeration unit.

As a second method of determining the relative ductility of the fractures, the fracture surfaces were evaluated in terms of percent ductile appearance. Figure 1 shows typical examples of fractures with 0, 20, and 70 percent ductile appearance.

Hardness measurements were taken after fracture on the upper (notched) surface of the specimen. At least three measurements were taken on each specimen using the Rockwell "C" scale.

Selected fracture faces were replicated using the one stage direct carbon method and examined in the electron microscope. Fractured specimens were also examined metallographically.

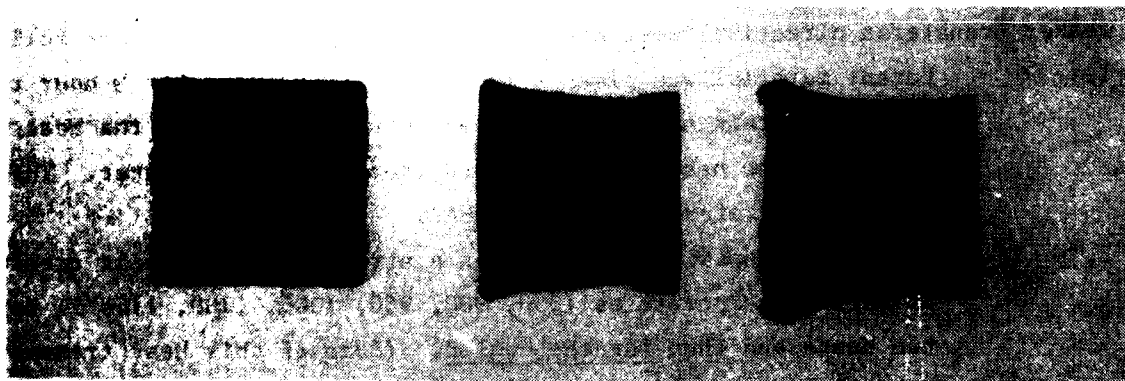


Figure 1. Charpy V-notch Specimen Fracture Faces with from left to right, 0%, 30% and 70% Ductile Appearance.

RESULTS

A. Preliminary Observations

Preliminary Charpy V-notch impact test results obtained from various HY130 materials are given in the table on page 5 (in foot-pounds).

Preliminary HY130 Charpy V-notch Results

(Tested at)	<u>As-Received</u>		<u>Stress Relieved 1 hr at 1150°F</u>			
	RT	-18°F	<u>Furnace Cooled</u>		<u>Air Cooled</u>	
			RT	-18°F	RT	-18°F
AMVD (parent)	87, 91	80, 84	102, 114	71, 66	102, 104	84, 84
ESR				117, 120+		120, 120+
AMVD (SIM-HAZ)	55, 59	38, 49	76, 79	32, 46	96 97	44, 49
ESR (SIM-HAZ)	69	72	104	52, 75	120+	107, 110
E14018 weld*		87, 88		42, 44		114, 110
E12018 weld*		27, 31		19, 20		48, 43
MIG weld **		67, 71	60, 60	36, 25	74, 76	62, 60

* ESR parent plate welded

** AMVD parent plate welded

The above preliminary results indicated that:

1. Both ESR and AMVD parent materials were very tough at -18°F, even after stress relief annealing at 1150°F and furnace cooling.
2. The SIM-HAZ material was reasonably tough in both ESR and AMVD.
3. The stick E14018 weldments appeared to be somewhat tougher than the other weldments.
4. In every case, the air cooling following stress relief annealing produced much better results than the furnace cooling.
5. The as-welded E12018 weldments showed considerably poorer impact properties than the E14018 and MIG weldments.
6. The lowest results obtained were for E12018 welds (at -18°F) which were furnace cooled after stress-relief annealing. Of all the results shown, only these might cause significant engineering concern if the material were used for a hydrofoil.

B. Experimental Results

Since there were reports that the parent HY130 steel was subject to temper embrittlement after being subjected to stress-relief heat-treating temperatures, some Charpy V-notch work was directed at both the ESR and AMVD material. Data relating to ESR HY130 parent and simulated heat affected zone material (which was subsequently furnace cooled) are shown in Figure 2, and similar data for AMVD material are shown in Figure 3. While there was a

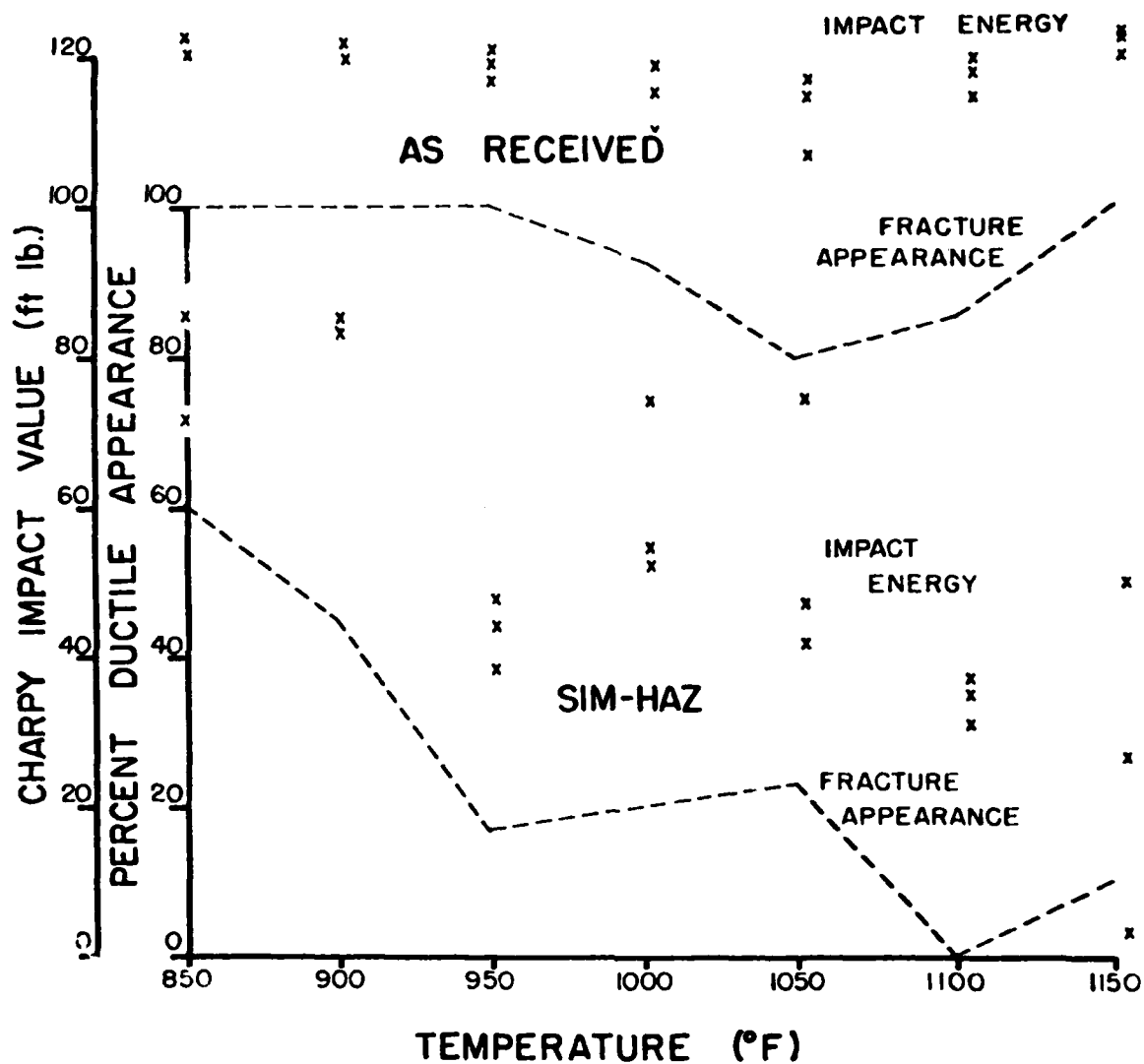


Figure 2. Impact Behaviour of HY130 ESR Parent Metal after Stress Relieving at Various Temperatures for 2 hours and Furnace Cooling showing both As-Received and Simulated Heat Affected Zone Material. Tested at -18°F.

