Heat-Affected Zone Characterization by Physical Simulations

An overview on the use of the Gleeble discusses the advantages and disadvantages of thermomechanical simulation

BY Y. ADONYI

Thermomechanical simulation can indeed be a useful development tool in the hands of those fully aware of its capabilities and limitations, and the Gleeble is the most well-known physical simulator. In the absence of standards, mistakes in simulation can be made and incorrect conclusions can be drawn.

This article provides an overview and discussion on the advantages and disadvantages of physical simulations from a user perspective, as applied to weld heat-affected zone (HAZ) characterization. Included are some warnings about improper use of the Gleeble and several successful case studies.

Answering Some Common Questions

Despite many years of successful use, I believe many questions regarding HAZ simulations still persist in the minds of potential Gleeble users in the welding community. I hope to address some of those concerns in this article.

The section below offers answers to some of the most frequently asked questions relating to Gleeble simulations.

Question 1: What does physical simulation mean, and how does it differ from virtual computer-based simulations?

Computer or virtual simulations are best known for modeling physical and other natural phenomena. Virtual reality, video games, interactive educational programs, flight and driving simulators use such computer simulations. However, physical simulators are real and use computers only for process monitoring and data acquisition. They are performed in the sometimes hazardous physical realm and should not be confused with the safe environment of the virtual world. Safety of operators becomes of utmost importance as electric shock, molten metal droplets, fast moving parts, large loads, and other physical hazards are managed in a safe working environment. All physical simulation performance should start with safety training.

Typical simulations use small specimens of the actual metal to be tested, typically uniform cylinders 9.5 mm (⅜ in.) in diameter and 127 mm (5 in.) in length, but can be as small as 1.0 mm (0.040 in.) thick and 12.7 mm (0.5 in.) wide. The specimens are resistively heated at rates of up to 10,000°C/s for specimens of 6.4 mm (0.25 in.) diameter, typical to thermal cycles experienced by arc weld HAZs. Tensile or compressive static loading of up to eight metric tons can be superimposed on this temperature cycle as well as strain rates of up to 50.8 mm/mm/s or 2 in./in./s. With these capabilities, the Gleeble is a dynamic physical simulator. Figure 1 shows the main elements of the simulator, together with the environmental chamber that provides vacuum or inert gas protection during experiments. Figure 2 schematically shows the main elements of the thermal and mechanical parts of the system working in a closed-loop control mode.

Question 2: Why use a Gleeble to simulate welds instead of making real welds?

It might appear simpler to test actual weld HAZs than use intricate equipment like the Gleeble. However, actual HAZs present a complex mix of microstructures within a small volume next to the fusion zone. Temperature gradients are so large that a different microstructure can be found within each hundredths of an inch (or tenths of a millimeter). Therefore, the properties of one single microstructure that has the worst properties becomes difficult to measure, and thus predict where the weld will most likely fail during service.

For example, Charpy V-notch tip radii are too large to sample such a single microstructure in the HAZ. Even sharp fatigue cracks produced for crack tip opening displacement (CTOD) tests are difficult to initiate and propagate within one single HAZ microstructure. Using straight K-type joints in the offshore industry has been one such effort aimed at keeping the crack within the coarse-grained HAZ. Similar weldability tests from TWI have been designed with the same straight HAZ idea in mind. However, the thermomechanical simulator can produce a homogenous single microstructure within a large volume of material, thus testing separately the properties of the coarse-grained HAZ, intercritically reheated HAZ, etc., for different heat inputs. Alloy screening becomes very effective this way when large, 12.7 × 25.4 mm (0.5 × 1.0 in.) cross section CTOD specimens are used (Ref. 1).

Additionally, real weld experiments introduce many sources of error due to differences in operator expertise, heat transfer efficiency changes from one welding process to another, and many other operator-related variables. On the other hand, the Gleeble is based on a computer controller that reliably sends and adjusts control signals and acquires up to 2000 samples per second. Under normal circumstances, it operates with great accuracy and reproducibility.

Question 3: How are physical simulations and other dedicated computer simulations of weld HAZs related?

Excellent and well-validated analytical models accurately model HAZ transfor-

Y. ADONYI is Professor and Omer Blodgett Chair of Welding and Materials Joining Engineering at LeTourneau University, Longview, Tex.

