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Lehigh University

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ABSTRACT

ASTM A710 microalloyed precipitation strengthened steel provides to potential users a constructional material of high strength and toughness combined with excellent fabrication weldability. Of importance to its application are the properties of its weldments, particularly the toughness, its response mechanical forming, and the effects of heat treatment after forming or welding on its properties. The study reported here was designed to provide data in these areas.

The A710 steel studied was 32 mm thick Grade A Class 3 plate and had a yield strength of 602 MPa and a tensile strength of 673 MPa. The transverse orientation 47 J Charpy impact transition temperature of the plate was -145C. Cold plastic strain of 5% increased the transition temperature to -113C. Aging at 370C for 10 hours did not increase the transition temperature further. Stress relief treatments of 2 and 10 hours at 620C decreased the transition temperatures to -127C or below.

The coarse grained heat affected zone of the A710 weldments had a lower toughness than the base metal, an effect that was greater at higher welding heat inputs. For heat inputs of 2 KJ/mm, the as-welded 47J transition temperature in the heat affected zone was -78C. High heat input welds, 5.3 KJ/mm, resulted in heat affected zones with a 47J transition temperature of -33C. Weld metals used for the study, typical of those used in construction, were adequate in strength but had transition temperatures above those of the heat affected zone in the same weldment.

Post weld heat treatment at 620C did not consistently improve heat affected zone toughness over the as-welded condition and 2 hour heat treatment cycles increased heat affected zone transition temperatures. Similar treatments had little effect on base plate toughness. The A710 showed potential for stress relief cracking in the modified Lehigh restraint test, the effect being greatest above 600C but observable at 482C. These latter two effects suggest that post-weld heat treatment should not be used on this steel for metallurgical reasons.

INTRODUCTION

The use of microalloyed steels for constructional and pressure vessel applications has a long history, going back to the 1940's when critical material shortages made the utilization of only small amounts of alloys in steel products mandatory. In the 1950's, a number of companies also introduced construction steels that contained, along with MN and other alloys, V, Ti, and Nb. Most of these steels are now covered by ASTM specifications A588 and A572 and may also be considered early microalloyed steels, although they were not identified as such. However, it was in the 1970's that the microalloyed steels with low carbon content, high Mn levels and microalloyed carbide and nitride formers really became identified as construction materials with high strength, good weldability and good low temperature toughness. These materials allow control of grain size and microstructure such that, either as-rolled or specially processed, steel with good combinations of properties are now available for a number of applications.

The use of Cu in amounts over 0.2% to strengthen structural steels also has a long history, starting at least in the 1940's, when it was used in some ship steels. Structural steels clearly using Cu for precipitation strengthening, forerunners to the current ASTM A710 grades, were actually introduced in the 1960's, but generated little interest at that time. However, engineering needs change, and there is now a considerable interest in the combination of properties that Cu bearing steel of the ASTM A710 type provide. Of special interest is the very low carbon content, below 0.07%, that virtually prohibits hard, crack sensitive heat affected zones on welding, making preheat for welding unnecessary. Because of the choice of alloys present and the strengthening mechanism, strength can be very high and transition temperatures, low. This combination makes it especially attractive for special ship steels but there are also structural and pressure vessel applications where one or more of its characteristics may be useful.

It was for these reasons that the Pressure Vessel Research Committee and the Center for Advanced Technology for Large Structural Systems at Lehigh University initiated a program in 1985 to study the strength, toughness and fabrication characteristics of the A710 steel as a complement to its then nearly completed study of conventional and newer microalloyed steels. The prior studies [1,2,3,4,5,6] covered the effects of heat treatment, forming operations and welding on the strength and toughness of A572, A588, and A737 Grades B and C steels. A parallel investigation of A808 steel has just been started and a similar study on A710 appeared a natural extension of this program. As in the previous work, were given emphasis, as were the effects of heat treatments following these operations. The philosophy followed was that base metal properties are relatively easy to document, but changes in these properties, especially toughness, during fabrication operations are often unknown and should be the focus of the investigation.

MATERIALS AND PROCEDURES

Materials

The base material was a 32 mm thick plate of A710 Grade A Class 3 steel. The composition and mechanical properties of the plate are given in table 1 along with the specified properties for the grade. During the welding program, two weld metals were used to produce the test weldments. The welds were used primarily to create joints to measure heat affected zone properties but were intended to be adequate in strength for the base plate. The major weld metal types used were AWS 5.20 70T-1 and 5.29 E91 T1-K2. Their typical chemical and mechanical properties are given in table 1. In the stress relief cracking studies, two additional weld metals were used to develop the restraint necessary for the test specimen, E110 T5-K4 and E8018-C1. They were selected for their nominal strength level, and their compositions and properties were not assessed.

Mechanical Properties Measured

The test program consisted primarily of Charpy impact tests performed in the transverse (TL) orientation to the rolling direction of the plates. This was the philosophy followed in the previous studies so that "worst case" or conservative data would be produced. Strength properties were a secondary consideration and were not measured for all conditions of testing. All tension and Charpy impact tests were performed in accordance with ASTM Specification E370. The impact specimens were standard size. The tension test specimens had a diameter was 6.4 mm and a gage length of 25.4 mm.

Strain Aging Study

The strain aging study was performed by tensile prestraining of bars 70 mm wide 13 mm thick and 457 mm long. This prestraining specimen is seen in figure 1. The bar was cut from approximately the quarter thickness position of the plate. Prestraining was done in a universal testing machine using scribe marks on the bar surface to control strain. The uniform strain gage length was 241 mm and approximately 16 standard Charpy V-notch specimens were prepared for each condition of test. Specimens were both strained and tested in the TL orientation. The conditions tested are given below.