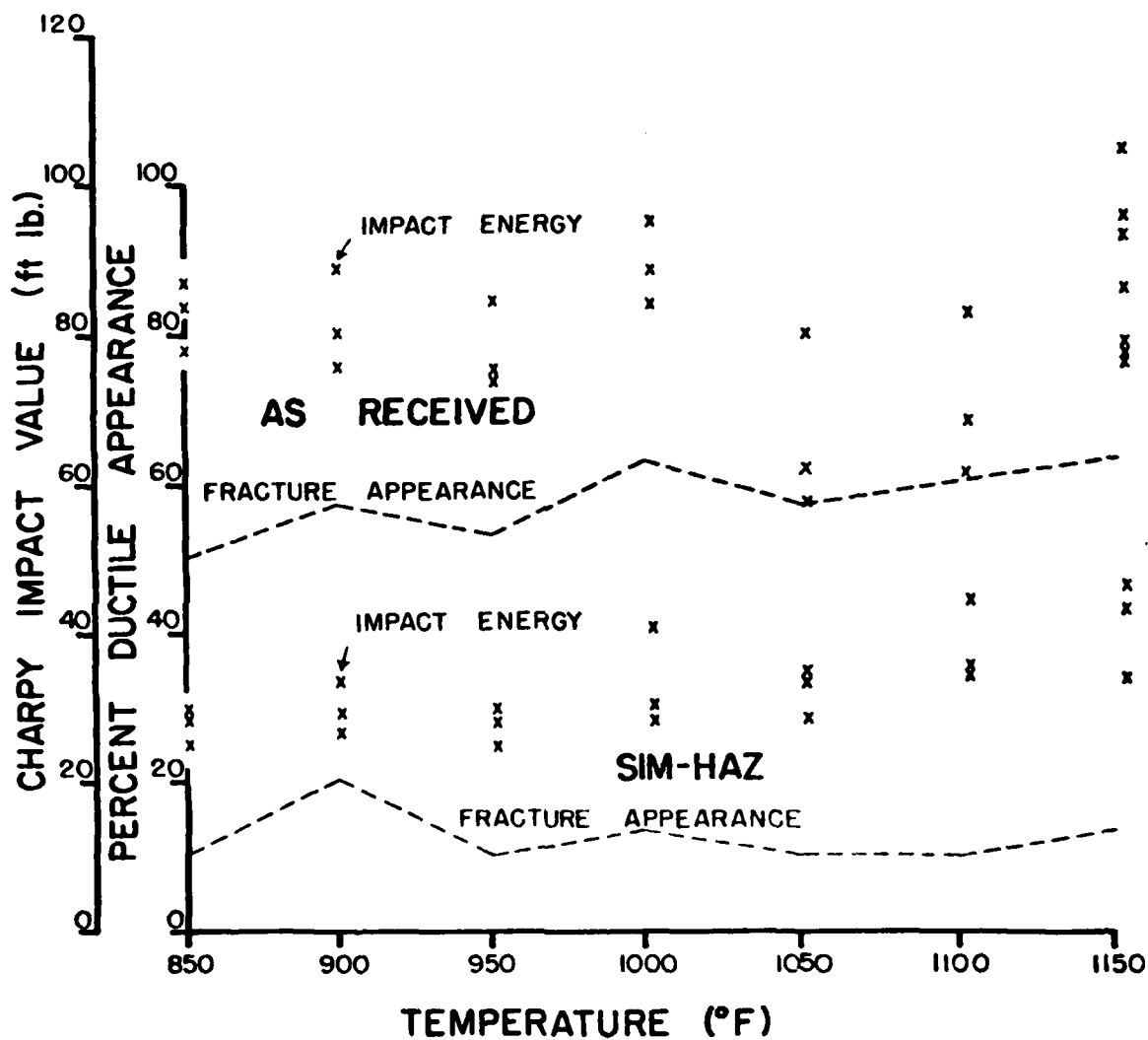


Figure 3. Impact Behaviour of HY130 AMVD Parent Metal after Stress Relieving at Various Temperatures for 2 hours and Furnace Cooling showing both As-received and Simulated Heat Affected Zone Material. Tested at -18°F.

slight dip in the "fracture appearance" curve of the parent material at 1050°F it would be misleading to use terms such as temper embrittlement to describe this excellent-quality 115 ft lb material. The impact strength of the SIM-HAZ material was considerably lower than the parent material and was affected by the stress-relief annealing temperatures.

A plot of hardness versus stress-relief annealing temperature, Figure 4, showed that a significant decrease in hardness (strength) took place when the parent material was heat treated for two hours at temperatures above 1050°F. Similar plots on MIG and E14018 weldments showed that these weldments did not soften appreciably below 1100°F when the material was heat treated for two hours, Figure 5.

The Charpy V-notch tests indicated that as-welded materials showed good engineering properties. MIG weldments, for example, showed impact strengths in excess of 50 ft lb even at -40°F, Figure 6.

When MIG and E14018 weldments were heat treated at 1150°F for 2 hours and then furnace cooled, the MIG welds produced significantly better results than did the E14018 welds, as shown in Figure 7. The Charpy V-notch results for the MIG weldments were in excess of 30 ft lb at -40°F while the E14018 weldments produced results less than 10 ft lb at this temperature. When the heat treated MIG results are compared with the as-welded MIG results, in Figure 6, some decrease in toughness is noted; however, the above results indicate that no dramatic decrease in engineering properties have resulted from the heat treatment.

When MIG and E14018 weldments were heat treated at 1150°F for 2 hours and air cooled, the dramatic drop in toughness did not take place in the E14018 weldments, Figure 8. The MIG weldments did not show significantly different results whether furnace cooled or air cooled and the as-welded MIG results were not dramatically different.

Figures 9 and 10 show the results from Charpy V-notch tests performed on MIG and E14018 weldments after heat treating at various temperatures for 2 hours followed by furnace cooling. While the MIG material (Figure 9) showed no apparent deterioration in properties at any temperature, the E14018 (Figure 10) showed deterioration at heat treatments above 1000°F.

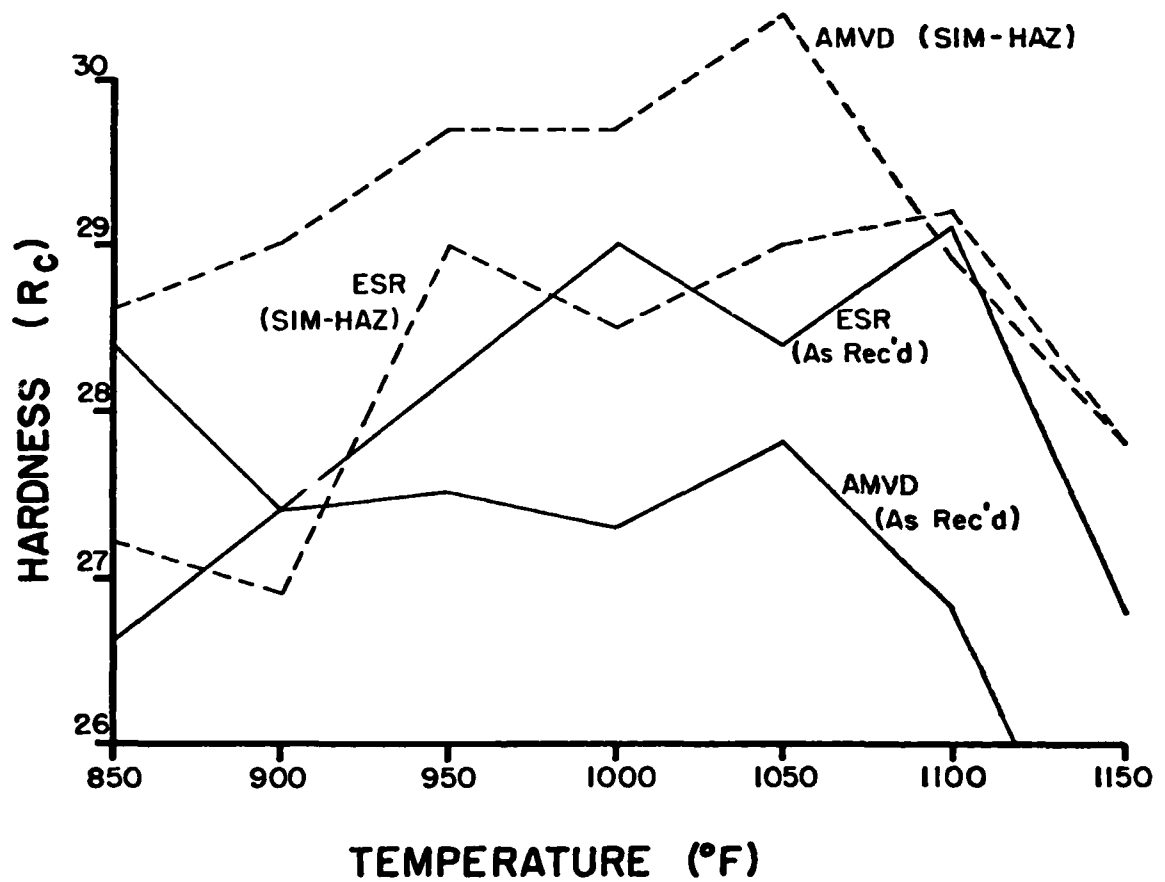


Figure 4. Hardness of ESR and AMVD Parent HY130 Metal after heat treating at Various Temperatures for 2 hours and furnace cooling.

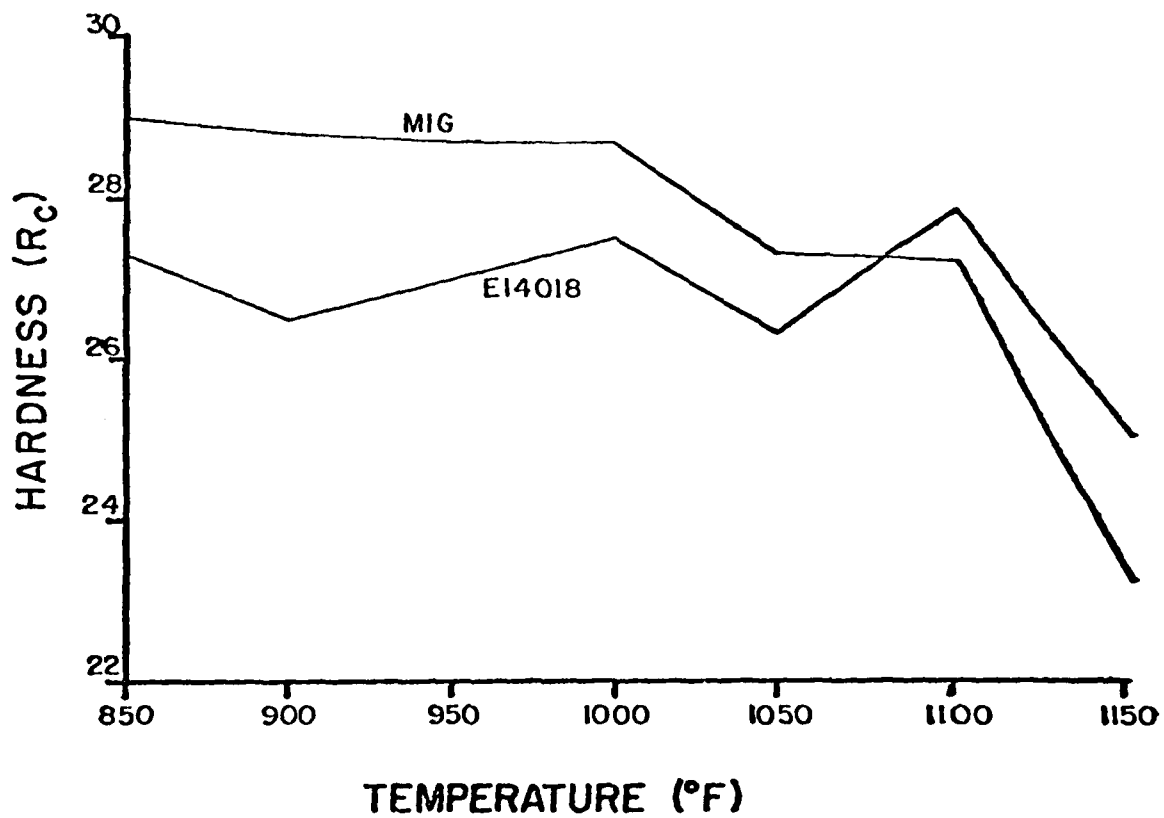


Figure 5. Hardness of MIG and E14018 Weldments after heat treating at various temperatures for 2 hours and furnace cooling.

