CONF-800316--2

A THERMO-MECHANICAL PROCESS FOR TREATMENT OF WELDS

MASTER

March 1980

R. K. Malik
EG&G Idaho, Inc.
P. O. Box 1625
Idaho Falls, ID 83415

Work performed under the auspices of the U. S. Department of Energy,
Contract No. DE-AC07-76ID01570

DISCLAIMER

A THERMO-MECHANICAL PROCESS

FOR TREATMENT OF WELDS[a]

ABSTRACT

Benefits from thermo-mechanical processing (TMP) of austenitic stainless steel weldments, analogous to hot isostatic pressing (HIP) of castings, most likely result from compressive plastic deformation, enhanced diffusion, and/or increased dislocation density. TMP improves ultrasonic inspectability of austenitic stainless steel welds owing to (a) conversion of cast dendrites into equiaxed austenitic grains, (b) reduction in size and number of stringers and inclusions, and (c) reduction of delta ferrite content. TMP induces structural homogenization and healing of void-type defects and thus contributes to an increase in elongation, impact strength, and fracture toughness as well as a significant reduction in data scatter for these properties. An optimum temperature for TMP or HIP of welds is one which causes negligible grain growth and an acceptable reduction in yield strength, and permits healing of porosity.

---

a. U. S. and foreign patents applied for by USDOE.

A THERMO-MECHANICAL PROCESS

FOR TREATMENT OF WELDS

Methods of minimizing weld defects in major energy coversion systems, such as nuclear reactors, coal-gasification and fossil-fuel plants, or magnetohydrodynamic generators are continually being sought to increase system reliability and safety and reduce mechanical property variation. Inhomogeneities, defects such as microporosity, cold laps, microfissures, and hot cracks, and difficult ultrasonic inspectability are of great concern.

A method of rectifying these problems is to subject completed welds to a thermo-mechanical treatment. This treatment, based on the concept of hot isostatic processing (HIP), uses elevated temperature and isostatic inert-gas pressure within an autoclave.[1] This process is ideal in that its application causes only negligible dimensional change or material migration, depending upon type of defects. Application of HIP for defect elimination in castings of aluminum,[2] superalloys,[3,4] titanium alloys,[3] and an 18%-nickel maraging steel[5] was positive and resulted in a marked decrease in mechanical property variation as well as an increase in stress rupture, elongation, and fatigue properties. In fact, HIP of castings having no defects detectable by nondestructive examination (NDE) methods resulted in noticeable property improvements.[1]

The collapse and healing of void-type defects as well as increased homogeneity are due to one or more of the following mechanisms:[1]

1. Creep

2. Compressive plastic deformation

3. Diffusion bonding of void surfaces

4. Vacancy diffusion from pore surfaces to grain boundaries

5. Dislocation density increases.

Application of TMP to Type 304/308 stainless steel welds should be equally positive since these weldments have fusion zones containing cast dendritic structures.

Because HIP noticeably reduces yield strength, methods to reverse or reduce this effect were studied. Recommendations include lower processing temperatures and additions of nitrogen and/or columbium.

A related problem concerns weld inspectability by ultrasonic techniques. As a part of the present effort, ultrasonic amplitude attenuation studies were conducted before and after HIP, to evaluate its effects in this respect.

2. PROCEDURE

Both plate and pipe welds of Type 304 austenitic stainless steel were selected because of their extensive application in nuclear reactors and other major energy production systems. Plate specimens were 2.5 cm thick and pipe specimens had an outer diameter (OD) of 14 cm and wall thickness (WT) of 1.9 cm. Type 308 filler wire was either 0.3 or 0.8 cm in diameter. Double V-grooves with 75-degree bevels were used for both sound and defective welds (Figure 1). All specimens were gas tungsten arc (GTA) welded. A few plate or pipe welds having 10 to 15% intentional porosity were prepared by using moisture, oily surfaces, or inadequate purging with argon. Surface porosity, as detected by either visual or liquid penetrant examinations, was sealed by GTA welding. All welds were X-rayed.

Fig. 1 Macrostructure (3.5X) of GTA-welded Type 304/308 plate, 2.5 cm (1.0 in.) thick, showing the double V-joint with 75 degree bevel and the layers and directions of grain growth in the filler metal during solidification.

A few test bars from either welded plate or welded pipe specimens were heat treated (HT) in argon at 1310 K (1900°F) for 3 h or at 1365 K (2000°F) for 1 h. One-third of the weldments were retained in the as-welded condition, whereas the remaining two-thirds were HIPed in an autoclave having a hot zone of 18 cm diameter and 46 cm length. HIP parameters were (a) temperatures of 1230 to 1365 K (1750-2000°F), (b) exposure times of 1 to 3 h, and (c) argon gas pressure of 105 MPa (15 ksi).

Welds and base metal were evaluated both before and after HIP by NDE techniques (radiography, liquid penetrant, and limited ultrasonic C-scans), chemical and metallographic analyses, and measurements of delta ferrite content and mechanical properties (tensile, charpy V-notch, and instrumented drop-weight impact). Tensile tests were conducted at both room temperature (RT) and 590 K (600°F), while other tests were conducted only at RT. In addition, limited evaluation was conducted of heat-treated welds by using metallographic analyses and tensile tests.

3. RESULTS

Data showed that HIPed welds had improved structure, inspectability, and mechanical properties.

3.1 Structural Changes

a) Cold-lap or void-type defects were healed by HIP but not by HT (Figures 2 and 3).

b) Cast dendritic structures of the fusion zone were converted into equiaxed austenitic grains by HIP, resulting in homogenization. This conversion was not seen after HT (Figures 2 and 3).

c) There was a reduction in size and number of stringers and inclusions after HIP but not after HT (Figure 4), possibly owing to breaking up and increased solubility of carbides, nitrides, or other intermetallic phases.