1. As received.
2. Stress relieved 2 hr at 620C.
3. Stress relieved 10 hr at 620C.
4. Plastically strained 5%.
5. Strained and aged at 370C for 10 hr.
6. Strained, aged and stress relieved 2 hr at 620C.
7. Strained, aged and stress relieved 10 hr at 620C.

Weld Heat Affected Zone Study

The heat affected zone study utilized weldments made on full thickness base metal using the flux cored arc process with varying weld heat inputs. The weld preparation was a single bevel on one side of the groove so that, after welding, a straight heat affected zone was produced on the unbevelled side of the joint. The joint preparation using and specimen locations are shown in figure 2. The shielding gas used was CO2. A multipass weld was deposited in the groove at a sufficient angle, usually 30 degrees, to the surface of the plate to produce good sidewall fusion of the unbevelled side. There was a 4 mm root gap and a backing plate was used to provide good root fusion. The variations in heat input were produced by changing arc amperage and travel speed. Wire diameters of 1.6 mm were used for heat inputs up to 2.0 KJ/mm. For higher heat inputs, wire diameters of 2.4 mm were used. One weld, at 4.0 KJ/mm, was made with the submerged arc process using an AWS 5.23 EM2 electrode.

The Charpy impact specimens for testing were taken from the quarter thickness positions in the plate in the coarse grained heat affected zone as shown in figure 2 and were notched within one mm of the fusion line. The plates were welded such that the specimens were in the TL orientation to the plate rolling direction. The specimens were etched prior to notching so as to locate the notch as precisely as possible.

Early tests made from plates welded with the relatively lower toughness AWS 5.20 70T-1 weld metal showed lower HAZ toughness values than expected and substantial test data scatter. Individual specimens were metallographically studied to determine if the fracture patch had incorporated a large amount of weld metal. In some cases this was true, but for many specimens, it was not. Additional tests made with the higher toughness AWS 5.29 E91 T1-K2 weld metal and using more accurate notch placement reduced the test scatter to some degree but by no means eliminated it. Moreover, the HAZ test results were not significantly changed. Eventually it was concluded that more scatter than normally encountered is a characteristic of this steel.

Stress Relief Cracking Study

The stress relief cracking study performed on the A710 steel used a modified Lehigh restraint specimen. This specimen is seen in figure 3. The specimen has an open slot in which the weld is made such that one end of the weld is free to contract transversely on solidification and subsequent cooling while the other is constrained by the width of the plate. The weld is deposited in the machined groove above the slot such that it does not penetrate through the land, leaving a notch in the root area. This root notch, in conjunction with the transverse constraint in the specimen, produces cracking in the weld heat affected zone in susceptible materials. Welding is from the open end toward the restrained (keyhole) end.

After welding, the specimen is given the stress relief treatments desired by charging in a preheated furnace and is cut transverse to the weld along a line 25 mm from the center of the keyhole, i.e., at the highly restrained end. The section is polished and etched to reveal the size and location of cracks. This test can also be used to reveal hydrogen induced cold cracking but A710 is very resistant to this phenomenon. The height of the crack at the 25 mm location is used as a measure of cracking potential. Tests show that the crack is highest at the 25 mm location and decreases toward the less restrained end. Thus the 25 mm crack height is a good parameter to characterize the cracking behavior.

Welding in this part of the study was done using an AWS E110 T5-K4 flux cored electrode with CO2 shielding at a heat input of 2 KJ/mm. This electrode overmatched plate strength and increased cracking potential. To study weld metal strength effects, a heat input of the test conditions was also made at the same heat input with the shielded metal arc process and a lower strength E8018-C1 electrode.

Metallography

Light microscopy was used to examine all of the stress relief cracking samples for determination of crack height. Many of the heat affected zone samples were examined by light and scanning electron microscopy for microstructure identification.

RESULTS AND DISCUSSION

Base and Weld Metal Properties

The data of table 1 illustrate the excellent combination of strength and toughness that the A710 Grade A Class 3 material can provide and also the influence of stress relief (post weld heat treatments) on its properties. For the material used in this investigation, strength properties were well above the minimums required and treatments at 620C for up to 10 hours did not decrease them below this level. Similarly, both weld metals met the minimum strength requirements for the base metal as welded. Based on the response of weld metal 1, they would be expected to do so for treatments of up to 8 hours at 620C.

The biggest disparity between the base and weld metals is in toughness. The base metal has a very low transition temperature, -145C, and maintains it after stress relief treatments of up to 10 hours at 620C. Weld metal 1, a typical structural weld filler metal, has a transition temperature over 150C higher than the base metal and weld metal 2, which would normally be considered a filler of good toughness, has a transition temperature 87C higher. This is not attributable to any deficiency on the part of these fillers but rather the unusually low transition temperature of the A710 Grade A Class 3 plate. The strength and toughness of the weld deposit is somewhat dependent on the heat input used in welding and table 3 shows that high heat inputs can increase the transition temperature of weld metal 2 by as much as 40C.

Strain Aging Study

The results of the study of the effects of straining, aging and stress relief are shown in table 2 and figure 4. As noted before, stress relief treatments alone have little effect, resulting in small decreases in transition temperature. Plastic strain of 5%, with or without aging at 370C, produces a 32C increase in transition temperature. About half of this is recovered by stress relief treatments at 620C. The increase in transition temperature on straining is similar to the 25C observed in most other microalloyed steels. The residual shift after stress relief is reduced to about 15C. In the light of its initially good toughness, strain aging must be considered a minor effect for this steel.

Welding Heat Affected Zone Study

Weld heat affected zones in A710 material studied here have a clear tendency to lower toughness than the original plate, as is evident from the data of table 3 and figure 5. An upward shift in transition temperature is evident even at low heat inputs, where it might be expected to be minimal, and increases with increasing heat input. The minimum transition temperature shift observed in as-welded material is 67C and the maximum is 112C. These shifts are substantial, exceeding those observed in other microalloyed steels, where they were typically no more than 30 to 40C and often much less[1].