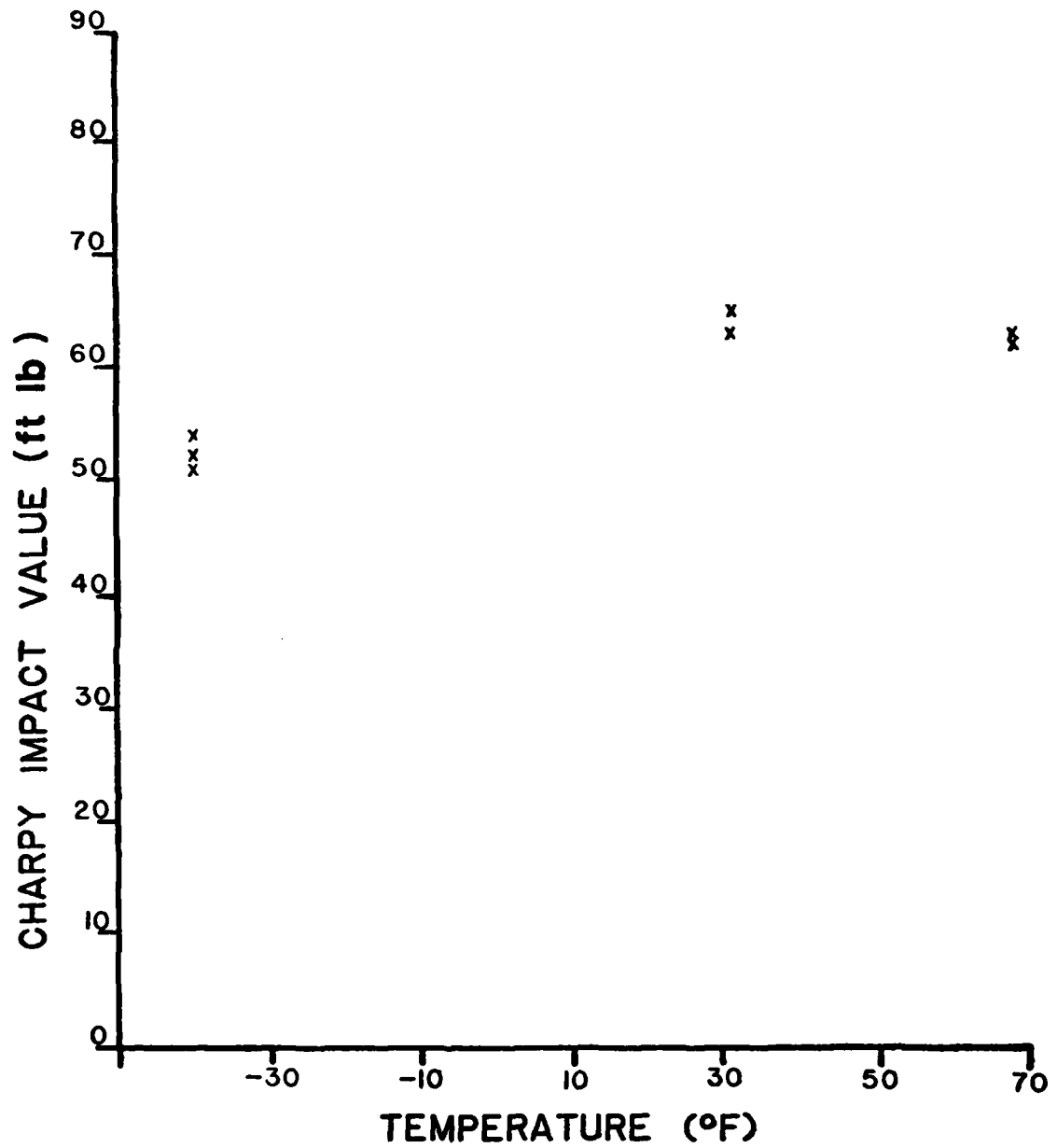


Figure 6. Impact behaviour of as-welded MIG Weldment.

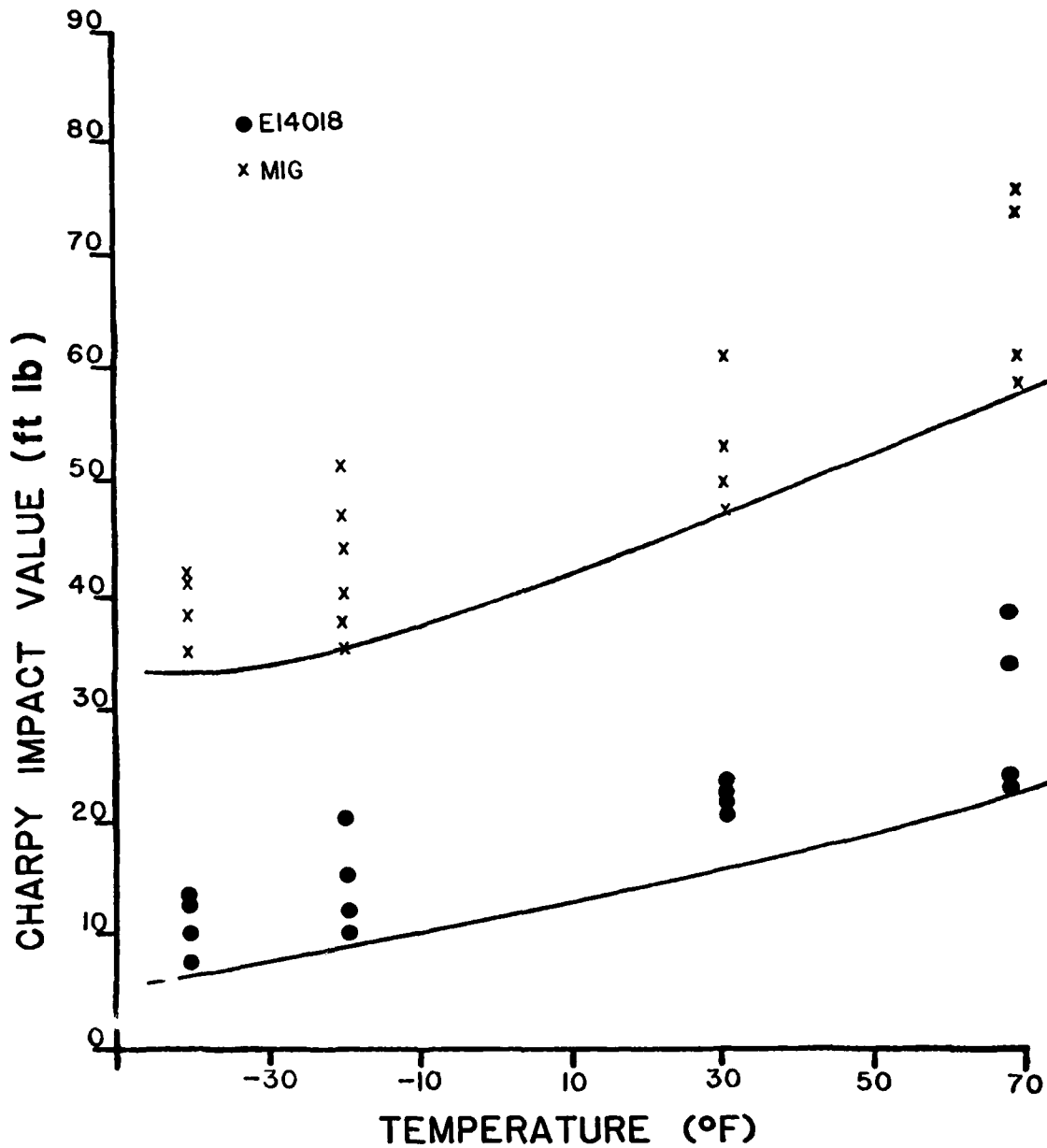


Figure 7. Impact strength at various temperatures of E14018 and MIG weldments after heat treating at 1150°F for 2 hours and furnace cooling.