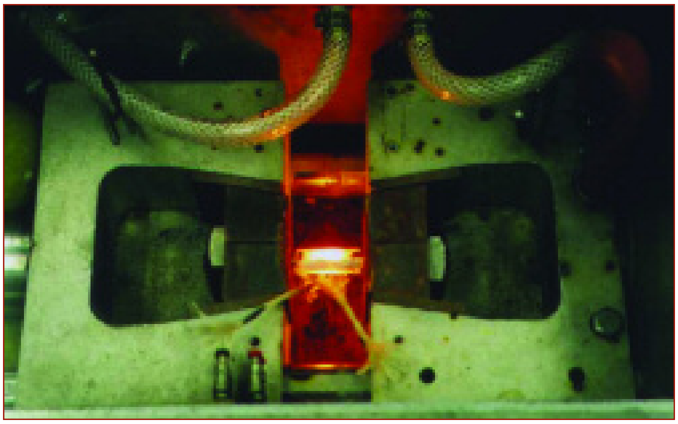


Fig. 1 — Top view of the Gleeble chamber. Arrow points at the sample heated resistively. Left jaw is mobile, right jaw is fixed.

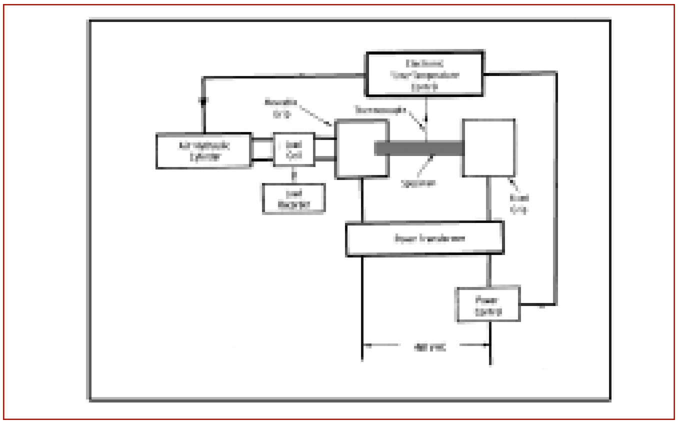


Fig. 2 — Schematic representation of the main components of the Gleeble, illustrating the sensors and feedback control loops. The test specimen is highlighted in red.

mations using moving heat source thermal models (Ref. 2). When introducing cooling rates in these models, predicting of microstructures is also possible. Furthermore, in-situ HAZ microstructural evolution can be monitored using the synchrotron from Lawrence Livermore National Labs (Ref. 3). Excellent coupled computer models of the transformation kinetics are available and good correlations have been found with actual HAZ properties (Refs. 4–6).

In spite of all this progress, these computer models are still limited to microstructural evolution and hardness predictions in transformation-hardened materials. However, their output is mostly limited to HAZ isotherms and temperature gradients. Local HAZ properties such as fracture toughness remain difficult to predict. This is where the thermomechanical simulator can provide complementary data for boundary conditions and analytical model validation.

Question 4: How representative are physical simulations of actual weld HAZs?

Doubters and believers must properly address this fundamental question. Finding correlations between microstructures and properties of simulated vs. actual samples consume 70–80% of any Gleeble simulation project. After the proper correlations are found, physical simulation becomes very reliable, easy to use, repeatable and cost effective.

Using handbook values for high-temperature properties of materials obtained in steady state do not apply to most manufacturing processes including welding, forging, heat treating, etc. This is because material properties and transformation behavior change with heating/cooling rates, as well as the rate of deformation. This is one additional area where the Gleeble can be useful in simulating all these complex processing conditions.

Question 5: How do HAZ physical simulations relate to other widely accepted weldability tests?

Heat-affected zone hardenability tests such as the Y-groove (Tekken) and implant tests provide excellent small-scale high-restraint geometries and methodologies to predict HAZ hydrogen-induced cracking behavior at different cooling rates. The problem with most of these tests is that they are self-restrained, thus the residual stresses are inherently controlled by thickness and temperature gradients. Additionally, while they use real welding processes, heating and cooling rates are process-dependent. On the other hand, thermomechanical simulations can isolate individual effects by performing hardenabilty or postweld heat treatment tests under constant tensile or even cyclic loading. A simple series of thermomechanical simulations can determine nil ductility temperatures on heating and cooling to complement small-scale weldability test results. Hot-ductility tests run at any point during an HAZ simulation can yield valuable cracking susceptibility data. Overall, Gleeble testing is complementary to most widely accepted weldability tests.

Categorizing Simulations and Defining Assumptions

In general, HAZ simulations can be divided in three categories: design, manufacturing, and service. First, in the design stage, thermomechancial simulation can be used for alloy screening to optimize chemistry and processing steps using small lab heats. Second, before manufacturing, the Gleeble can be used to simulate cold- and hot cracking susceptibility, heat input and pre- and postheating effects on HAZ properties such as reheat cracking susceptibility. Third, weld HAZ service conditions can be simulated in different corrosive environments and different loading conditions.