To provide a comparison to this work, table 4 is a listing of weldment data taken from the open literature and private sources for both A710 Grade 1, Classes 2 and 3 and HSLA-80, a version of this material of interest to the U.S. Navy. The A710 studies listed on table 4 show a similar, but smaller, shift in HAZ transition temperature on welding. They also appear to show a dependence of the transition temperature on heat input, as noted in the current work, and on plate thickness. These points are illustrated in figure 6 where the extent of the shift decreases with increasing plate thickness and increases with increasing heat input. The studies on HSLA-80 listed in table 4 do not show such a dependence. The shifts, which range from 11C to 44C, appear definite but fairly random, averaging about 28C.

If the transition temperature shifts are a direct result of the effect of welding heat on the base metal, a dependence on heat input might be expected. Indeed, a study of simulated heat affected zones in HSLA-80[7] has shown just such an effect and the data from the study are listed in table 5. Transition temperature shifts observed ranged from 50C to 114C for heat inputs of 1 to 4 KJ/mm, about the range in the current work. The authors of the study attributed these shifts to a change in microstructure with increasing heat input from fine packet martensite to coarse bainite. These observations were supported with microhardness measurements.

In the current work, a coarsening in microstructure was observed with increasing heat input but hardness changed little and in all cases corresponded with the range for higher heat input welds in the HSLA-80 study, about 250 VHN. In the low heat input heat affected zones in the A710 work reported here, the structure appeared to be acicular ferrite. In the higher heat input welds the structure was bainite. Grain size increases in the heat affected zone alone can account for some of the transition temperature increases, but changes in fine structure unit sizes, reported in the HSLA-80 work, must also play a role. This is a subject of continuing study at Lehigh University.

The effects of post weld heat treatment on the toughness of the weld heat affected zones are also shown in table 3 and figure 5. Post weld heat treatment at 620C for 10 hours results in a modest benefit in toughness in two out of three conditions studied but short time treatments increase transition temperature. This mixed effect has been observed in some other microalloyed steels [5,8] and is undoubtedly a result of coarsening and precipitation processes that occur during the post weld heat treatment. Preliminary microstructure studies on the A710 heat affected zone samples show that the microstructure coarsens by what appears to be a recovery process after 2 hours at 620C, but new grain boundaries resulting in a finer structure appear after 10 hours. These observations do not include TEM studies of precipitate behavior and thus must be considered incomplete.

Stress Relief Cracking Studies

The results of stress relief cracking tests using the modified Lehigh restraint specimen are listed in table 6 and shown in figure 7. The potential for reheat cracking in this steel has been reported previously[9] and this work confirms the effect. The temperature range of cracking extends from about 500C to over 600C and can occur for times as short as 15 minutes. Some of the cracking reported for the higher temperature treatments may have occurred during heating of the specimen to the temperature of the heat treatment furnace. Complete cracking in the test corresponds to crack heights of about 2.5 mm and thus some of the cracks reported here are substantial.

A large number of stress relief or reheat cracking tests were performed at Lehigh University in the 1960's on low alloy quenched and tempered steels using a similar specimen[10]. In comparing the results seen in figure 7 with the previous work, the A710 appears to be neither the least nor most sensitive material Lehigh has tested. It is more sensitive to cracking than A517J steel for which little cracking was reported in service but less than A517F, which was reported to have a high cracking sensitivity. Potential for reheat cracking was found to exist in a number of low alloy steels, especially those with precipitation processes occurring in their weld heat affected zones during post weld heat treatment. For most of the steels, post weld heat treatment could still be applied successfully if proper attention was given to control of weld discontinuities. For the more sensitive steels, it was recommended that they should be used in the as-welded condition, with post weld heat treatment to be applied only after careful consideration of all the factors involved. Since A710 steel relied on precipitation processes for most of its strength, it is perhaps not surprising that it is also susceptible to reheat cracking.

EVALUATION AND SUMMARY

The studies performed on A710 Grade Class 3 steel show it to be a material of high strength and very high toughness. Fabrication operations, both straining (with or without aging) and welding (with or without post weld heat treatment), will result in an upward shift in transition temperature. This will be small after straining and aging, but can be substantial after welding. However, the increase in transition temperature on welding must be placed in the context of the use of the steel. With an initial transition temperature of -145C, an increase of 110C in the heat affected zone from high heat input welding, 5.3 KJ/mm, still results in a transition temperature of -33C. For most structural applications, this is well below what would be required. Moreover, it is also well below that of the relatively tough weld metal from the same weldment, which was -18C.

Lower heat input welding, for example 2 KJ/mm, results in heat affected zone transition temperatures around -80C and weld metal transition temperatures close to -60C, a level superior to most other structural materials at this or any strength level. Welding at 4 KJ/mm, a common industry practice, results in a heat affected zone transition temperature of -55C, which is still a very satisfactory level. Thus the loss in transition temperature on welding, while substantial, may not be so significant.

The effects of post weld heat treatment on the A710 studied here suggest that the material can best be used in the as-welded condition. Post weld heat treatment must be applied for relatively long times to have any beneficial effects on heat affected zone toughness, and even then, improvement is modest. In addition, potential for stress relief cracking exists, and this may preclude post weld heat treatment for joints whose design might promote cracking, such as those incorporating partial penetration welds. Because of the high toughness of the steel, its low tendency for hydrogen induced cold cracking and its moderate heat affected zone hardness at normal heat inputs, many of the reasons for post weld heat treatment are obviated. Thus post weld heat treatment may not be necessary in most cases and is not desirable from the metallurgical viewpoint.