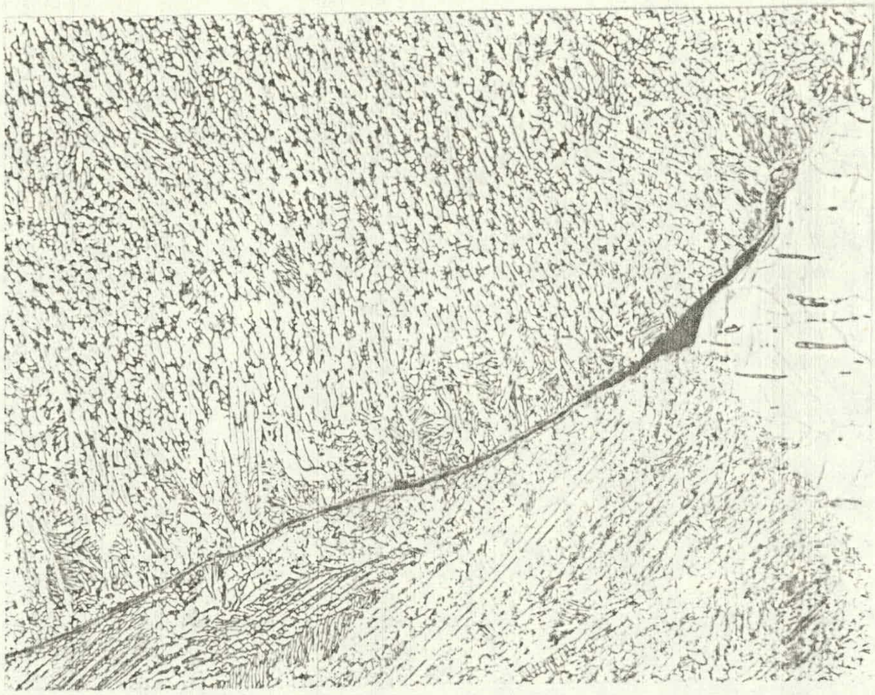
d) Most of the delta ferrite was transformed into austenite, resulting in a decrease in the average ferrite number (FN) from 12.3 to 1.7 after HIP, the average FN for HT welds was 11.1. Decreased ferrite content generally increases ductility and creep life, reduces tensile yield or ultimate strength and improves impact strength of austenitic stainless steels, and their weldments.[6]

e) HIP at 1310 to 1365 K (1900-2000°F) for 1 h caused grain growth in pipes from ASTM size 5 to 3, and in plates from ASTM size 5 to 2; after HIP at 1255 K (1800°F) for 3 h, there was negligible grain growth (Table 1).

f) HIP caused a reduction in the average microhardness values of welds from 220 to 128 DPN (diamond pyramid number) and for the base metal from 191 to 125 DPN, respectively (Table 1).

3.2 Ultrasonic Response

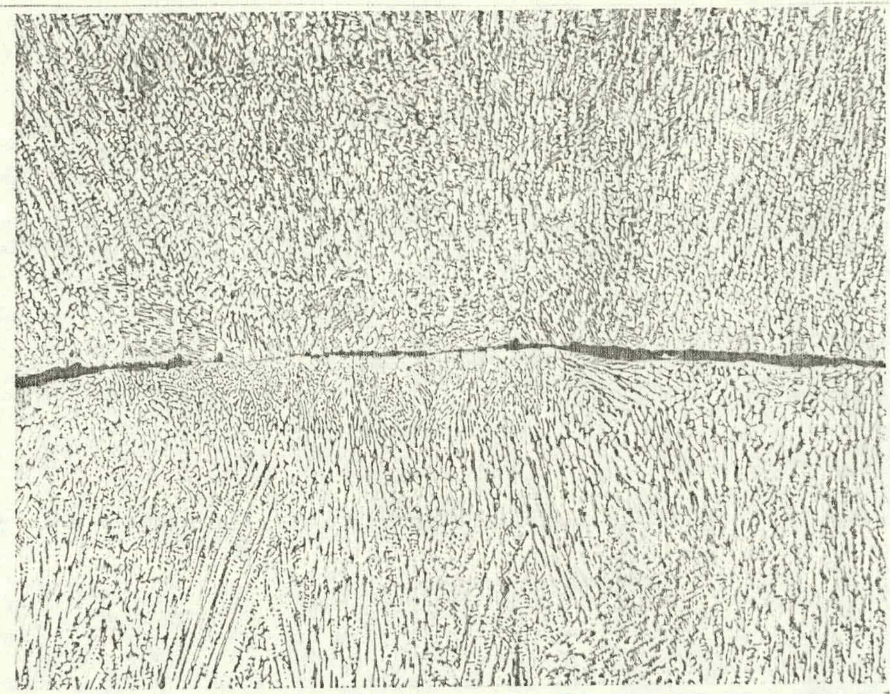
Ultrasonic beam attenuation and/or scatter in welds are due to variations in composition, solidification patterns, and micro and macrostructures



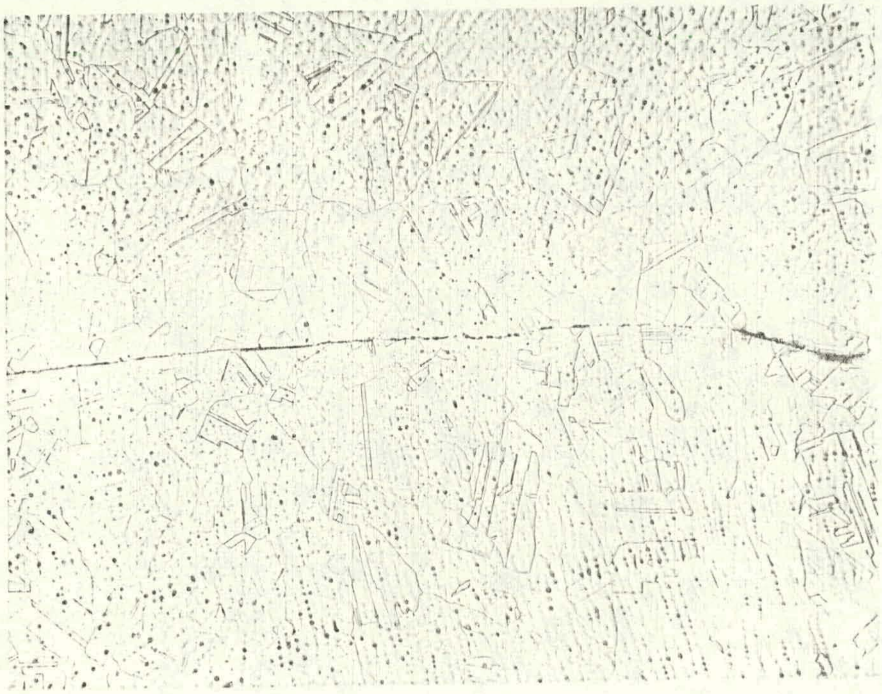
(A) Dendritic structure and a defect (cold lap) in the fusion zone. The heat affected zone shows austenite (γ) grains, annealing twins and stringers of ferrite, carbides and other inclusions.

(B) The transformed equiaxed austenitic grain structure shows short dark streaks of the transformed ferrite and stringers of inclusions, carbides, etc. in the fusion zone. The HAZ shows γ grains, annealing twins and stringers.

Fig. 2 Microstructures (100X) of Type 304/308 GTA welds A) in the as-welded condition, and B) after HIP, showing healing of the cold lap defect.