The assumptions used in physical simulations need to be reviewed to explain the case studies that follow. First, the real processing parameters are assumed to be well known and reproducible. Second, the simulated microstructures have to be similar and representative of the real ones. This constantly reoccurring question of how close a simulated microstructure is relative to a real product is essential to be addressed from the very beginning of simulation.

To start with, typical weld HAZ thermocycles can be accurately recorded adjacent to arc welding or cutting moving heat sources. Figure 3 shows such a series of real temperature/time graphs that can be subsequently programmed into the Gleeble controller computer. Alternately, analytical heat transfer equations such as Rosenthal 2-D and 3-D solutions can be used for input.

Typically, seven specimens must be subjected to each condition, actual thermal and mechanical parameters recorded, and anomalies eliminated by repeating questionable tests. Destructive testing, metallography, and optical and electron microscopy are used to characterize the results.

Case Study No. 1 — New Product Development, High-Performance Steels (HPS)

Coarse-grained HAZ (CGHAZ), or the area next to the weld interface that experiences the highest peak temperatures in the HAZ, is known to be the area of the lowest toughness (Refs. 5, 6). The grain size, microstructure, and hardness of the

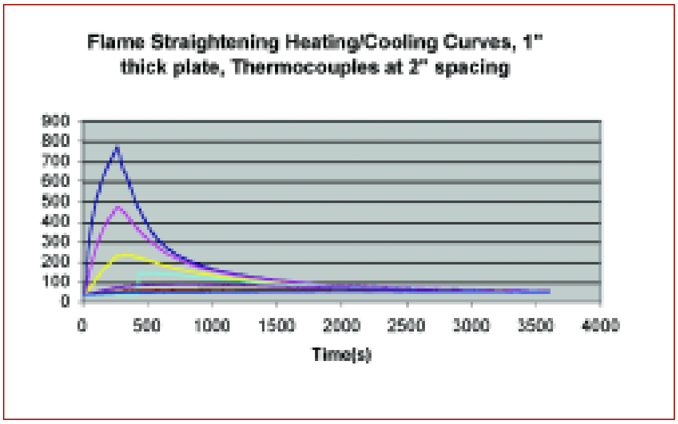
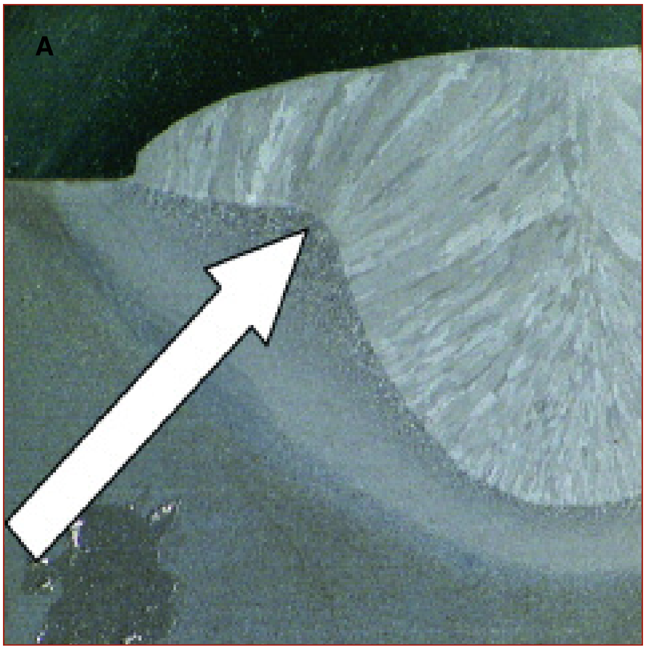


Fig. 3 — Typical temperature vs. time plots measured with a series of thermocouples during actual flame reheating, taken at different distances from the heat source. Note that weld HAZ peak temperatures are higher, typically 1350°C.