ACKNOWLEDGEMENT

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LIST OF TABLES

LIST OF FIGURES

Table 1. Composition and Mechanical Properties of the A710 Grade A Class 3 Plate and Weld Metals Used in the Weldment Study

A. Chemical Composition (Wt %)

Material	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V	Nb
A710 Plate	.05	.53	.008	.003	.24	.98	.72	.21	1.13	.027		.008
Weld Metal 1	.07	1.45	–	–	.48	–	–	–	–	–		
Weld Metal 2	.06	1.13	.006	.011	.37	1.78	.03	.02	.02	–	.02	

B. Mechanical Properties

Material and Heat Treatment	Yield Str. MPa	Tensile Str. MPa	Elong. %	Red. of Area %	47 J Trans. Temp. C
A710 Plate	602	673	29.9	78.3	-145
SR 2hr 620C	573	640	29.9	79.4	-147
SR 10hr 620C	542	610	30.0	78.5	-148
(ASTM Spec.)	515	585	20	–	–
Weld Metal 1[1]	535	615	26	–	+8
SR 8hr 620C	515	609	26	–	–
Weld Metal [2]	595	665	23	–	-58

1. As welded, flux cored electrode, AWS 5.20 E70 T1, typical composition and properties. Transition temperature measured as welded at 2 KJ/mm.

2. As welded, flux cored electrode, AWS 5.29 E91 T1-K2, typical properties. Transition temperature measured as welded at 1.8 KJ/mm.

Table 2. Results of the Strain Aging Study on A710 Grade A Class 3 Plate

Condition	47J Transition Temperature, C	Shift in Transition Temperature, C
As received plate	-145	–
Stress relieved 2hr 620C	-147	-2
Stress relieved 10hr 620C	-148	-3
Prestrained		
As strained 5%	-113	32
Strained and aged 10hr 370C	-113	32
Strained, aged, stress relieved		
Stress relieved 2hr 620C	-131	14
Stress relieved 10hr 620C	-127	18

Table 3. Summarized Charpy Impact Test Results For Heat Affected Zone and Weld Metal Studies on A710 Grade A Class 3 Weldments

Material	Heat Input KJ/mm	Post Weld Heat Treat. 620C, hr	47 J Trans. Temp., C	Shift in Trans Temp[1], C
Base Plate	none	none	-145	none
	none	2	-147	-2
	none	10	-148	-3
Heat Affected Zone	1.8	none	-78	67
	1.8	2	-60	85
	1.8	10	-97	48
	2.0	none	-78	67
	2.0	2	-59	86
	2.0	10	-75	70
	4.0	none	-55	90
	4.0[2]	none	-55	90
	5.3	none	-33	112
	5.3	10	-44	101
Weld Metal 1	2.0	none	8	-
Weld Metal 2	1.8	none	-58	-
	5.3	none	-18	-

1. Shift from base metal without stress relief.

2. Test of SAW weld HAZ in same base plate.

Table 4. Shifts in Transition Temperature Between Plate and Heat Affected Zone for As-Welded A710 Grade A and HSLA-80 Steels.

Plate Type, Number and Thickness, mm	Welding Process	Heat input KJ/mm	Shift in Transition Temperature, C
A710 (1) 9.5	SAW	1.0	3
		2.0	24
		3.0	40
A710 (2) 19.1	FCAW	3.0	24
A710 (3) 19.1	SAW	2.0	27
		3.0	26
		4.9	85
A710 (4) 57.2	SMAW	1.8	16
		1.8	11
A710 (5) 63.5	SAW	3.0	10
		4.9	34
HSLA-80 (1) 15.8	SAW	1.3	27
	SMAW	1.7	25
	SMAW	3.3	26
	SAW	3.9	25
HSLA-80 (2) 15.8	GMAW	2.0	11
HSLA-80 (3) 19.1	SAW	1.2	42
	FCAW	1.2	29
	SMAW	1.8	44
	SMAW	3.9	26

Table 5. Shifts in Simulated Heat Affected Zone Transition Temperature for Various Heat Inputs in HSLA Steel[1].

Simulated Heat Input, KJ/mm	Cooling Time $T_{800-500}$, S	Hardness DPH	Shift[2] in Transition Temperature, C
1	5	316	-
2	11	288	50
3	25	275	87
4	45	247	114

1. From reference 7.

2. Basis for comparison is 1 KJ/mm heat input samples. Plate thickness not specified but estimated from cooling rates to be about 25 mm.

Table 6. Results of Stress Relief Cracking Tests Using the Modified Lehigh Restraint Specimen on A710 Grade A Class 3 Plate[1]

Post Weld Heat Treatment Conditions		Total Crack Height
Temperature, C	Duration, hr	mm
482	2	0.10
510	2	0.00
	10	1.02
537	2	0.51
565	2	0.00
593	2	0.00
	10	0.20
607	0.25	0.76
	2	0.51[2]
	2	1.27[3]