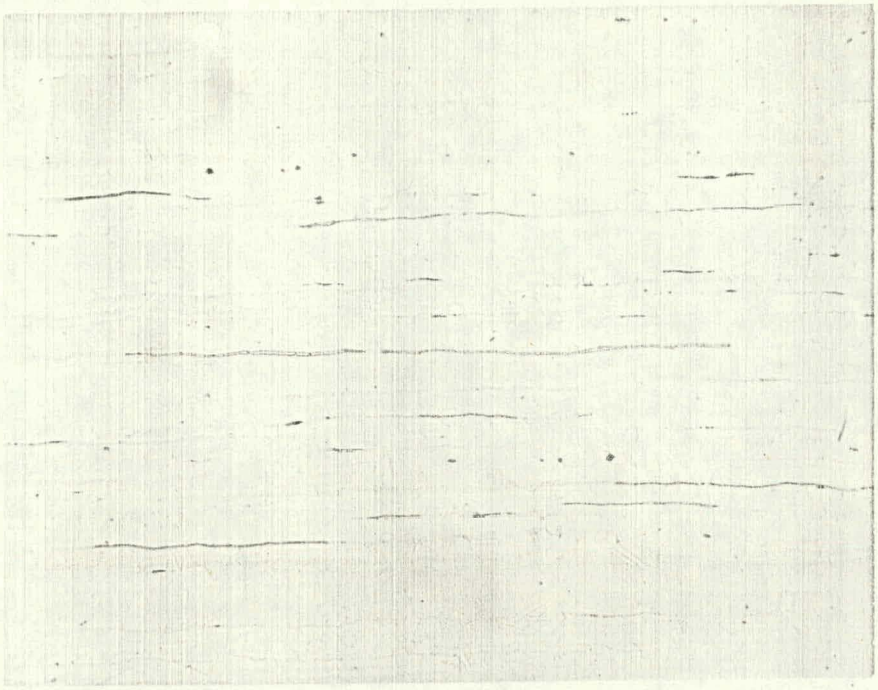


(A) As-welded dendritic cast structure and cold lap.

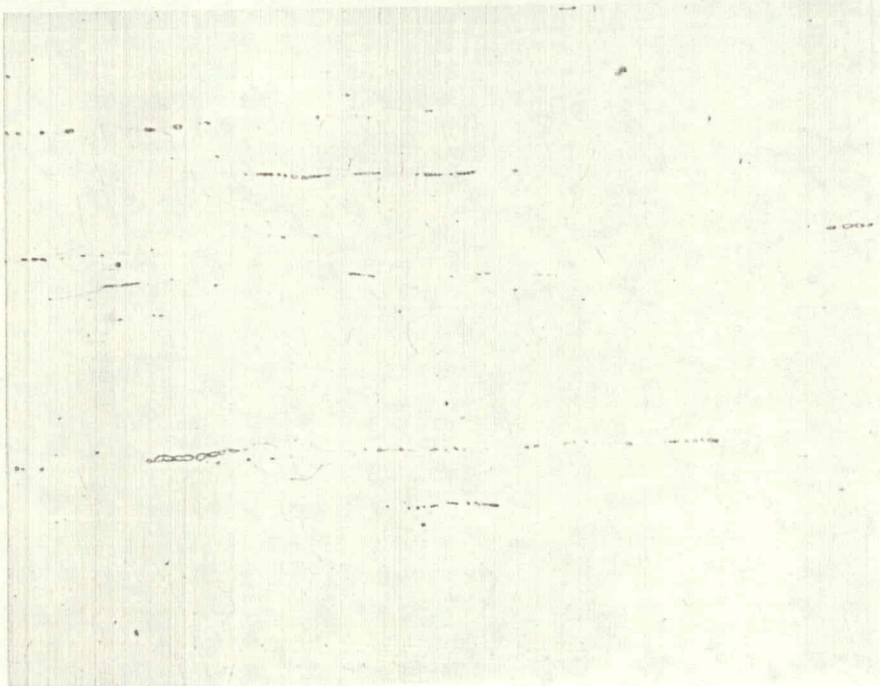


(B) After HT at 1365 K (2000°F) - 3 h. Transformed austenitic grains, annealing twins, and streaks of delta-ferrite. Cold lap not eliminated.

Fig. 3 Microstructures (100X) in the fusion zone of Type 304/308 GTA welds, before and after heat treatment (HT). The cold lap could not be healed by HT.



(A) As received



(B) After HIP at 1310 K (1900°F) - 3 h -105 MPa (15 ksi).

Fig. 4 Microstructure of Type 304 stainless steel, before and after HIP. (100X).

TABLE 1. GRAIN SIZE AND MICROHARDNESS VALUES FOR TYPE 304 STAINLESS STEEL AND TYPE 304/308 GTA WELDS

Condition	ASTM Grain Size of Type 304 Base Metal	Average Microhardness (Diamond Pyramid No.)		
		Base Metal	HAZ	Fusion Zone
As-welded	5	191	225	220
HIP*	3 (pipe) & 2 (plate)	123-128	123-130	124-13
HT*	4 (pipe)	137-152	135-153	143-14

*HIP or HT in the temperature range of 1310-1365 K (1900-2000°F) for 1 to 3 h and isostatic gas pressure of 105 MPa (15 ksi) for HIP (no pressure for HT).

(including coarse-grained dendrites, two-phase structures, inclusions, and stringers).[7] The structural homogenization and healing of internal voids anddefects after HIP (Section 3.1) makes welds more transparent to ultrasound.

Preliminary data show that ultrasonic transmission in Type 304/308 welds and the base metal increased by 89 and 7%, respectively (Table 2), after HIP at 1255 K (1800°F). HIP at 1310 to 1365 K (1900-2000°F) produced an increase of 47% in ultrasonic transmission in the fusion zone but a decrease of 37% in ultrasonic transmission in the base metal (Figure 5). Overall there was a 25 to 30% reduction in amplitude variation between the base metal and fusion zone after HIP at 1310 to 1365 K (1900-2000°F). This more uniform response of HIPed welds should allow greater interrogative wave amplitudes for ultrasonic inspections and consequently an improved capacity for defect detection.

TABLE 2. ULTRASONIC SIGNAL FROM TYPE 304/308 WELD

Condition	Signal From Base Metal	Fusion Zone
As-Welded	250 mV	90 mV
HIP-1800	180 mV	170 mV