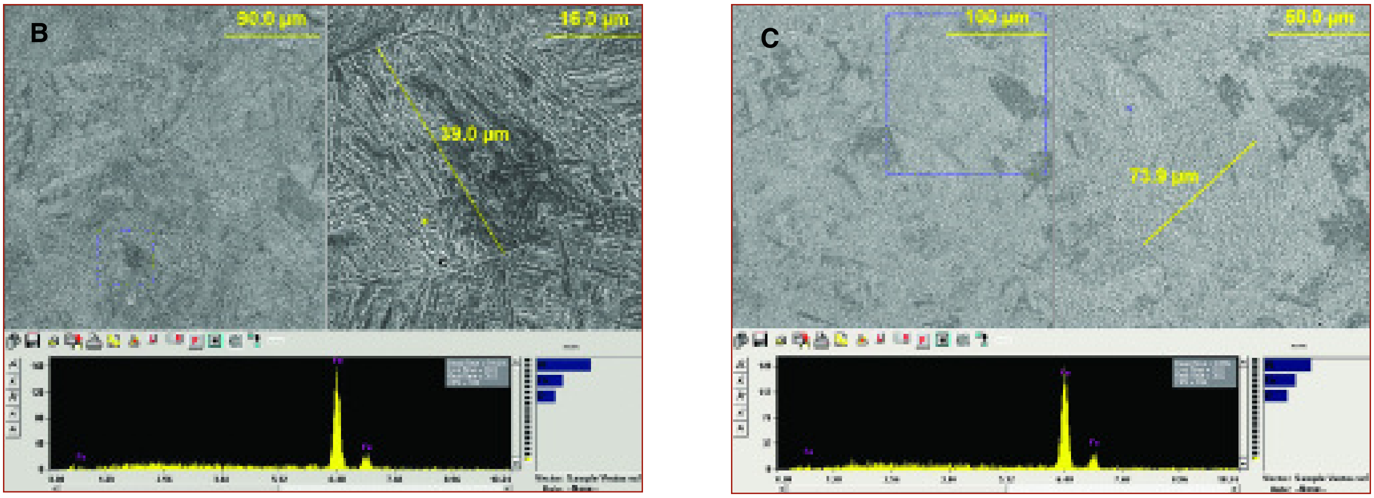


Fig. 4 — A — Typical high-heat-input SAW weld cross section (200 kJ/in.) showing the location of the coarse-grained HAZ used for reference; B — simulated CGHAZ, 50 kJ/in. heat input, 2-in.-thick HPS 100 CuNi plate; C — simulated CGHAZ, 150 kJ/in. heat input, 2-in. plate, HPS 100 CuNi.

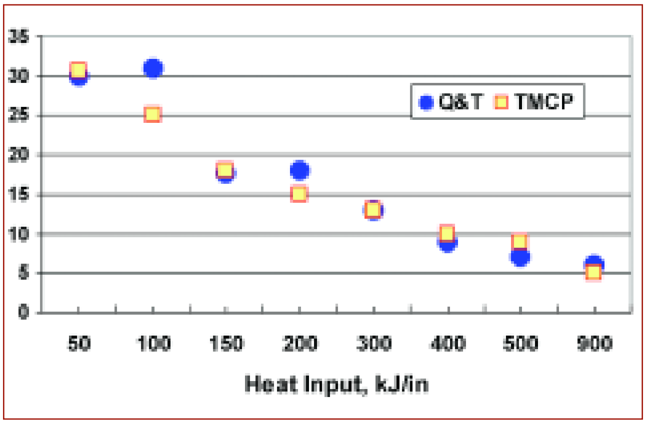


Fig. 5 — Coarse-grained HAZ (CGHAZ) Charpy V-notch (CVN) impact energy vs. heat input, 50–900 kJ/in., HPS 70W. Base metal toughness was 52 and 69 ft-lb at –20°F for the TMCP and Q&T materials, respectively (TMCP = thermo mechanically controlled processing; Q&T = quenched and tempered).

simulated HAZ sample have to be identical to that of real welds. Figure 4A, B, and C show these correlations on high-heat-input submerged arc welds in HPS steels, where the average grain size was 39 microns at 50 kJ/in. and 73.9 microns at 150 kJ/in. heat input.

Beyond microstructural comparisons, one of the most common validation tools for simulation experiments is hardness testing. Table 1 shows the correlation between average hardness in the HAZs for 50.8-mm (2-in.) -thick HPS 100W CuNi steel welds.

The toughness of the simulated HAZs in the HPS 70W grade as a function of heat input shows that toughness drops below the minimum required value of 20 ft-lb/–20°F at heat inputs above 100 kJ/in. — Fig. 5. Therefore, the simulation predicted that unusually high heat inputs should be avoided, considering that the average heat input used for submerged arc welding of 2-in. plate is usually performed in the 50–75 kJ/in. range.