1. E110 T5-K4 flux cored filler metal used to overmatch the strength of the plate for most welds.

2. Lower strength E8018-C1 shielded metal arc electrode used.

3. Two cracks at weld root, one on each side.

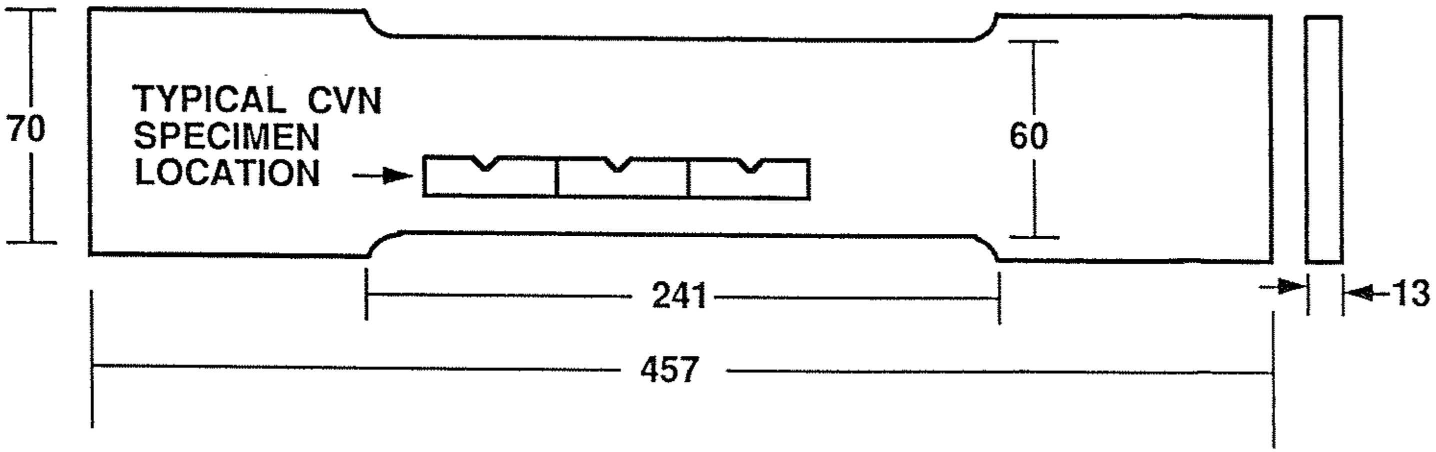

Figure 1. Specimen Configuration used in the Strain Aging Study.

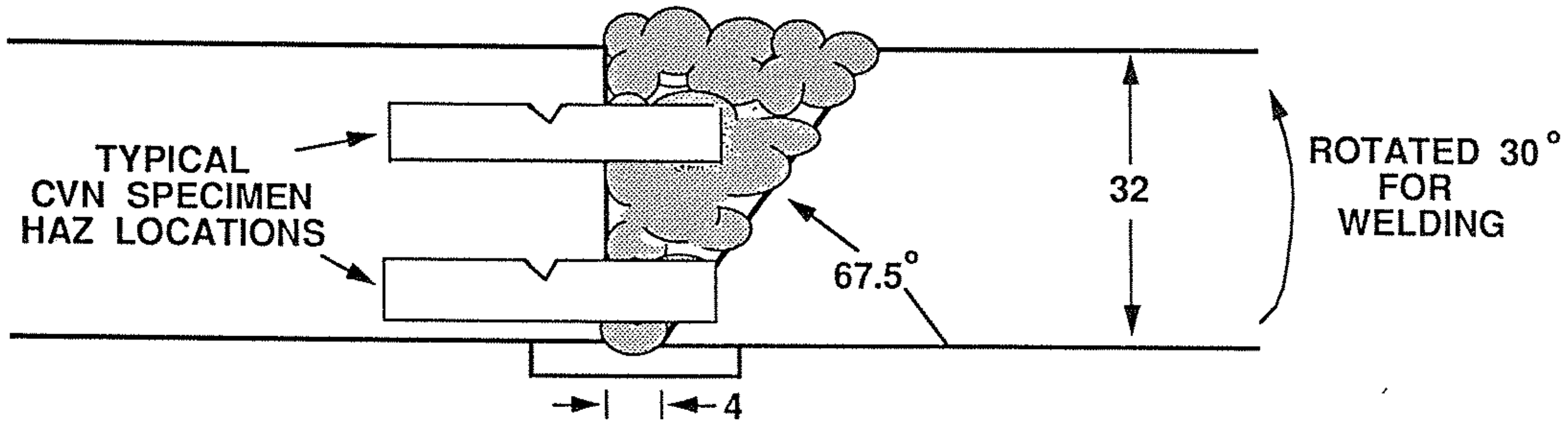

Figure 2. Weldment Configuration and Specimen Location for the Heat Affected Zone Study.