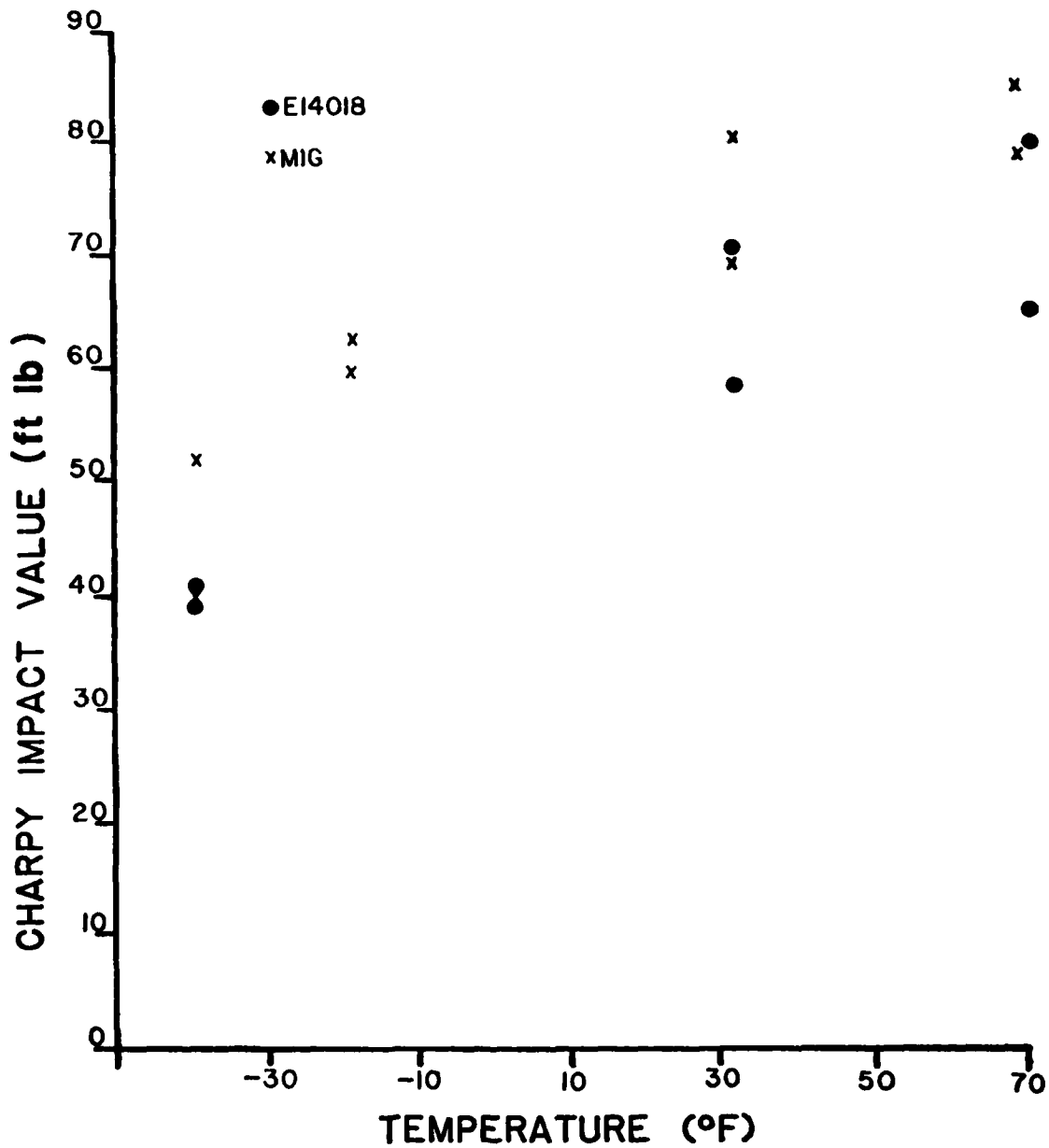


Figure 8. Impact strength at various temperatures of E14018 and MIG weldments after heat treating at 1150°F for 2 hours and air cooling.

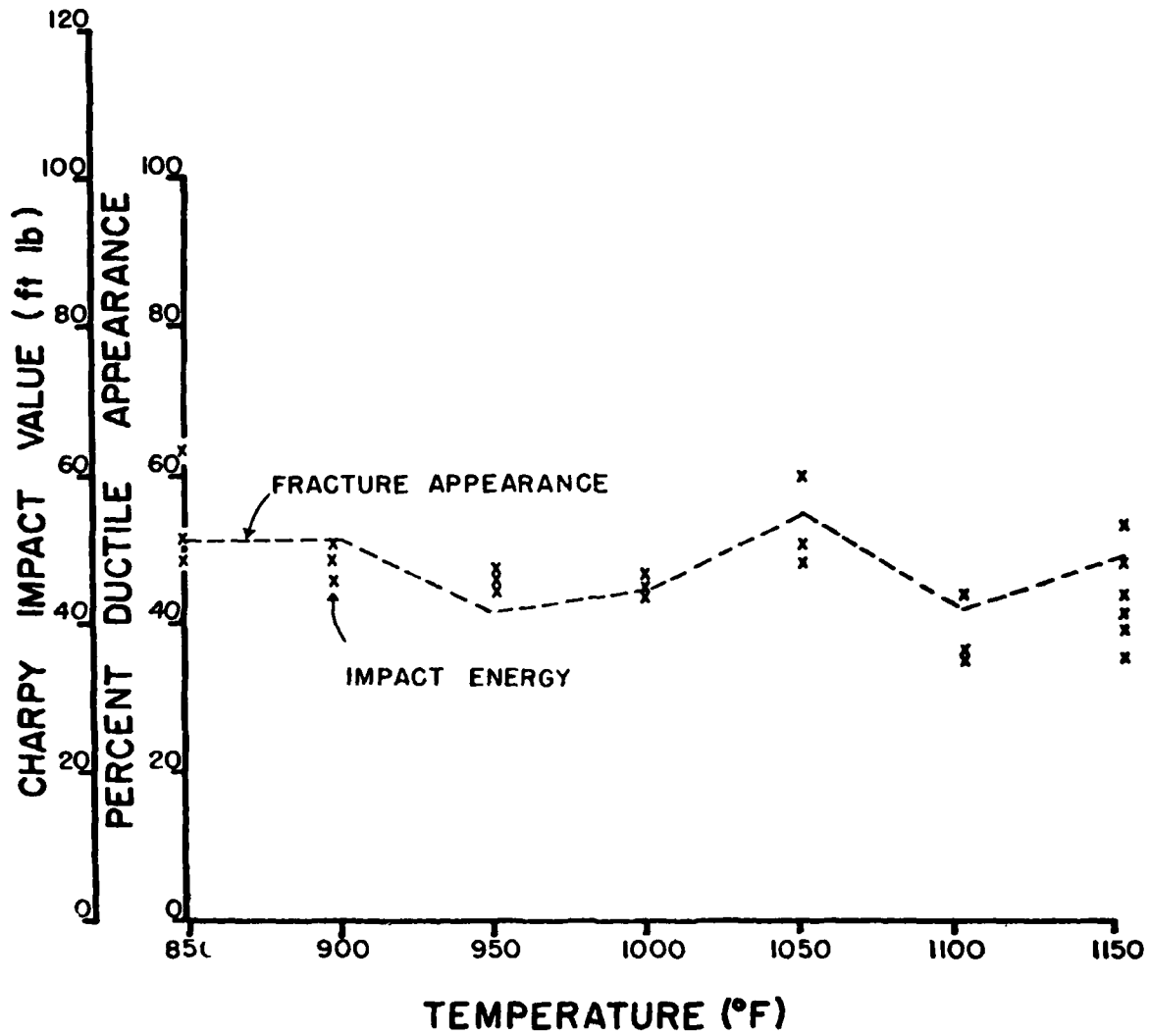


Figure 9. Impact Behaviour of MIG weldments after heat treating at various temperatures for 2 hours (in Argon) and furnace cooling. Tested at -18°F .

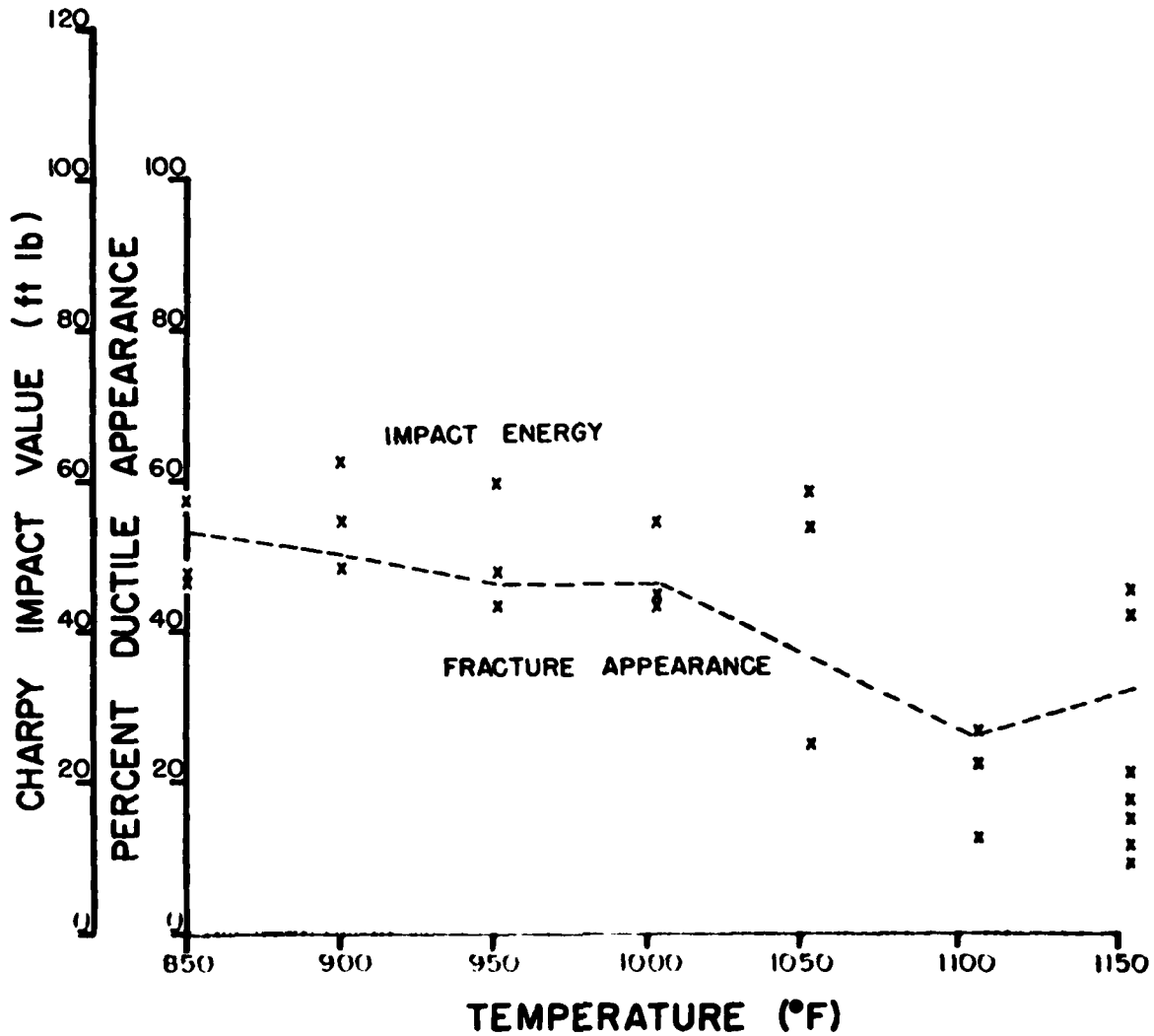


Figure 10. Impact behaviour of E14018 weldments after heat treating at various temperatures for 2 hours (in Argon) and furnace cooling. Tested at -18°F .