Note that the very high heat input of 900 kJ/in. used to simulate the narrow-groove electroslag welding (NG-ESW) process can be expected to have poor HAZ toughness. Past well-known failures in ESW welded bridges, such as the one on I-79 in Pittsburgh, Pa., that initiated

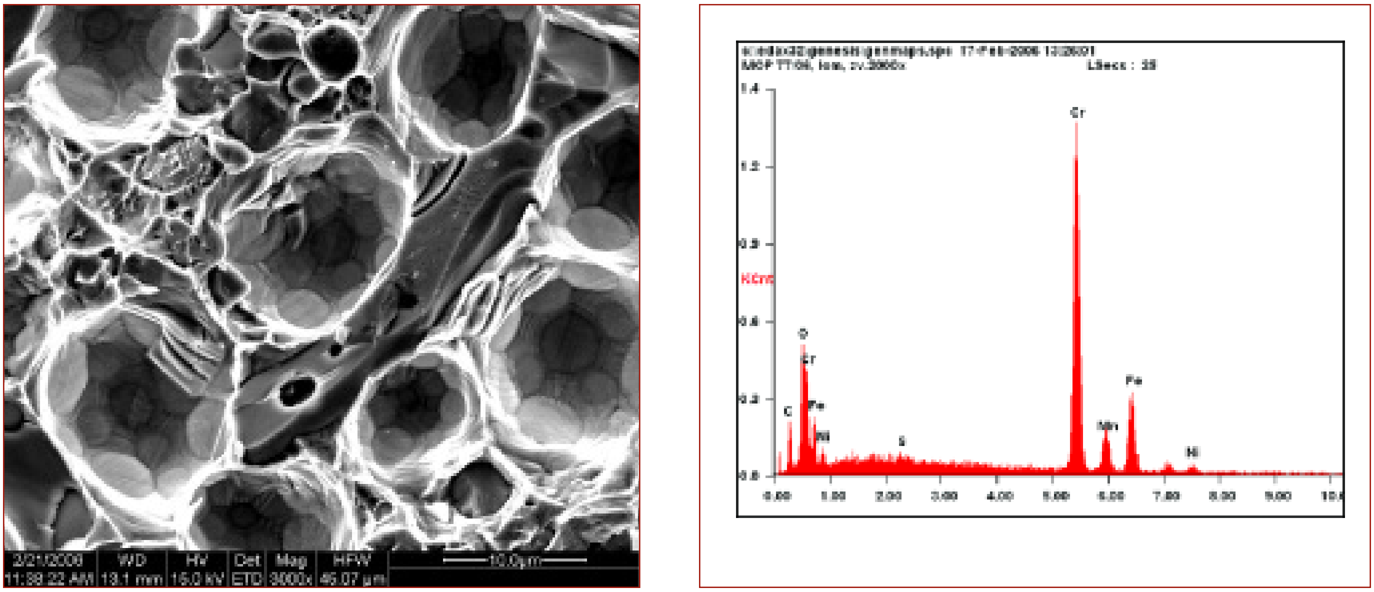


Fig. 6 — Fracture surfaces, actual vs. simulated high-temperature exposure.

in the CGHAZ, confirm the validity of this observation. It remains important to remember that Gleeble results should never be used alone for predicting weldability behavior. Small-scale tests for cracking susceptibility such as Y-groove and G-BOP tests should be used to complement results. Ultimately, welding procedure qualifications and full-scale section welds should be tested before implementation of all weldability related findings (Refs. 4–6).

Table 1 — Average Vickers Hardness (HV) in Actual and Simulated HAZ (1 kg load)

Heat Input, kJ/in.	50	100	150	200
$t_{8\text{-}5}$/s(a)	20	30	40	50
Actual HV	300	280	250	250
Simulated HV	270	275	250	245
Difference between Actual and Simulated	-30	-5	0	-5

(a) Cooling rate expressed in time spent on cooling in the intercritical range between Ac_1 and Ac_3, typically 800°C to 500°C, also known as 8-to-5.

Table 2 — Average Chemical Composition of the Two Types of HPS 70W Steel

	C	Mn	P	S	Cu	Ni	Cr
Q&T	0.084	1.24	0.017	0.008	0.31	0.40	0.58
TMCP	0.154	1.27	0.010	0.008	0.30	0.32	0.64

Note: Other alloying elements and residuals were similar in both, i.e. 0.06%V, 0.01%Ca, 0.08% Mo, 0.002% Ti, 0.00002%B.

Case Study No. 2 — Weld Repair Simulation, Austenitic Stainless Steel

Thermomechanical simulation can be useful not only in new alloy and process development, but also in predicting weld repair feasibility. One such example is taken from continuous annealing furnace radiant tube failures and repairs. The 127-mm- (5-in.-) diameter, 12.7-mm- (0.5-in.-) thick wall, centrifugally cast, 25% Cr-12%Ni austenitic stainless steel tubes work at temperatures between 950° and 1000°C. Failure analysis of some premature product leaks revealed heavy intergranular carbide precipitation along which the cracks initiated and propagated — Fig. 6.