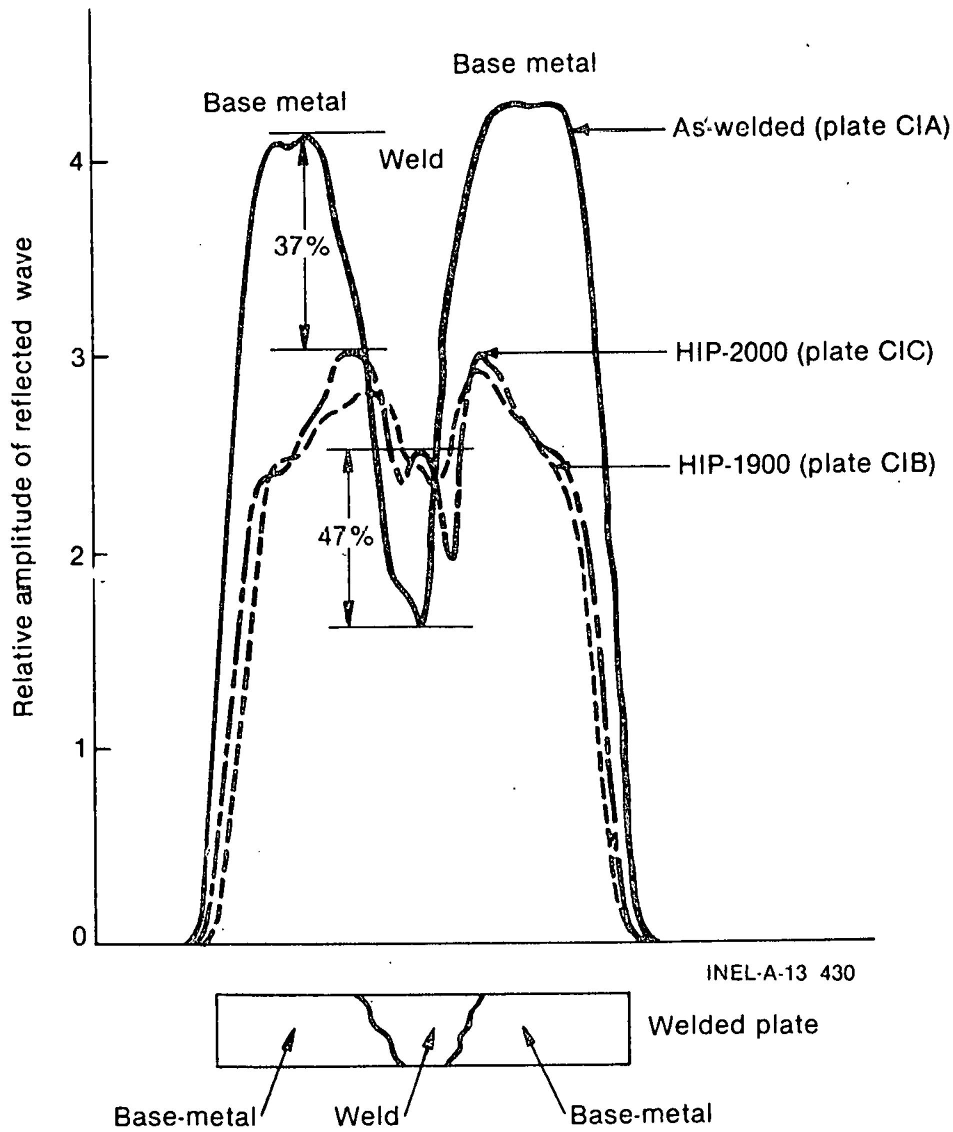


Fig. 5 Amplitude of the ultrasonic wave from Type 304/308 GTA weldments before and after HIP.

3.3 Tensile Properties

Effects of HIP or HT on tensile properties of welds are shown in Figures 6, 7, and 8.

3.3.1 Ductility Increases

Elongation increases owing to HIP of defective pipe or plate welds were 140 to 173% at RT and 233% at 590 K (600°) and of nondefective welds were 26 to 36% (Figures 6 and 7). The increased elongation, structure homogenization, and healing of void-type defects demonstrated the potential of HIP for weld repair. Elongation increase, especially near the ductility minimum temperature of 620 K (650°F) could minimize or eliminate strain-age cracking or weld embrittlement during service exposures around 620 K (650°F).

3.3.2 Ultimate Strength Changes

There was an increase of up to 10% in the RT ultimate strength of defective welds (Figures 6 and 7), but a decrease of up to 8% in the strength of sound welds (Figure 8).

3.3.3 Effects of HIP versus HT

Tensile properties of sound welds after HIP or HT (Figure 8) are summarized in Table 3. HIP produced with respect to HT:

- 17.5 to 21.5% greater ductility (elongation)
- up to 4.5% lower yield strength, and
- a reduction in tensile property variation

Improvements in tensile properties of defective welds are even more pronounced by HIP than by HT, as the former treatment can heal void-type defects such as cold laps (Figures 2 and 3).

3.3.4 Property Equivalence after HIP

Tensile properties of longitudinal welds and base metal after HIP at RT

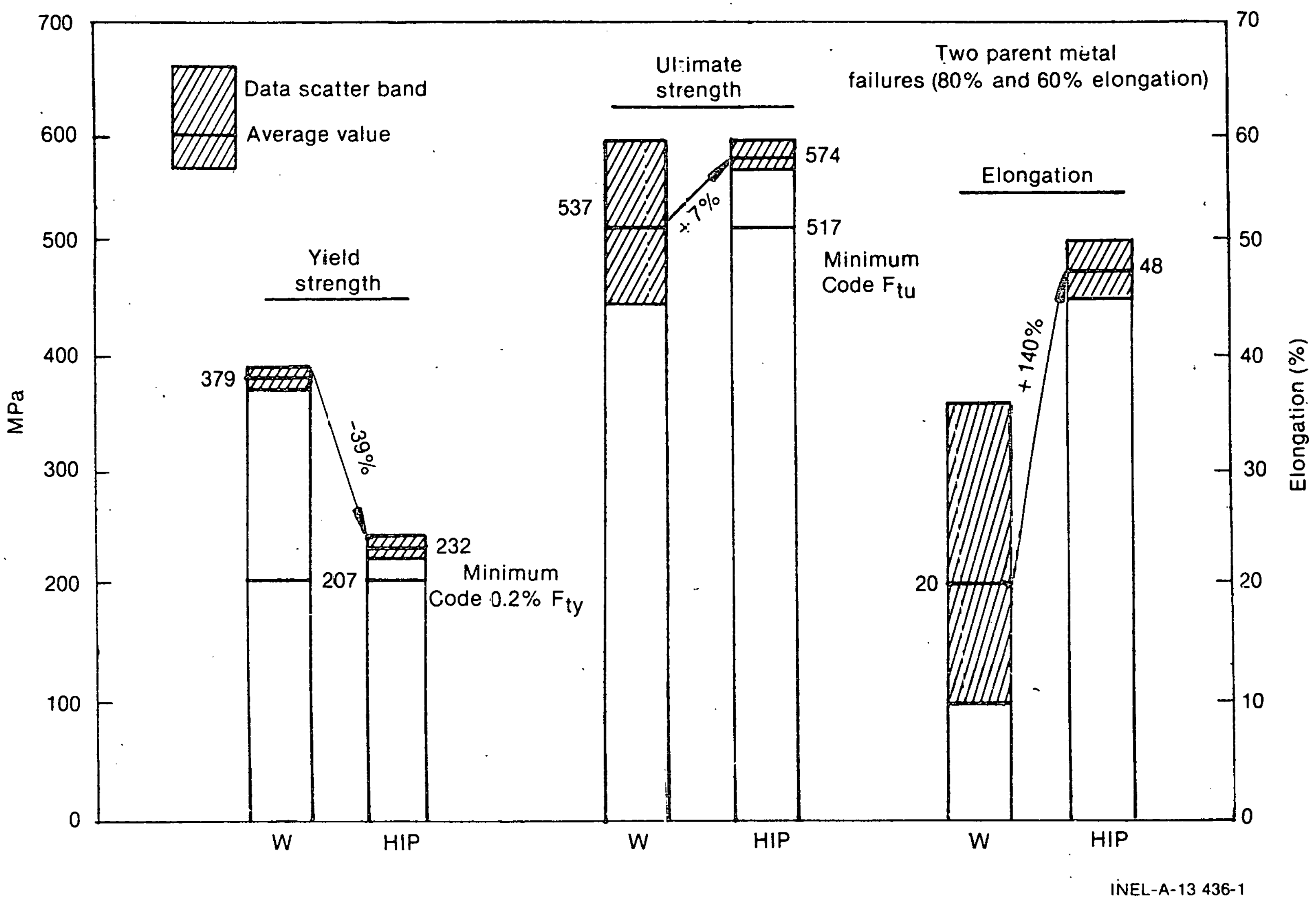


Fig. 6 Room temperature tensile test data for Type 304/308 GTA circumferential pipe welds (defective), before and after HIP.