In another series of experiments, E14018 weldments were heat treated at 1150°F for various times, as shown in Figure 11. It was noted that the Charpy impact strength of the material was improved by the prolonged heat treatment. Also, the data appeared to break into two groups at 2 and 8 hours. In an effort to understand the large spread of data shown at these times, the Charpy results were correlated with hardness as in Figure 12. It became apparent that the tough samples were softer than the more brittle samples. Also, when samples which were relatively hard after an 8 hour heat treatment (and from the data would have shown poorer impact properties) were heat treated for an additional 16 hours at 1150°F, the impact properties of these weldments were high. Spectrographic analysis revealed no differences between the hard and soft weldments.

AMVD parent plate was also given prolonged heat treatments at 1150°F and furnace cooled, Figure 13. While the long 24 hour heat treatment resulted in some deterioration in the Charpy V-notch impact properties of this material, the impact strengths recorded were all high.

Prolonged heat treatments were also performed at lower temperatures. When the MIG and E14018 weldments were heat treated for 6 hours at 1000°F and then furnace cooled, the 2 weldments showed similar toughness properties, Figure 14. While longer heat treatments affected the MIG weldments only slightly, Figure 15, the longer heat treatments produced very poor properties (less than 10 ft lb) in the E14018 weldments, Figure 16. MIG and E14018 weldments were also heat treated for 24 hours at 900°F and furnace cooled, Figure 17, with no deleterious effects.

The above data (Figures 7, 10, 11) indicate that E14018 weldments are subject to temper embrittlement after a 2 hour heat treatment at 1150°F followed by furnace cooling. When this embrittled material (with its Charpy V-notch (CVN) toughness of 8-15 ft lb) was re-heat-treated at 1150°F and air cooled the properties of the material were markedly improved (46-51 ft lb CVN). When this tough material was again furnace cooled from 1150°F, CVN values ranging from 16.5 to 22 ft lb were obtained. It might be added that each heat treatment resulted in some softening (weakening).

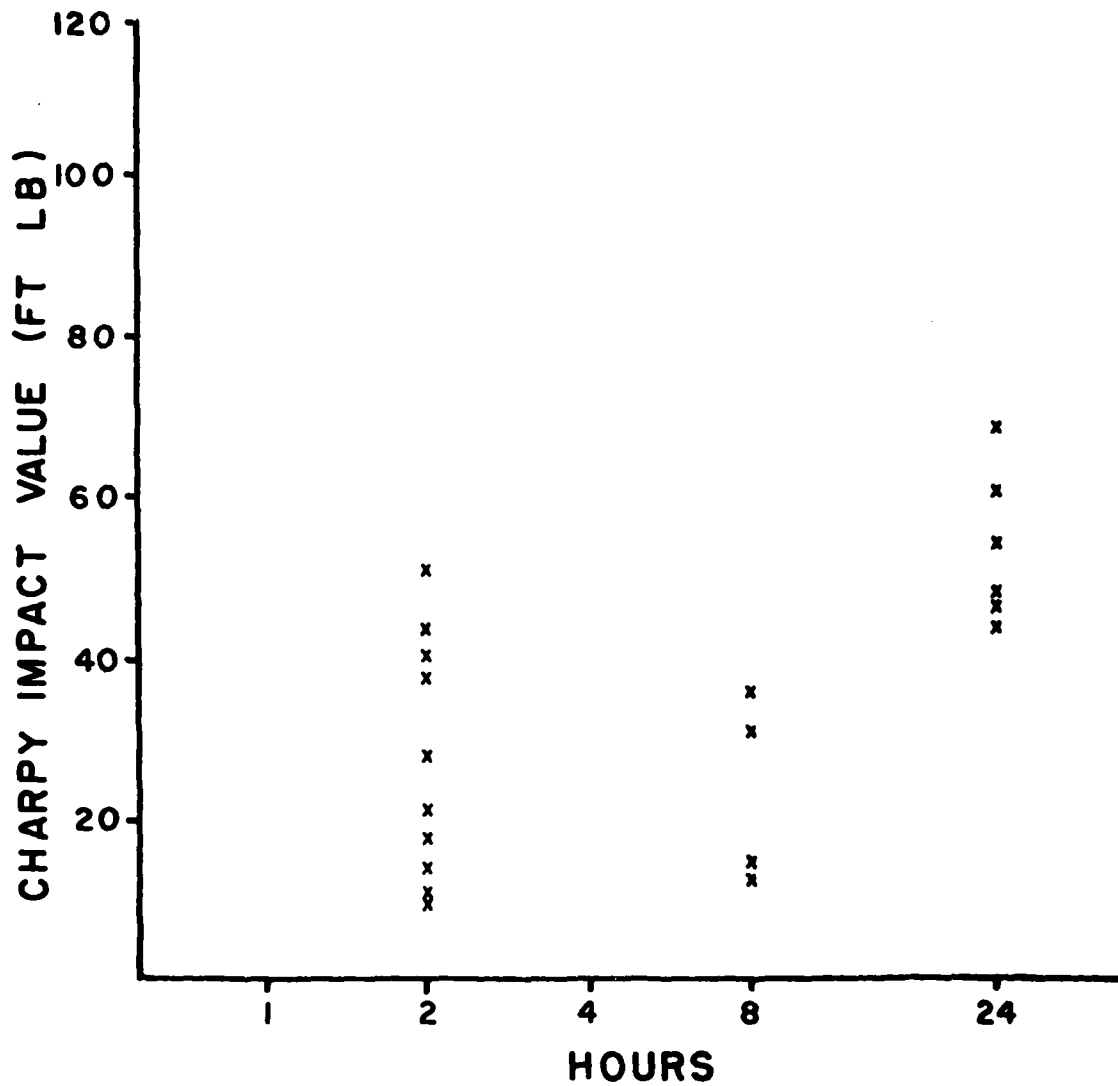


Figure 11. Impact behaviour of E14018 weldments after heat treating at 1150°F for various times and furnace cooling. Tested at -18°F.

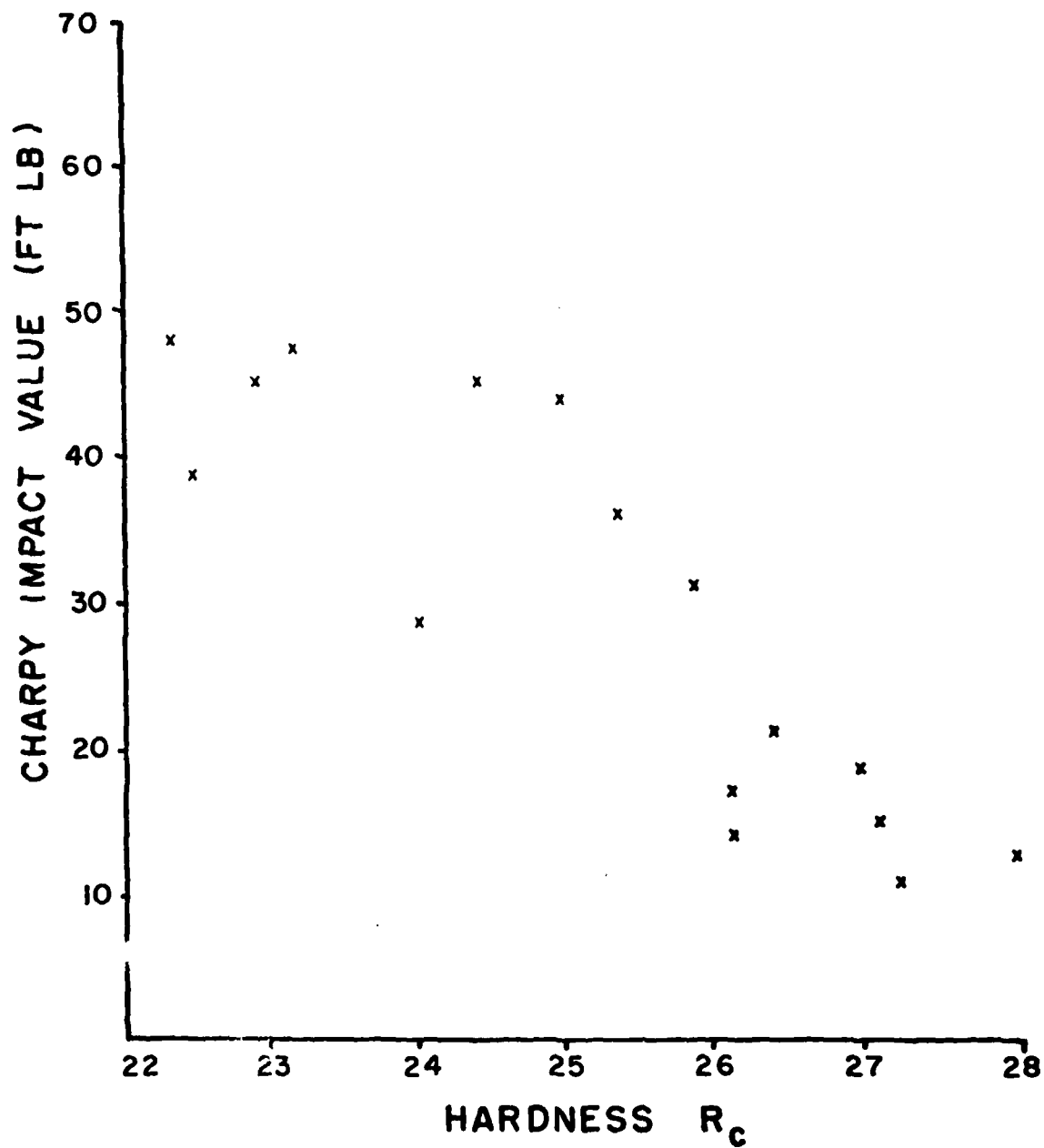


Figure 12. Correlation between Charpy V-notch impact strength and hardness for E14018 weldments heat treated at 1150°F and furnace cooled. Tested at -18°F.