When reheated specimens were tensile tested in the Gleeble at high temperatures, a good correlation was found between the actual and simulated fracture surfaces. The additional information gathered from the tests were the tensile strength and ductility values that assessed the degree of thermal damage to these tubes. After three years of exposure, it retained 21 and 32% ductility at 900°C and 1050°C, respectively.

Assuming that the tube examined was representative of the 170 similar tubes in the furnace, one can conclude that the useful life left in these products was greatly reduced by high-temperature exposure.

In order to establish the feasibility of weld repairs on these used tubes, Charpy-size specimens were removed from a failed product and reheated in the simulator using a CGHAZ thermal cycle typical to a shielded metal arc weld (SMAW) repair. Metallographic analysis showed liquation cracking in the HAZ, phenomenon confirmed on actual weld repair trials — Fig. 7.

It was concluded that weld repair caused potential damage and replaced the high-temperature base metal cracking problem with another, i.e., weld partially melted zone cracking. Therefore, the planned weld repair alternative was abandoned, saving the company considerable funds and potential downtime. This early decision based on simulation also provided enough lead time to order new tubes at acceptable cost.

Case Study No. 3 — Manufacturing Simulation, Flame Reheating

Flame reheat simulations were needed to differentiate between the response of two types of steel to high-temperature exposure for the eventuality that the maximum allowed peak temperature of 1150°F was accidentally exceeded during manufacturing. The two HPS 70 W steels examined had very similar compositions, but were made using separate processing

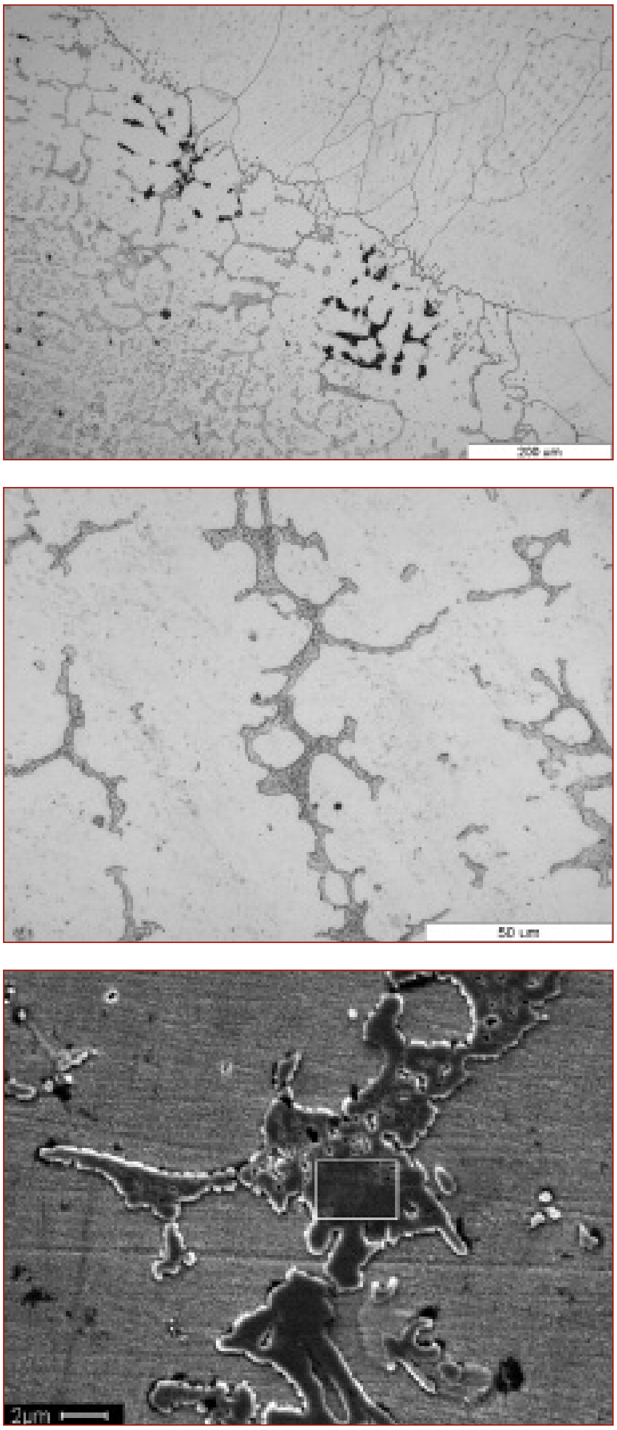


Fig. 7 — A — Liquation cracking in actual weld repair HAZ, partially melted zone or PMZ, 200X; B — Liquation cracking, eutectic in simulated PMZ, 1000X magnification.