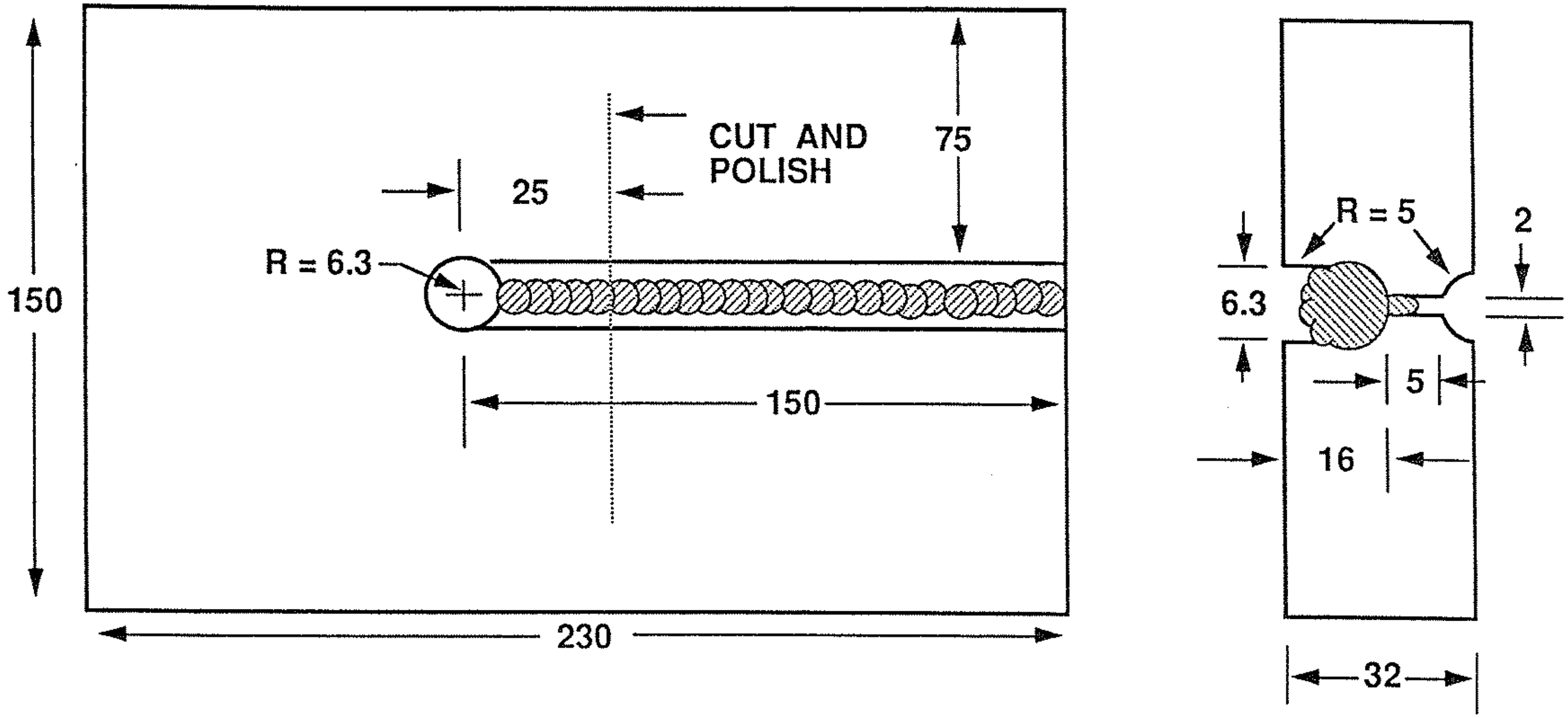

Figure 3. Modified Lehigh Restraint Specimen For Stress Relief Cracking Tests.

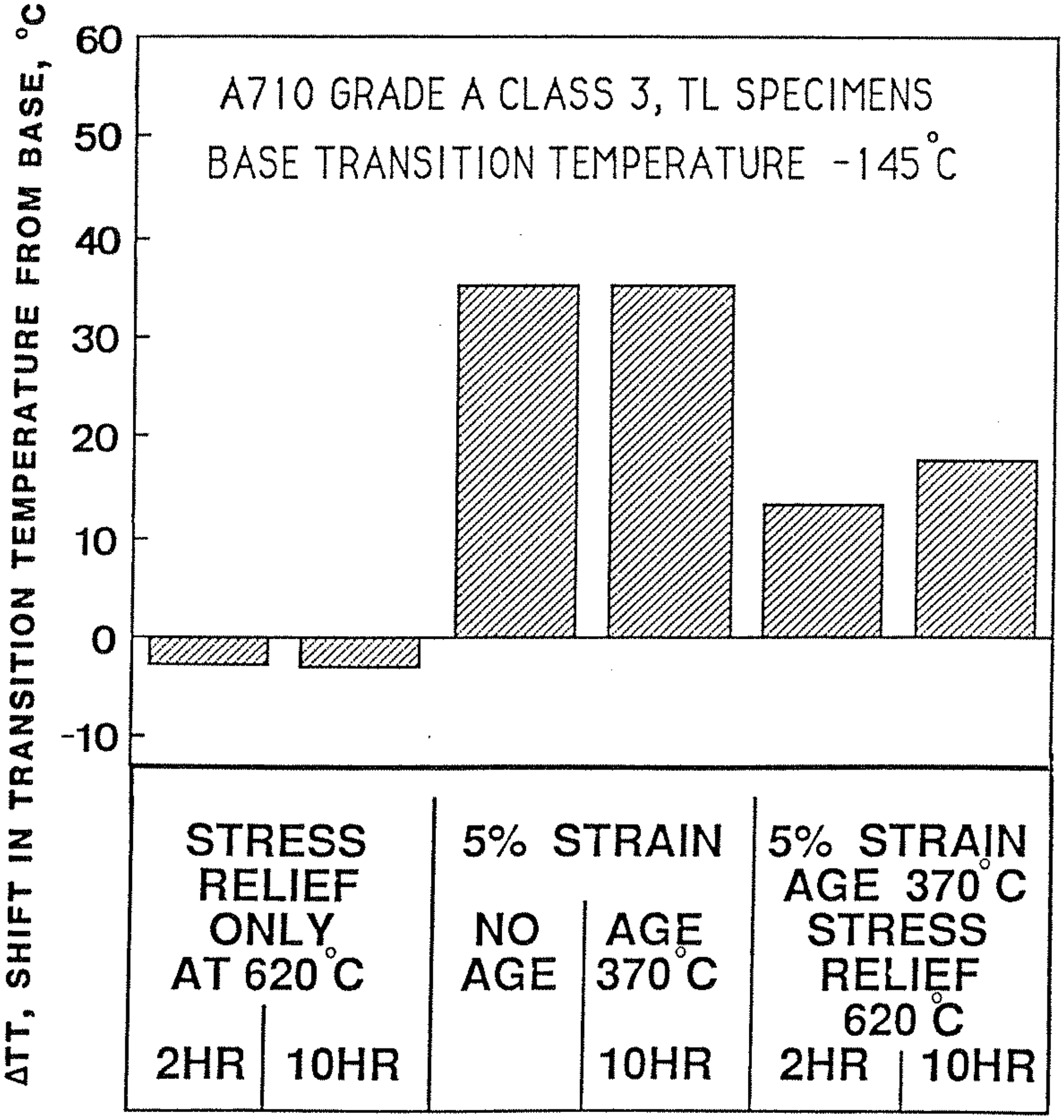

Figure 4. Results of Strain Aging Tests on A719 Grade A Class 3 Plate.