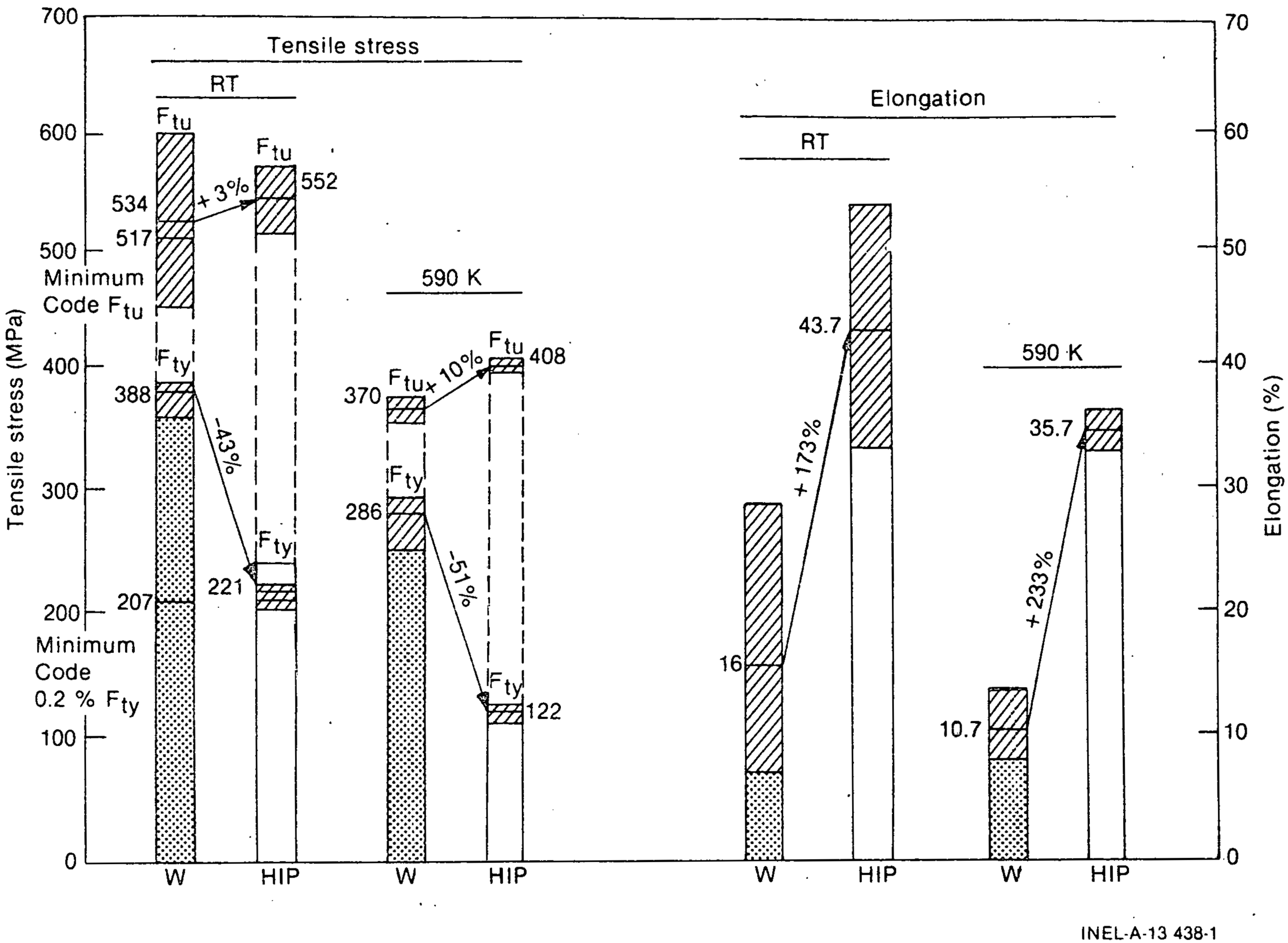


Fig. 7 Tensile properties of Type 304/308 GTA transverse plate welds, before and after HIP.