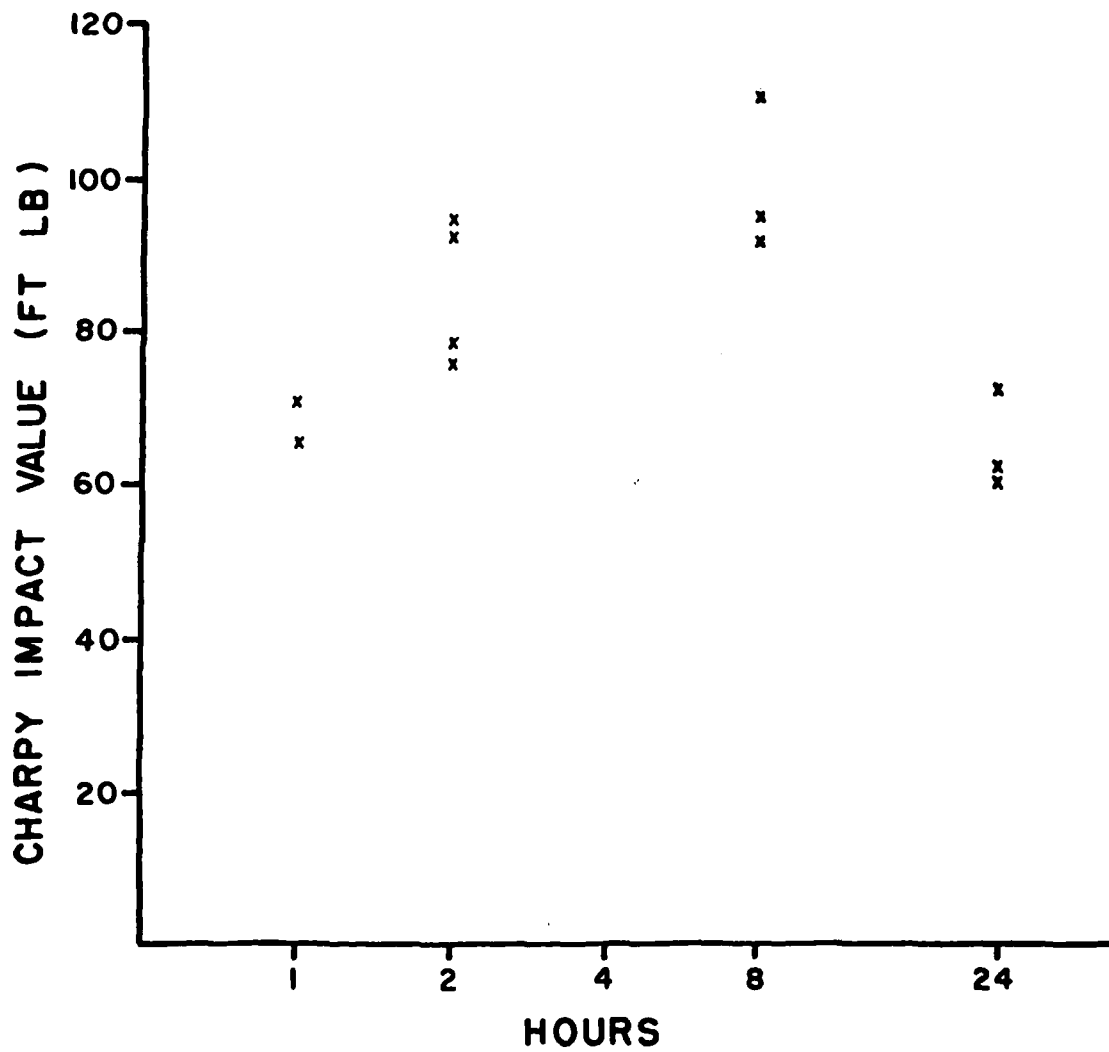


Figure 13. Impact behaviour of AMVD HY130 steel after heat treating at 1150°F for various times and furnace cooling. Tested at -18°F.

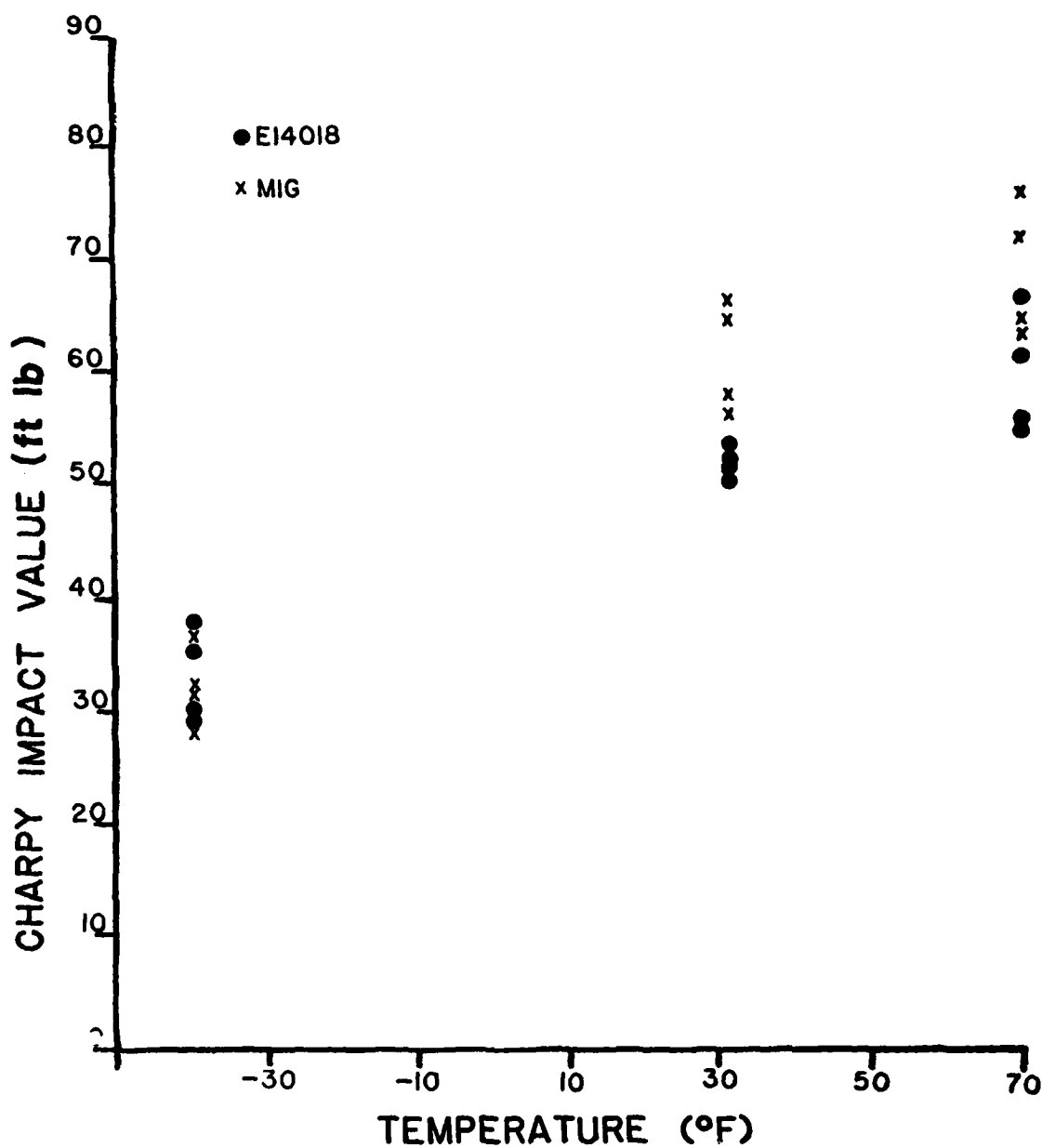


Figure 14. Impact Strength at various temperatures of E14018 and MIG weldments after heat treating at 1000°F for 6 hours and furnace cooling.

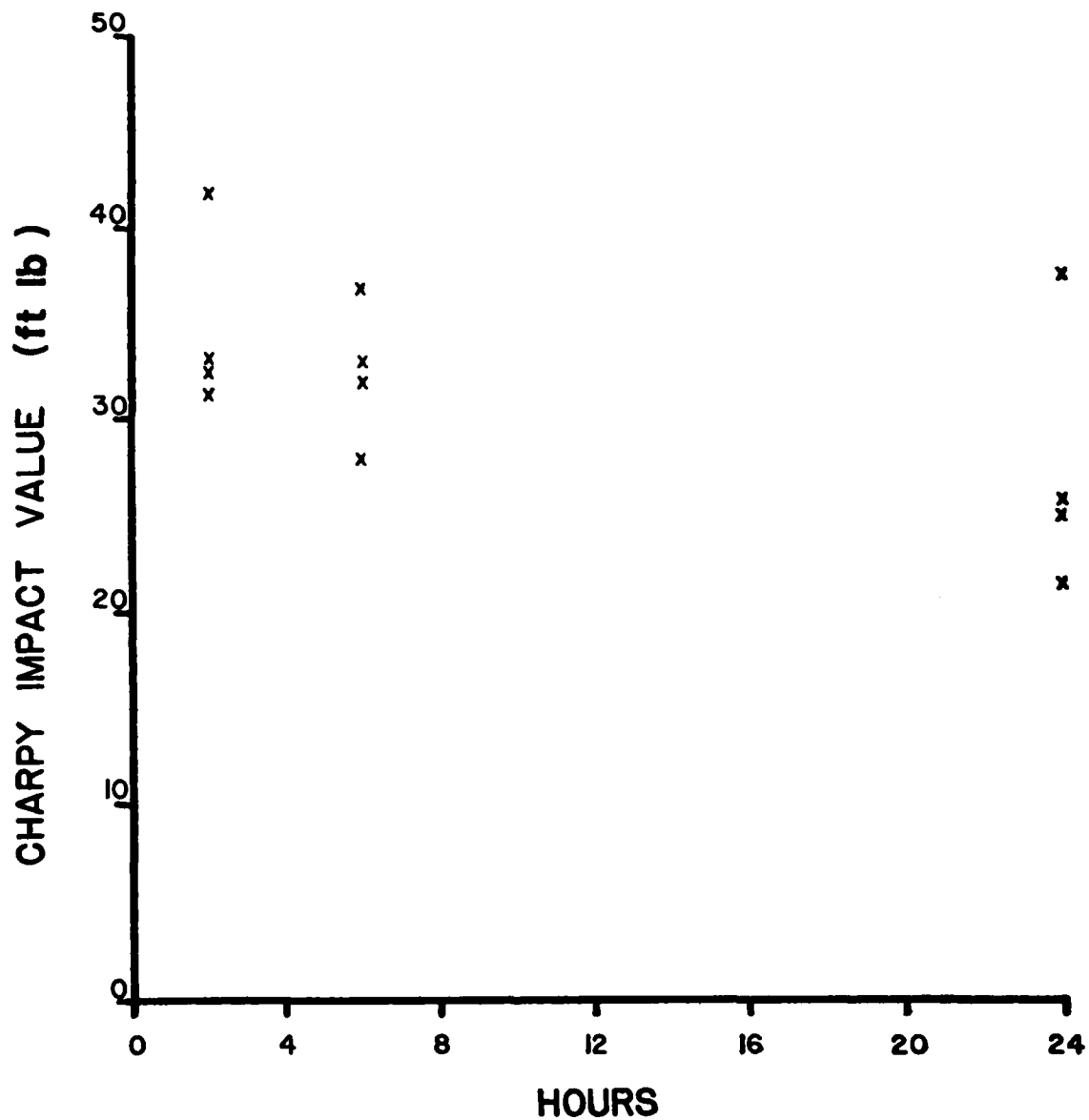


Figure 15. Impact strength of MIG weldments after heat treating at 1000°F for various times and furnace cooling. Tested at -40°F.