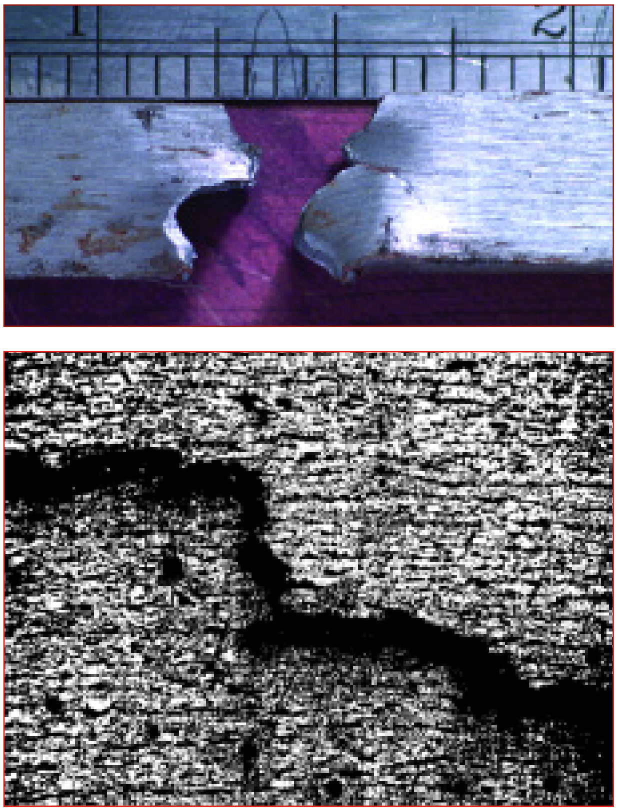


Fig. 8 — Side view of impact tested simulated TMCP HAZ samples. A — Arrow points at initial CVN notch; B — note banded microstructure along crack propagation path.

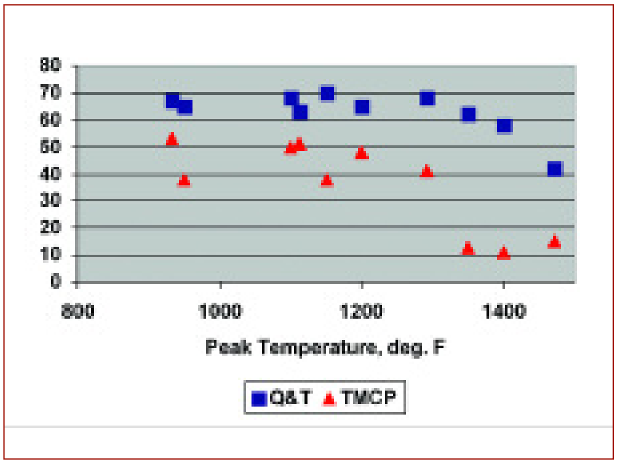


Fig. 9 — Simulated flame reheat toughness (Charpy V-notch energy at –20°F) for both types of HPS 70W steel. The dashed line represents the currently recommended maximum reheat temperature of 1100°F.

routes as in Case Study 1. These were, specifically, quenched and tempered (Q&T) and thermomechanically controlled processing (TMCP). In spite of these differences, the final mechanical properties of the two steels were similar (Table 2, Ref. 4).

During manufacturing of curved bridge girders, the welded steels are differentially heated to accomplish given radii.

Flame reheat simulations were performed at different peak temperatures on Charpy size specimens. The fracture surfaces of the TMCP Charpy samples exhibited an uncharacteristic mix of ductile and brittle failure mode, hence the larger scatter in data points — Figs. 8 and 9.

The reheated sample toughness values were below the base metals for both types of steels — Fig. 9.

Note the difference between the average initial toughness between the two types of HPS 70W base metal, i.e., 50 ft-lb at –20°F for the TMCP and 69 ft-lb for the Q&T product. These values remained high after the simulated reheat, but started dropping off as the peak temperature exceeded 1300°F.

To verify the validity of these predictions, full-scale flame reheat samples were tested at one Navy shipyard, both TMCP and Q&T samples exhibited higher toughness of 140 to 160 ft-lb between 1000° and 1300°F, almost twice those predicted by the Gleeble simulations.