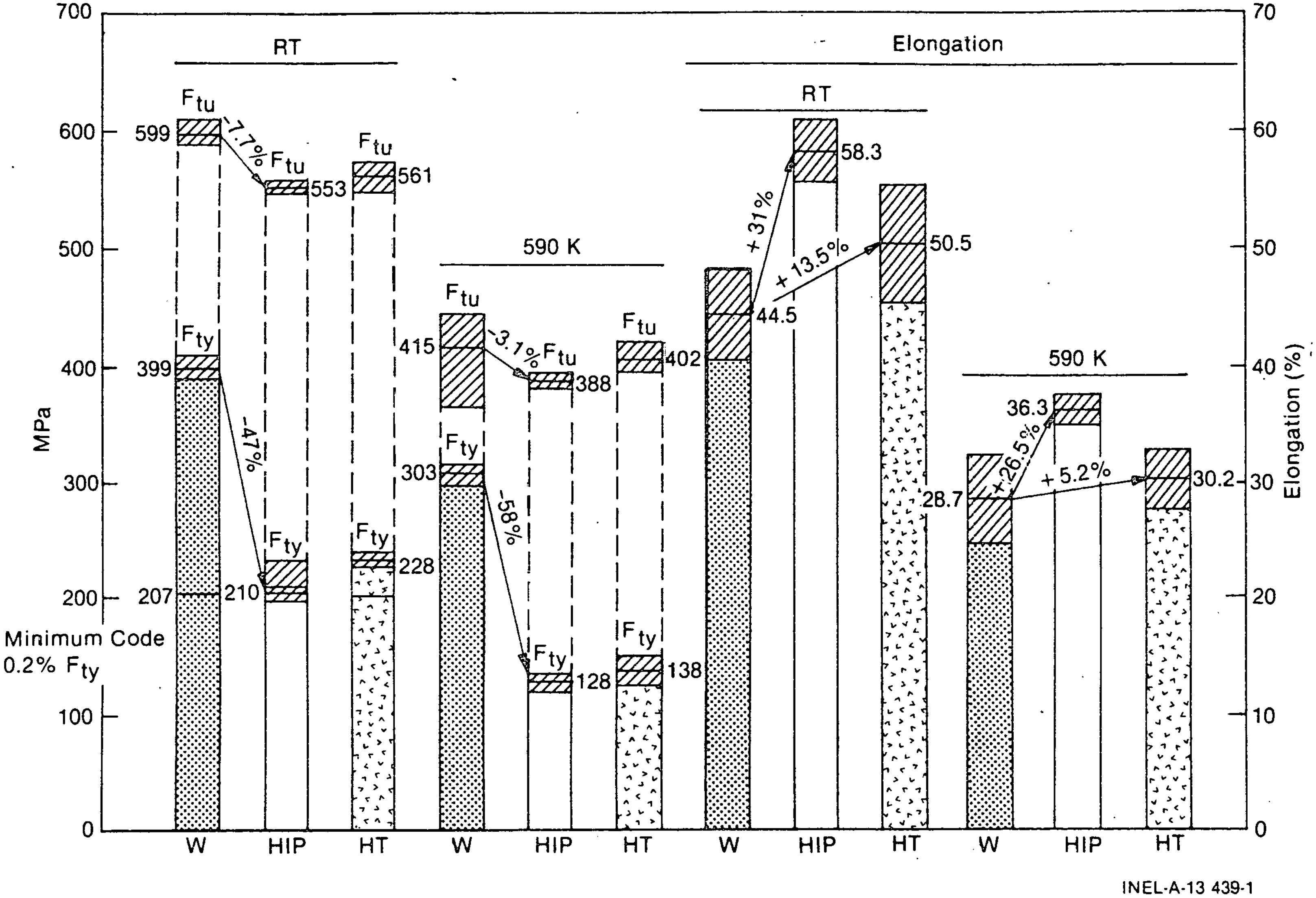


Fig. 8 Tensile properties of Type 304/308 GTA circumferential pipe welds before and after HIP or HT.

and 590 K (600°F) were nearly equivalent (Table 4). Before HIP, Type 304/308 welds had a 20% higher yield strength and a 23% lower elongation than Type 304 base metal. These differences were essentially eliminated by HIP through structural homogenization (Section 3.1).

TABLE 3. TENSILE PROPERTIES OF TYPE 304/308 GTA WELDS AFTER HIP OR HT

	Percent Change[a] in Tensile Properties at					
	F_{ty}	F_{tu}	% Elongation	F_{ty}	F_{tu}	% Elongation[b]
HIP-1900	-47.4	-7.7	+31.0	-57.8	-6.5	+26.5
HIP-1900	-42.9	-6.3	+13.5	-54.5	-3.1	+ 5.0

a. Decrease is shown by - sign and increase by + sign.
b. Elongation in 3.56 cm gage length.

TABLE 4. RT TENSILE PROPERTIES OF TYPE 304 AND TYPE 304/308 WELDS, BEFORE AND AFTER HIP

Property	Type 304	Type 304/308 Weld	Type 304 B-HIP-1900	Type 304/308 Weld, W-HIP-1900
F_{ty}(0.2%),	335	420	197 ± 6	299 ± 7
Elongation, %	66	53.6	72.5 ± 3.5	72.2 ± 1.8

3.3.5 Failure Location

All thirty (30) tensile test specimens from Type 304/308 GTA transverse (plate or pipe) welds after HIP at 1255 K (1800°F) failed in the base metal during testing at either RT or 590 K (600°F). The as-welded specimens or welds after HIP at either 1310 K (1900°F) or 1365 K (2000°F) failed in either the HAZ or fusion zone.

3.3.6 Orientation Effects Minimized

HIPed welds showed nearly equivalent tensile properties in both longitudinal and transverse orientations (Figure 9) owing to structural

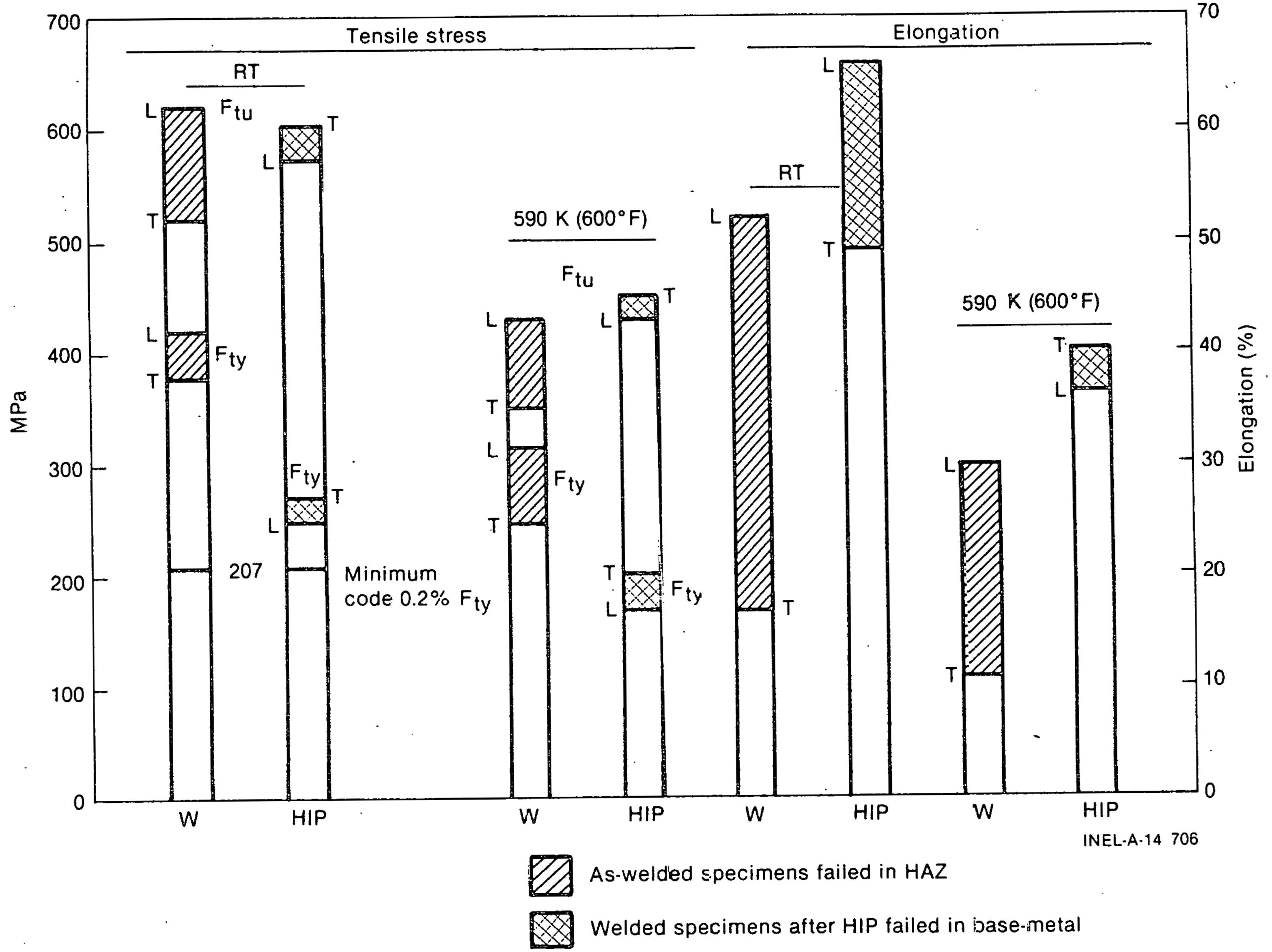


Fig. 9 Tensile properties of Type 304/308 GTA plate welds, showing minimum orientation effects after HIP. L - Longitudinal, T - Transverse.