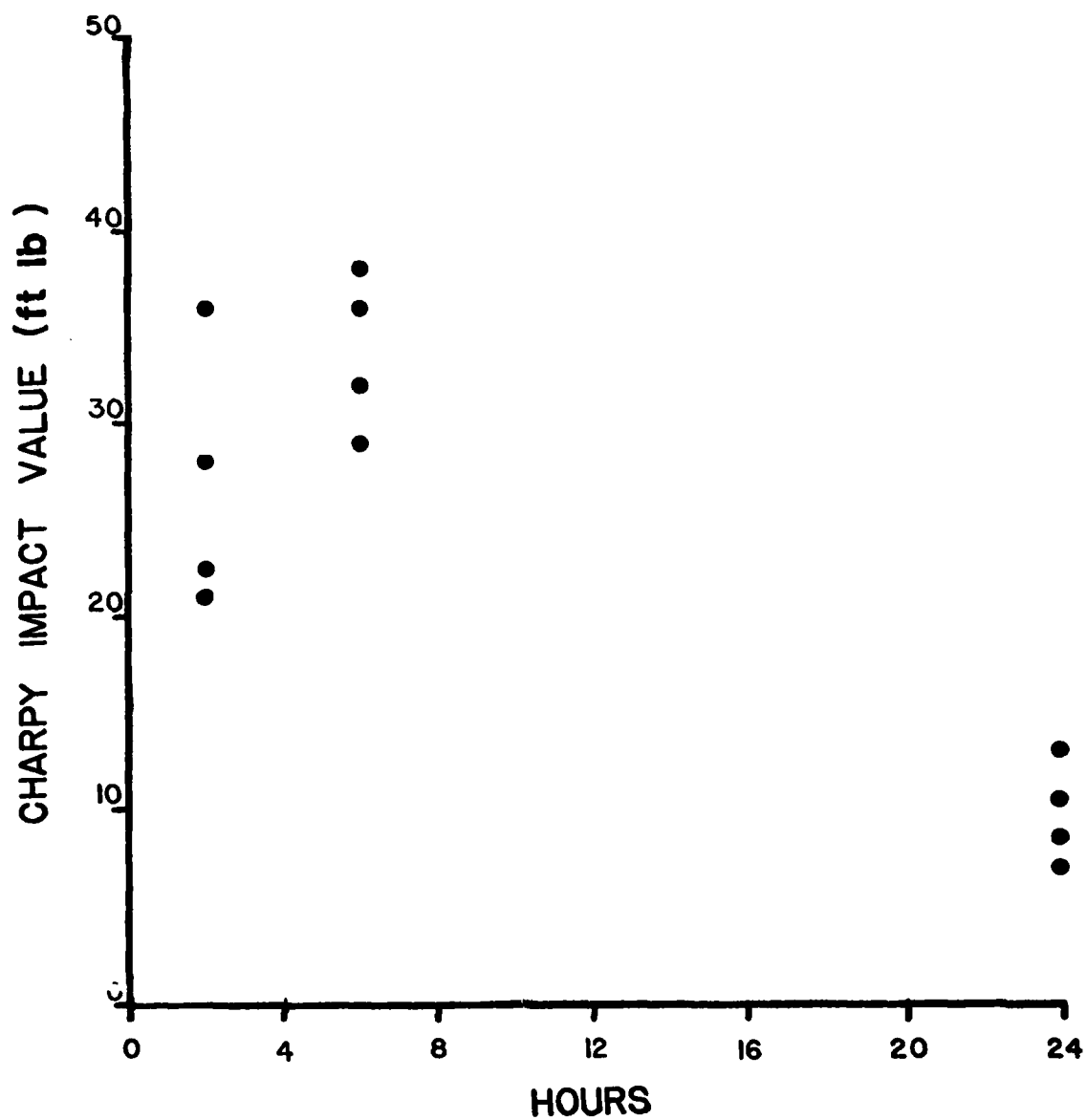


Figure 16. Impact behaviour of E14018 weldments after heat treating at 1000°F for various times and furnace cooling. Tested at -40°F.

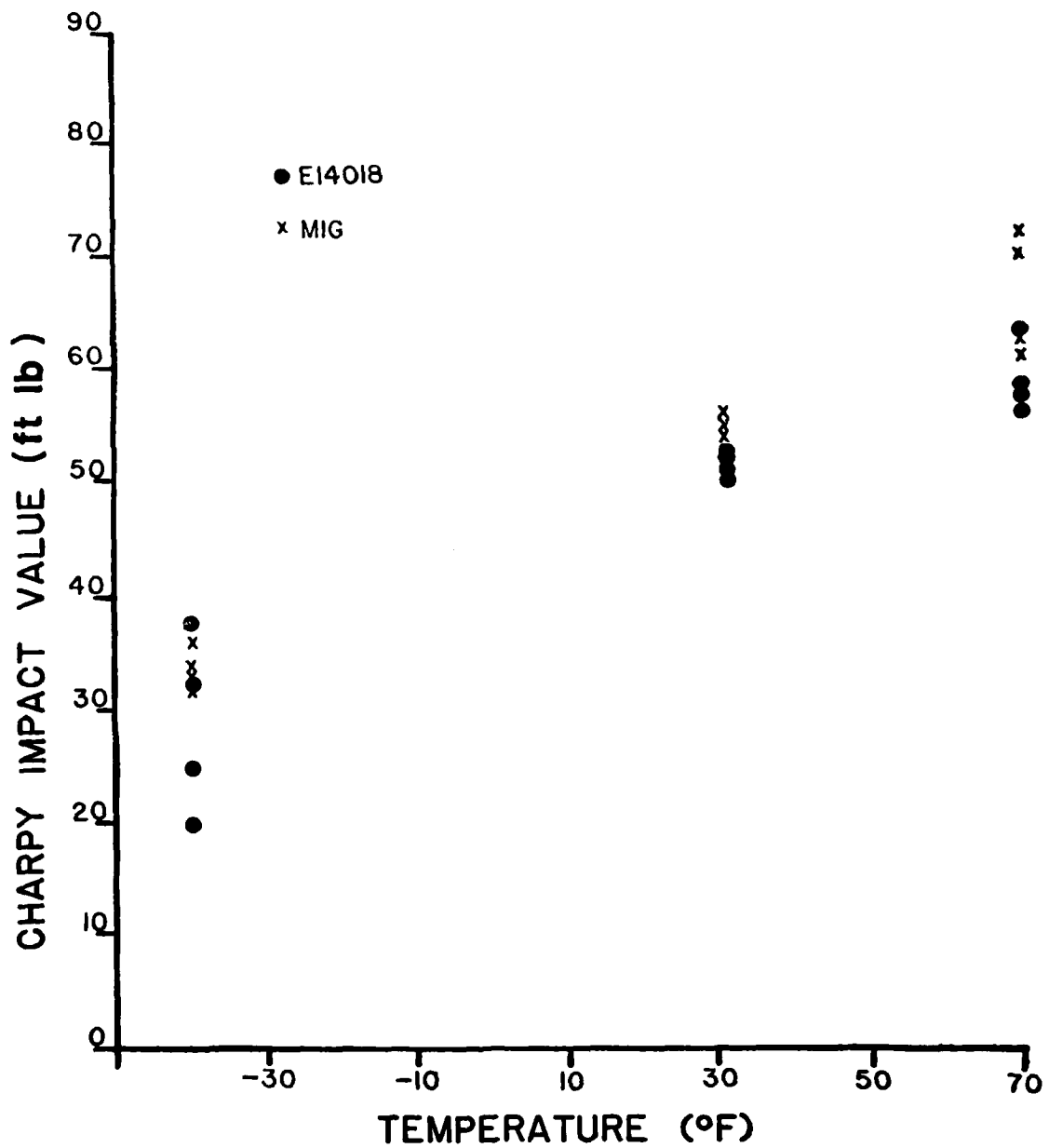


Figure 17. Impact strength at various temperatures of E14018 and MIG weldments heat treated at 900°F for 24 hours and furnace cooled.

A number of the above specimens were examined both metallurgically and fractographically. Metallographic evaluation showed that subsurface intergranular cracking, Figure 18, took place while fracturing in the low impact strength specimens. No such evidence was found in the tougher material. Electron fractography confirmed that the specimens with low Charpy values had separated intergranularly and that there was evidence of cleavage while the tough material showed dimpled rupture.



Figure 18. Section through E14018 Charpy specimen showing subsurface cracking.

DISCUSSION

A. The Charpy V-notch and Hardness Data

The above results indicate that the Charpy V-notch impact strength of parent HY130 is very good. Stress-relief heat treatments do not affect the properties of the material to any practical degree. E14018 weldments are affected very significantly when stress relief heat treatment is followed by furnace cooling. MIG weldments show intermediate properties.

The MIG welds are not very susceptible to temper embrittlement. The air cooled samples (Figure 8) showed Charpy impact strengths only slightly better than the furnace cooled samples (Figure 7).