This disagreement can be explained in two ways: 1) full-scale reheating was monitored at the surface only, so peak temperatures in the plate mid section were lower, or 2) the Gleeble thermal cycles were too extreme and predicted worse behavior. While the "jury is still out" on this case study, no actual failures have been reported so far on over 200 new bridges made using the HPS steels in the U.S. during 2003–06.

Conclusions

This overview of weld HAZ simulations and case studies describes the basic assumptions and methodology needed for successful physical simulations. Evidence shows that extreme care should be used when designing and performing Gleeble experiments, as well as in interpreting the results in the context of other weldability tests. In conclusion, below are some advantages and disadvantages of Gleeble HAZ simulations.

Advantages

- Accurate and reproducible simulation of physical processes.
- Feasible and flexible, useful in design, manufacturing, and service.
- Small size samples required, low material costs.
- Simulated microstructures are homogenous and can be reliably tested.
- Can apply a wide variety of thermal and mechanical loads at high rates.
- It can separate thermal from mechanical effects during processing.

Disadvantages

- The specimen must be electrically conductive (metals and metal matrix composites).
- The simulated process parameters must be well known.
- Extrapolating Gleeble results to full-scale applications can be difficult.
- Equipment, maintenance, and training can be costly.
- Simulating high cooling rates can be difficult, as additional He or water jets can be necessary.

When all advantages and disadvantages are well understood and a proper methodology is established, the Gleeble remains an excellent tool for HAZ characterization.◆

Acknowledgments

I would like to thank Alina Adonyi and Jeremy Vosburgh from DSI for helping in editing this paper, as well as many former students from LeTourneau University, among them Dan Ryan, Garrett Atkins, Ben Pletcher, Sunny Henry, Caleb Roepke, and Brent Ellis. I would also like to thank Doctors Jurko, Lesko, and Petercakova from US Steel Kosice, Slovakia, for their help in providing data for this paper.

Disclaimer: The enclosed information is based on personal experience, hence it can be biased. This article does not endorse any product or service mentioned.

References

1. Defilippi, J. D., Kapadia, B. M., Adonyi, Y., and Domis, W. F. 1992. Development of HSLA steel with 80 ksi yield strength for offshore applications. *Proceedings at the 11th International Conference on Offshore Mechanical and Arctic Engineering*, Vol. 3, Calgary, Alberta, Canada.

2. Bhadeshia, H. K. D. H. 2004. Reliability of weld microstructure and property calculations. Adams Lecture. *Welding Journal* 83(9): 237-s to 243-s.

3. Elmer, J. W., Palmer, T. A, Babu, S. S., and DebRoy, T. 2004. Direct observations of austenite, bainite and martensite formation during arc welding of 1045 steel using time-resolved X ray diffraction. *Welding Journal* 83(9): 244-s to 254-s.

4. Pletcher, B., Atkins, G., and Adonyi, Y. 2002. Flame reheating effects in high performance steels. Presentation at the 83rd Annual AWS Conference, Chicago, Ill.

5. Adonyi, Y. 1999. Recent advances in weldability research of high performance steels. *NaBRO (National Bridge Research Organization) Conference.* Kansas City, organized by University of Nebraska.

6. Adonyi, Y. 2000. Weldability of high performance steels. *NaBRO Conference on Steel Design and Construction for the New Millennium*, Baltimore, Md.

CORRECTION

Resistance Spot Welding of Coated High-Strength Dual-Phase Steels, by Murali D. Tumuluru, published in the August 2006 *Welding Journal*, page 33.

Table 2 — Hot-Dip Coated Dual-Phase Steel Composition Ranges, under the column Influence and Reason For Adding:

The two references to "Ferrite stabilizer" should read "Austenite stabilizer," and the three references to "Austenite stabilizer" should read "Ferrite stabilizer." The correct Table 2 is printed here.

Table 2 — Hot-Dip Coated Dual-Phase Steel Composition Ranges

Alloying Element (Wt-%)	Influence and Reason For Adding
C (0.06–0.15)	1. Austenite stabilizer 2. Strengthens martensite 3. Determines the phase distribution
Mn (1.5–2.5)	1. Austenite stabilizer 2. Solid solution strengthener of ferrite 3. Retards ferrite formation
Cr, Mo (each up to 0.40)	1. Ferrite stabilizer 2. Retards pearlite and bainite formation
V (up to 0.060)	1. Ferrite stabilizer 2. Precipitation strengthener 3. Refines microstructure
Nb (up to 0.04)	1. Ferrite stabilizer 2. Reduces M_S temperature 3. Refines microstructure