homogenization (Figure 2). Orientation effects are more pronounced in the as-welded condition.

3.3.7 Decrease in Scatter of Tensile Data

Tensile property variations were decreased by HIP for almost all weld specimens by as much as 90%, with defective welds exhibiting considerably greater reduction of scatter than sound welds.

3.4 Impact Strength and Fracture Toughness

The RT impact strength of Type 304 base metal and Type 304/308 GTA welds was increased substantially by HIP (Figure 10). Welded and HIPed Charpy V-notch specimens would bend but not fail when tested at loads up to the machine limit of 325 J (240 ft-lb.), necessitating the use of instrumented drop-weight impact tests. (The Charpy specimens, per ASTM E-23 design, were not fatigue-precracked).

The increase in V-notch impact strength after HIP was 70% for the base metal, 147% for welds with notches in the HAZ/base metal, and 235% for welds with notches in the fusion zone. These increases reflect both structure homogenization and an average ferrite number reduction from 12.3 to 1.7.

HIP not only increased impact strength but also improved fracture toughness. The dynamic fracture toughness plane stress elastic equivalent, K_d, for welded specimens with notches in the fusion zone increased by 67% and specimens with notches in the HAZ/base metal increased by 42% after HIP (Figure 11). The K_d of weld material was greater for specimens notched in the HAZ/base metal than for specimens notched in the fusion zone, both before and after HIP. This could be due to greater hardness values and more complex microstructure in the fusion zone than in the HAZ/base metal.

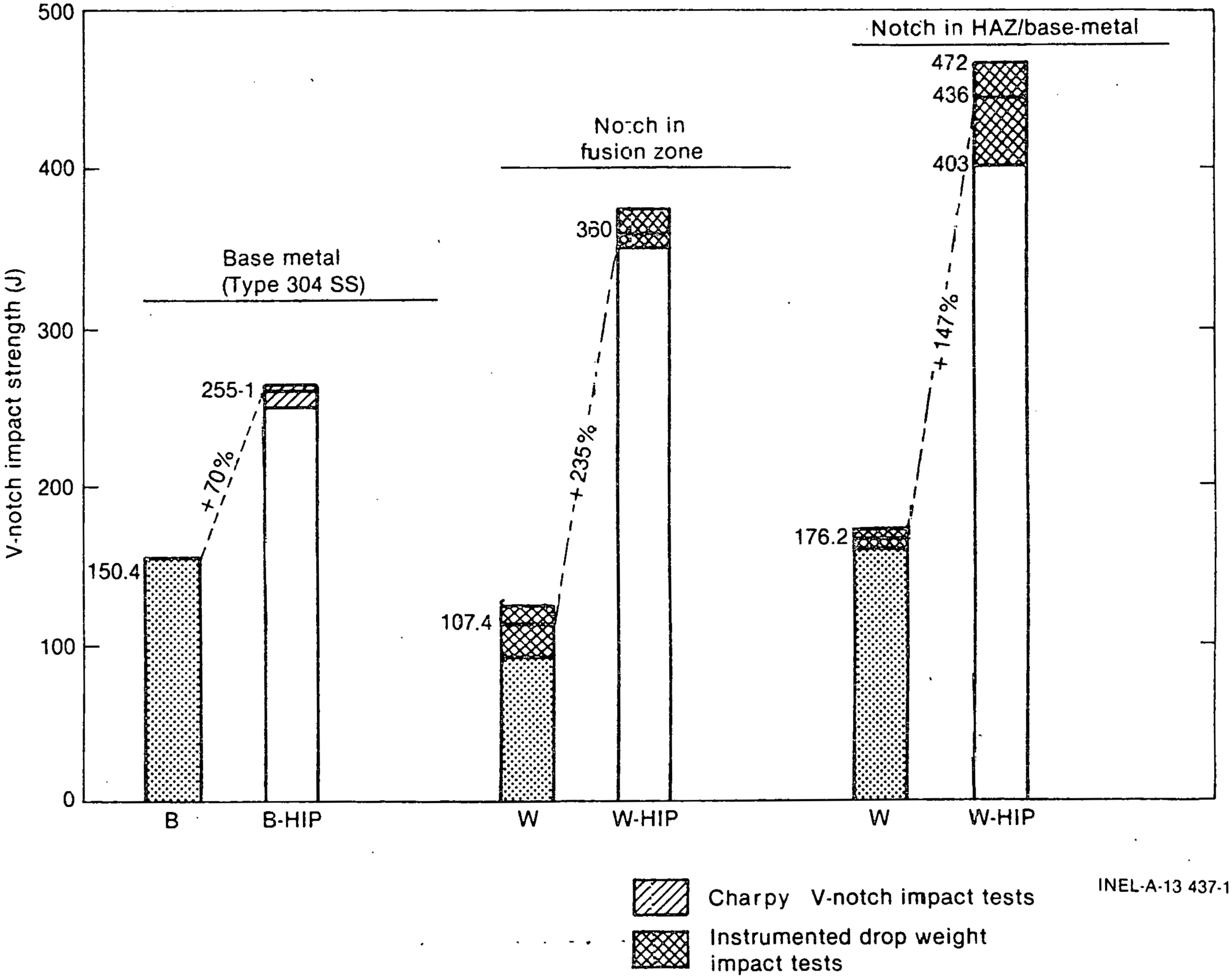


Fig. 10 Impact strength of Type 304 stainless steel and Type 304/308 GTA transverse plate welds, before and after HIP.