On the other hand, the E14018 weldments were shown to suffer significantly from temper embrittlement. Also, the DREP results confirm that the "temper embrittlement" is reversible;⁷ that is, reheating to 1150°F followed by air cooling removes the temper embrittling effects. When this material is again furnace cooled, it is again embrittled. The slight improvement in toughness after the second embrittlement over the first embrittlement may be associated with a softening which takes place during the repeated 1150°F heat treatments.

Considering softening, it is noteworthy that while the 2 hour 1150°F heat treatment followed by furnace cooling does not decrease the impact properties of the parent material and MIG welds significantly, it does soften the materials. The MIG welds appear to be affected most significantly; that is, the above heat treatment softens the welds about 5 points on the Rockwell C scale or about 15,000 psi in UTS. While the 1000°F heat treatment, even the long ones, result in less softening, there does appear to be a greater degree of temper embrittlement of the MIG welds with prolonged heat treatments at this temperature. A suitable stress-relief heat treatment for the MIG (MIL 140S) weldments would appear to be 1075°F for 2 hours.

B. Fracture Mechanics Considerations

While it is recognized that none of the quantities measured in the standard Charpy impact test are related directly to K_{IC} ,⁸ some empirical correlations have been made which may be useful in giving design significance to the CVN results obtained in this study.

Barsom and Rolfe⁹ have shown that the relationship:

$$\frac{K_{Ic}}{E} = 2 (CVN)^{3/2}$$

is valid for steels in the transition region, where

K_{Ic} is expressed $\text{ksi } \sqrt{\text{in}}$

E is the elastic modulus (ksi), and

CVN is expressed in foot pounds.

For data examined by Barsom and Rolfe, the spread in K_{Ic} for any given CVN for steels evaluated was about $\pm 12\%$. For Ni-Cr-Mo-V alloys (114-155 ksi YS), all of the K_{Ic} values were higher than those predicted by the equation from Charpy data. Figure 19 is a graph relating valid K_{Ic} and Charpy data for these steels.

If, in any proposed hydrofoils, the welded material used was one inch thick and was subjected to working stresses of 35,000 psi, one could calculate the local stress intensity factor for a through thickness crack of length $2c = 1.5$ inches from the following equation:

$$K = \sigma \sqrt{\pi c}$$

where K is the stress intensity factor

σ is the applied stress

c is crack size

The above type of defect would result in a leak in the foil (which could be sensed) rather than cause a rupture. It would produce at a working stress of 35,000 psi a stress intensity factor of approximately 55 ksi $\sqrt{\text{in}}$.

Since the as-received material has a plane strain fracture toughness of over 140 ksi $\sqrt{\text{in}}$ and a higher plane stress fracture toughness, there is no fear of fracture of the basic material in the "just leaking" situation. Considering data from Figure 19, an "embrittled" material with a Charpy V-notch impact strength as low as 15 foot pounds would also leak before fracturing. But even if the material was required to stand up to stress intensities of 100 ksi $\sqrt{\text{in}}$ at -18°F (35 foot pounds CVN), MIG results would, in each instance, be adequate in the as-welded, air cooled or furnace cooled (after stress relief) conditions. However, the E14018 weldments would be satisfactory only in the as-welded or air cooled (after stress relief) conditions.

x Ni-Cr-Mo-V Steel
(114-155 ksi YS)

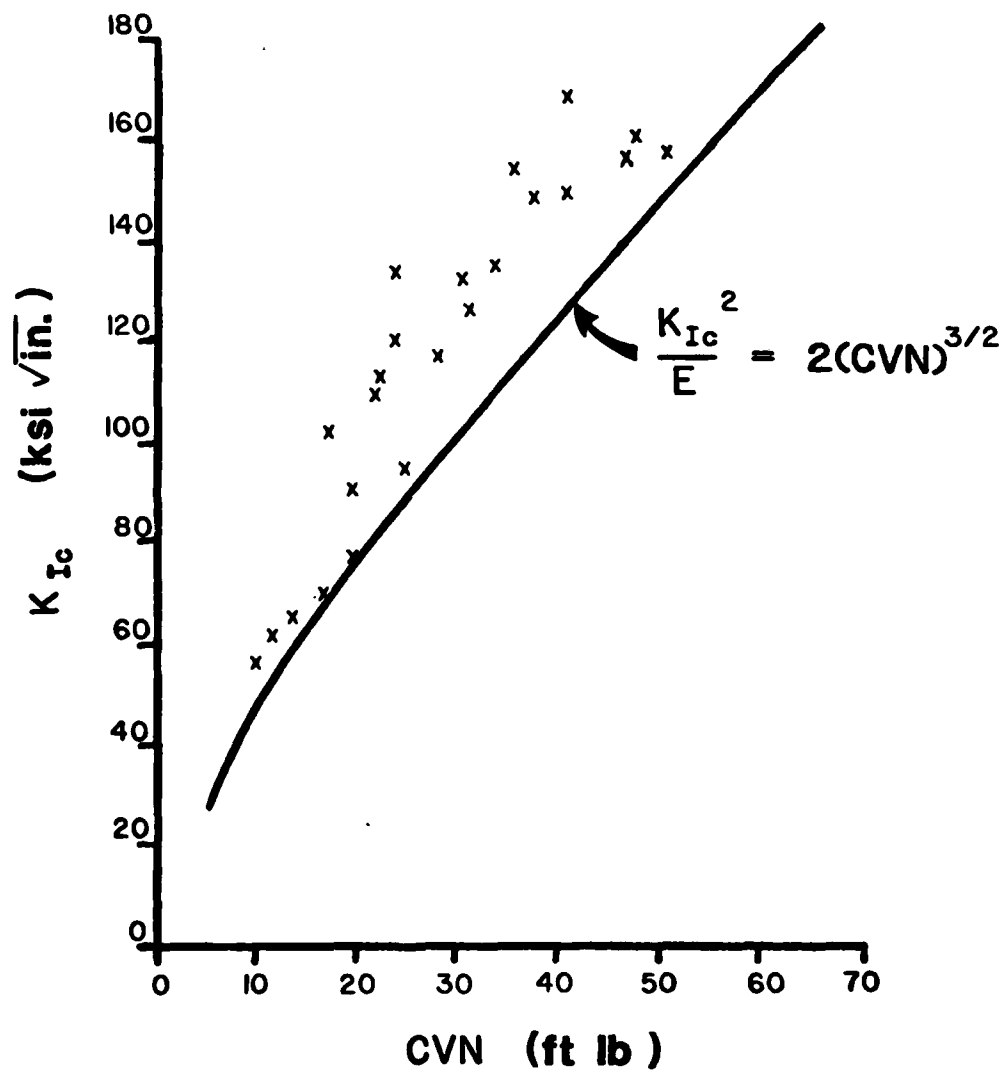


Figure 19. K_{Ic} and CVN correlation for steels in transition range, from Barson & Rolfe.⁹

C. Some Design Considerations

The following should be taken into consideration when determining whether a HY130 hydrofoil should, in fact, be heat treated after welding:

1. In HY130, a stress relief is not required to guard against SCC and hydrogen cracking. These cracks do not initiate in the welded material at yield point stresses.³ Large totally-unacceptable (for fatigue reasons) cracks would have to be present to initiate the corrosion cracking process.
2. DREP work has shown that stress relief heat treatments do not improve the fatigue crack initiation resistance of welded HY130.⁴ In fact, stress relief can lower the fatigue crack initiation properties of the weldments because beneficial residual compressive stresses in the weld metal are removed by the heat treatment and softening takes place.
3. The stress relief heat treatment will reduce all residual stresses to a relatively low level, (less than 3000 psi). If the welded foil is furnace cooled no new stresses of significant magnitude will be produced. If the welded foil is air cooled, long range stresses (which may affect fatigue life)⁴ will be produced. Recent DREP work suggests that these might be as high as 15,000 psi.
4. Fatigue crack growth rate in stress relieved and furnace cooled HY130 material may be more than twice as fast in the stress relieved material than in as-received material.¹⁰

Accordingly, and in view of the results of this study, there appears to be very little reason to stress relieve a hydrofoil made from HY130. If a stress relief is, however, shown to be necessary it would appear (considering, again, the weldments evaluated at DREP only) that the MIG (MIL 140S) weldments should be utilized. The stress relief should be kept below 1100°F (i.e. 1075°F for 2 hours) and the foil should be furnace cooled.

The above considerations are based on the Charpy V-notch impact result indications. Before engineering decisions are made on actual structural components (such as a hydrofoil), the properties of the recommended materials/heat treatments should be confirmed by dynamic tear testing.

CONCLUSIONS

The Charpy V-notch impact strength data in this report indicate that:

1. Parent HY130 steel (both ESR and AMVD) is not appreciably affected by normal stress relief heat treatments, even when followed by furnace cooling.
2. While MIG (MIL-140S) weldments show some decrease in impact strength due to stress relief heat treatments, this decrease does not have a large engineering significance. Air cooling of the MIG weldments after the residual stress relief heat treatment produces only slightly better results than furnace cooling.
3. E14018 weldments are subject to temper embrittlement when furnace cooled after stress relief heat treating. Much better impact properties are obtained when the E14018 weldments are air cooled.
4. E12018 weldments have generally poorer impact properties than both the E14018 and MIG weldments.
5. The 1150°F (2 hrs) heat treatments of HY130 steel and its weldments has the deleterious effect of softening (weakening) the material. In MIG welds, the hardness of the material drops 5 points on the Rockwell C scale or weakens approximately 15,000 psi in UTS with this heat treatment.

The above results indicate that if a HY130 hydrofoil requires stress relieving, MIG (MIL140S) weldments should be used and the foil should be furnace cooled after stress relieving at 1075°F for two hours.

ACKNOWLEDGEMENTS

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13. ABSTRACT A Charpy V-notch impact testing study has been conducted on samples of HY130 steel (ESR and AMVD) and its weldments (MIL 140S MIG, and E12018 and E14018 stick). The parent materials and MIG weldments do not suffer from an appreciable decrease in impact strength when subjected to stress-relief heat treatment followed by air cooling or furnace cooling. E14018 weldments suffer significantly when furnace cooled but not when air cooled from the stress-relief heat-treating temperatures.			

KEY WORDS

Impact Strength HY130 Steel temper embrittlement
 E14018 weldments MIG weldments
 Stress relief heat treatments Charpy V-notch

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