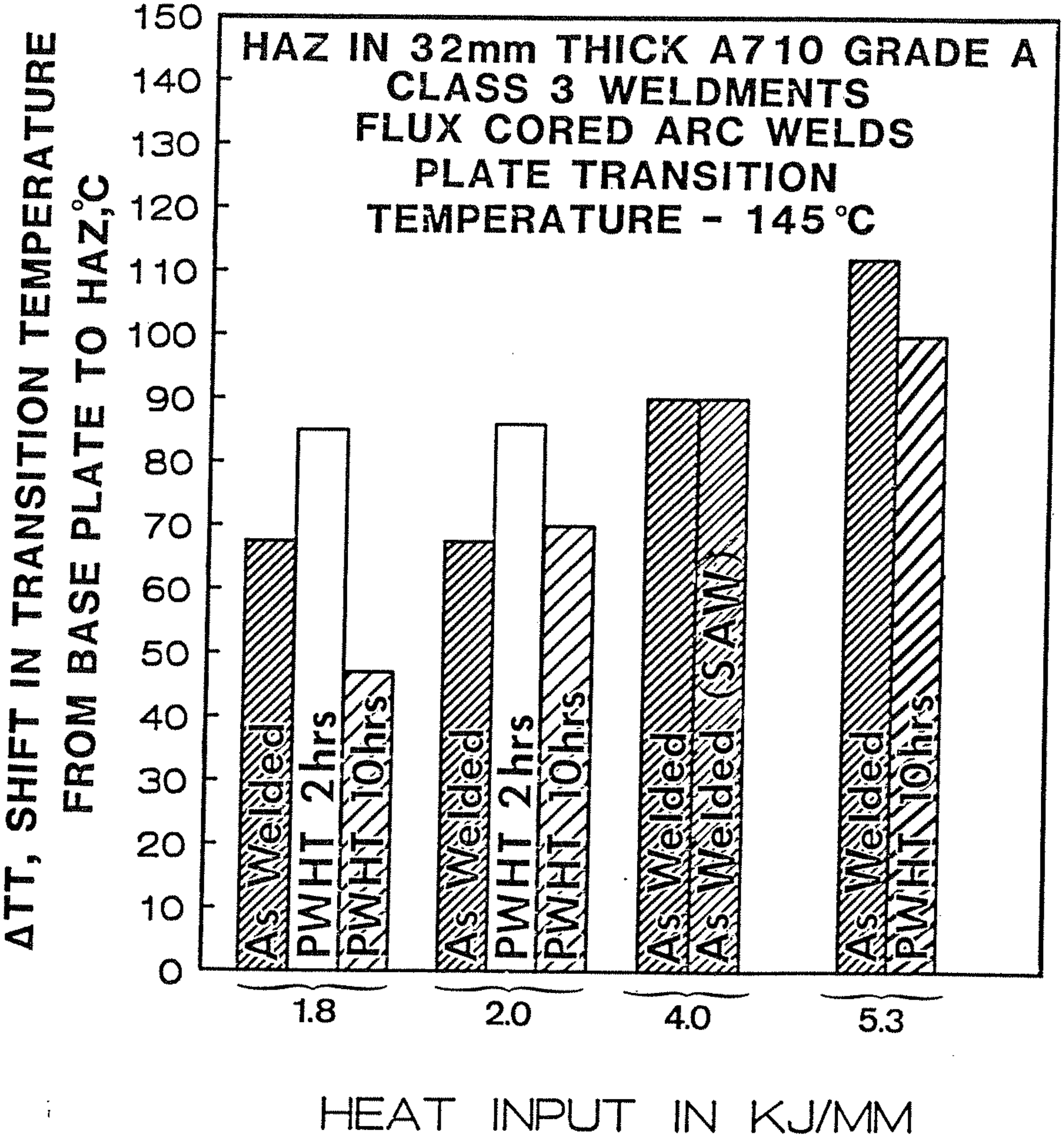

Figure 5. Results of the Heat Affected Zone Tests on A710 Grade A Class 3 Weldments.