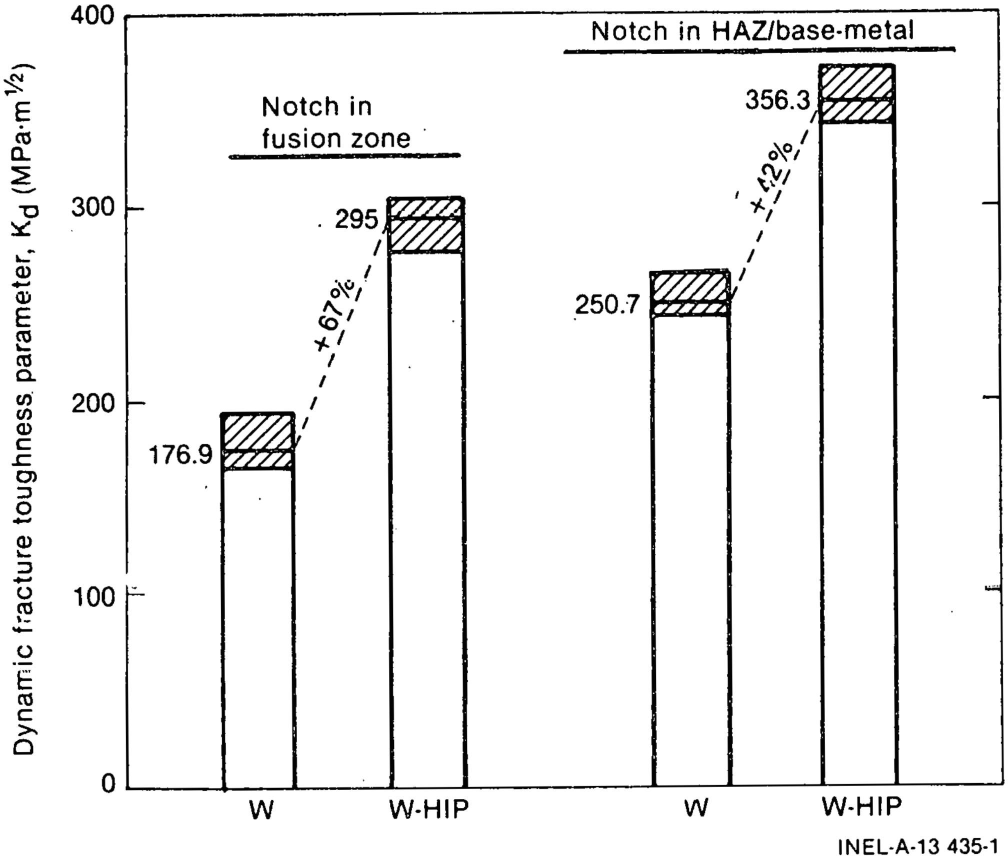


Fig. 11 Dynamic fracture toughness (plane stress elastic equivalent, K_d) for Type 304/308 GTA welds before and after HIP. (Sub-size Charpy V-notch specimens, not precracked).

4. POTENTIAL PROBLEMS AND APPLICATIONS OF HIP WELDS

4.1 Potential Problems with HIP Welds

Potential problem areas are (a) surface-connected porosity, (b) yield strength reduction, (c) application to field welds, and (d) costs.

4.1.1 Surface-Connected Porosity

Surface-connected pores do not close on HIP and, in fact, the gas pressure may even open them. These surface-connected pores must therefore be sealed by welding. However, microporosity, microfissures, and lack of fusion between weld bead and substrate generally are internal defects and amenable to healing by HIP.

4.1.2 Yield Strength Reduction

The average F_{ty} at RT of welds after HIP at 1310-1365 K (1900-2000°F) was 216.5 MPa (31.4 ksi), which was only slightly greater than the minimum Code value of 207 MPa (30 ksi) for Type 304 base metal. Welds HIPed at 1255 K (1800°F) had an average yield strength of 266 MPa (38.6 ksi).

Higher nitrogen and/or columbium contents, but still within acceptable AISI composition limits, provide higher yield and ultimate strengths in stainless steels. For example, an increase of 0.12% in nitrogen content in Type 304 stainless steel resulted in (a) an increase of 25 and 50% in F_{tu} and F_{ty}, respectively, and (b) a decrease of only 10% in elongation[7]. The higher corrosion resistance of higher nitrogen modifications such as Types 304N and 304LN was essentially the same as that of standard Type 304 values. Type 304LN has a low carbon content to avoid sensitization, and higher nitrogen content to retain strength levels at Type 304 values.

Oak Ridge National Laboratory found that additions of 500 to 1000 ppm columbium significantly improved resistance to intergranular corrosion (without simultaneously introducing hot-cracking problems) and increased creep and creep-rupture strength values.[8]

4.1.3 Application To Field Welds. Field welds can not be HIPed because isostatic pressure can not be readily applied. However, over 70% of the weldments in nuclear reactors are in-shop fabricated.

4.14 HIP Costs. Austenitic stainless steel welded parts of various sizes can be HIPed during the same cycle with the only qualification being autoclave size. Thus, costs can be distributed over a relatively large number of items. Treated welds have reduced repair and NDE requirements, leading to substantial cost savings. In addition, scrap losses are reduced. Like HIP of castings, no special tooling or canning is require for treatment of welds. In fact, HIP is being presently used by the aerospace industry for upgrading castings on a production basis. Costs for HIP, with due consideration for benefits, could be no more than for postweld heat-treatment.

4.2 Potential Applications of HIP Welds

Applications of HIPed welds are numerous, with uses ranging across both nuclear and non-nuclear applications. Some of the potential applications are:

(a) Welding thick components

(b) Weld repair of castings

(c) Weld cladding of surfaces

(d) Transitions or joints between dissimilar metals

(e) Weld repair without remelting

(f) Repair of weld defects in hard-to-reach areas of components

HIP of weld-deposited wear-resistant coatings on Type 316 plugs and seats in nuclear valves is currently being explored at the Idaho National Engineering Laboratory to improve homogenization of structure, adherence of the coating to the substrate, and inspectability.

5. REFERENCES

1. H. D. Hanes, D. A. Seifert, and C. R. Watts, Hot Isostatic Processing, MCIC-77-34, Battelle Columbus Laboratories, Columbus, OH, November 1977.

2. D. L. Kerr, R. C. Lemon, and E. E. Stonebrook, "Casting", U. S. Patent 3,496,624 (February 20, 1970).

3. G. E. Wasielewski and N. R. Lindblad, "Elimination of Casting Defects Using HIP", Proceedings of the Second International Conference on Superalloys Processing", September 1972, MCIC-71-10.

4. L. E. Dardi and W. R. Freeman, Jr., "Integrity of Hot Isostatically Processed Investment-Cast Nickel-Base Superalloys," Paper Presented at the Materials Science Symposium, Detroit, MI; October 22, 1974.

5. W. R. Freeman Jr., "HIP'ing Raises Castings Performance Levels", Metal Progress, August 1977, pp. 33-38.

6. Source Book on Stainless Steels, Metals Park, OH: American Society for Metals, 1976.

7. M. Macecek "Metallurgical Causes of Difficulties with Ultrasonic Inspection of Austenitic Welds", Paper presented at the Joint ASME/CSME Pressure Vessel and Piping Conference, Montreal, Canada, June 25-30, 1978.

8. H. E. Chandler, and D. F. Baxter, "Technology Forecast 79," Metal Progress, January 1979, pp. 34-35.