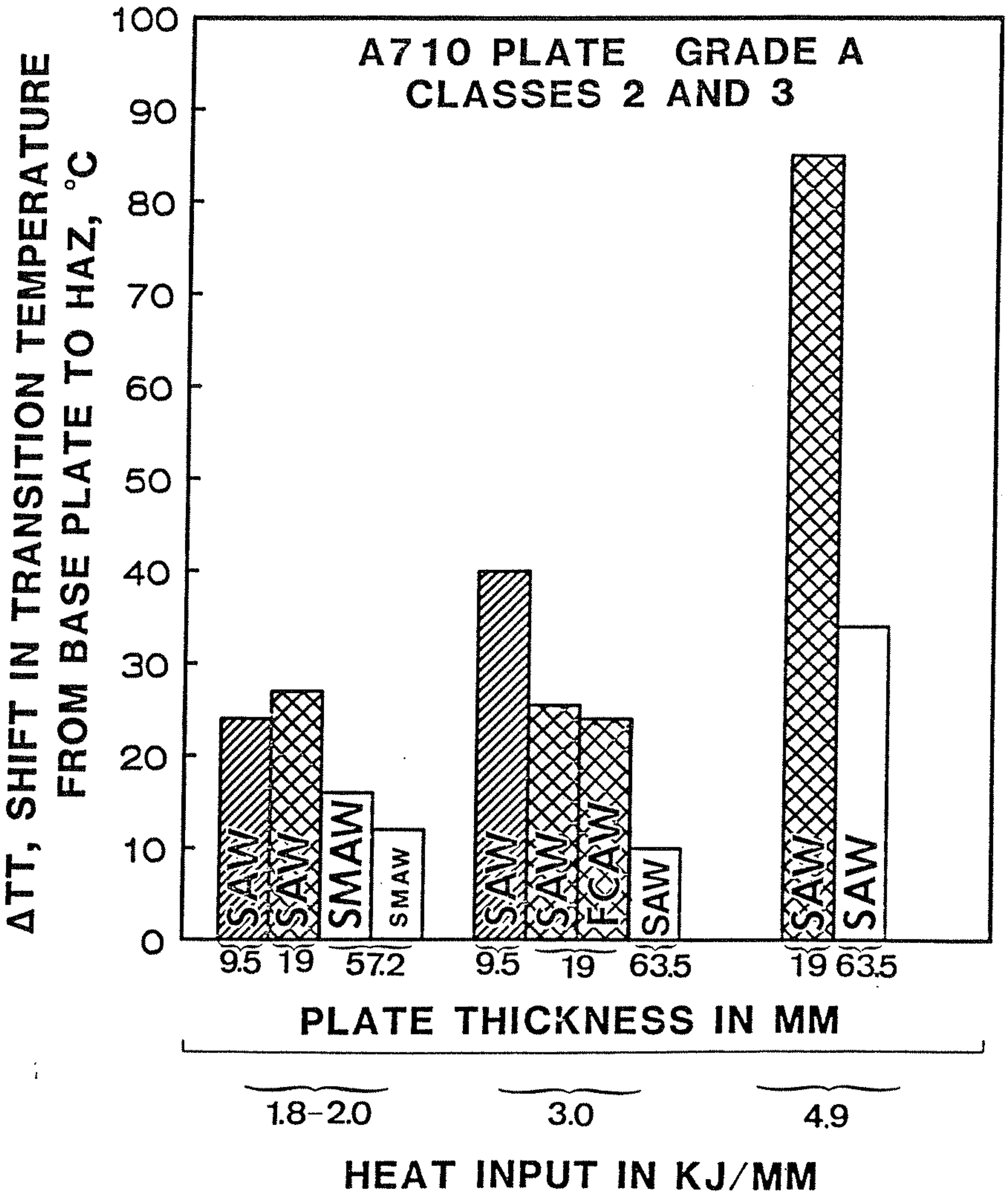

Figure 6. Literature Data on the Effect Heat Input and Plate Thickness on Heat Affected Zone Toughness in A710 Weldments.

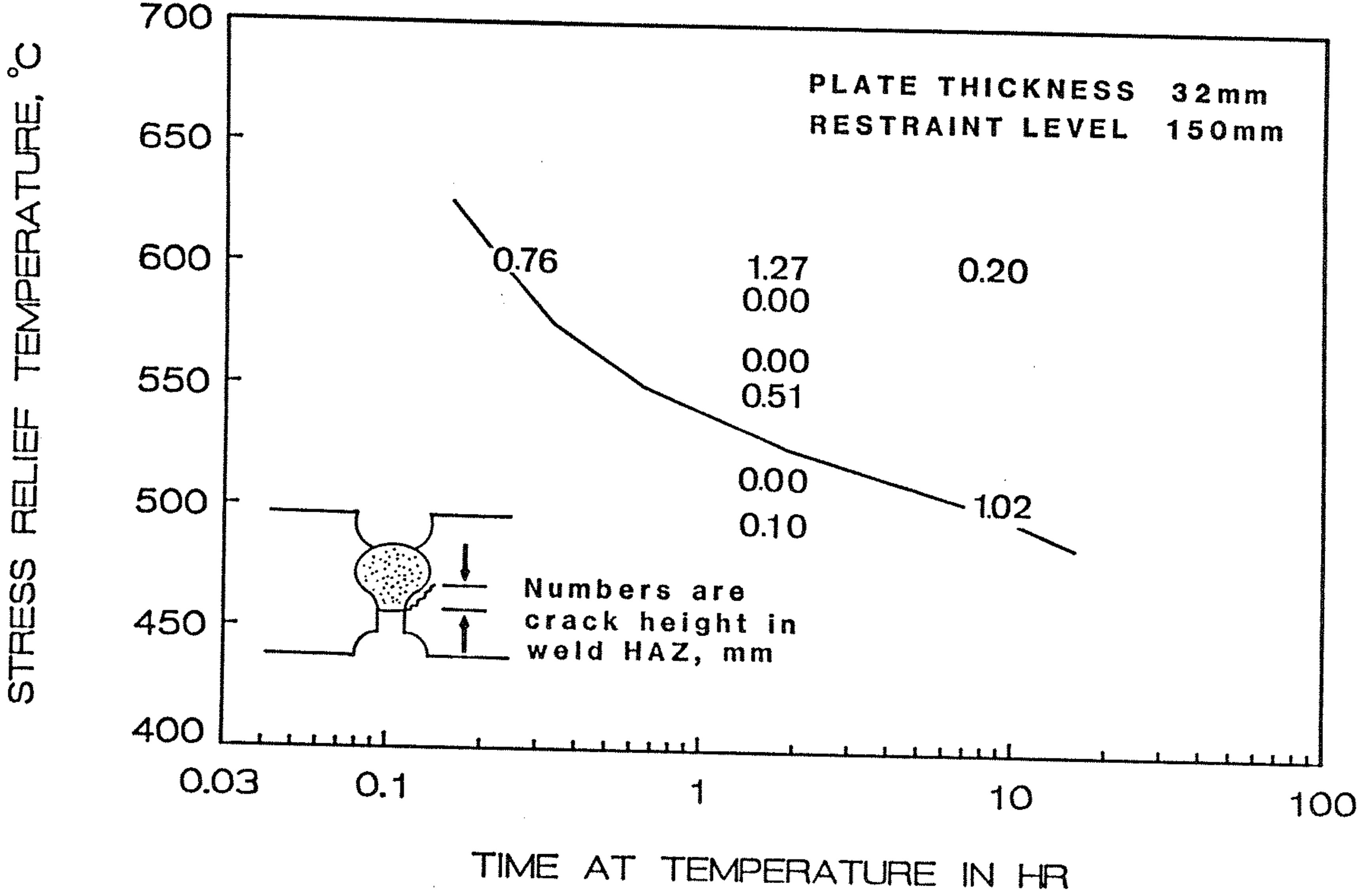

Figure 7. Results of Stress Relief Cracking Tests on A710 Grade A Class 3 Plate.