Correlation of Physical and Numerical Simulations of DDC in Multipass Welds

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1. Problem Statement

- Austenitic (face-centered cubic; FCC) alloys are essential components to industry due to their corrosion resistance and strength.
- Ductility-dip cracking (DDC) can occur when welding FCC alloys in large, multipass welds as in Figure 1 and the precise mechanism is unclear.
- Figure 2 illustrates the relationship between temperature and ductility of a DDC-prone material [2].
- DDC is a reject-able defect in high-impact industries such as nuclear power generation.
- A multipass welding FEA model was created by EPRI to examine welding conditions leading to DDC [3].
- Gleeble simulation of welding was conducted in a separate project where a possible unifying quantity was identified: imposed mechanical energy (IME) [4].

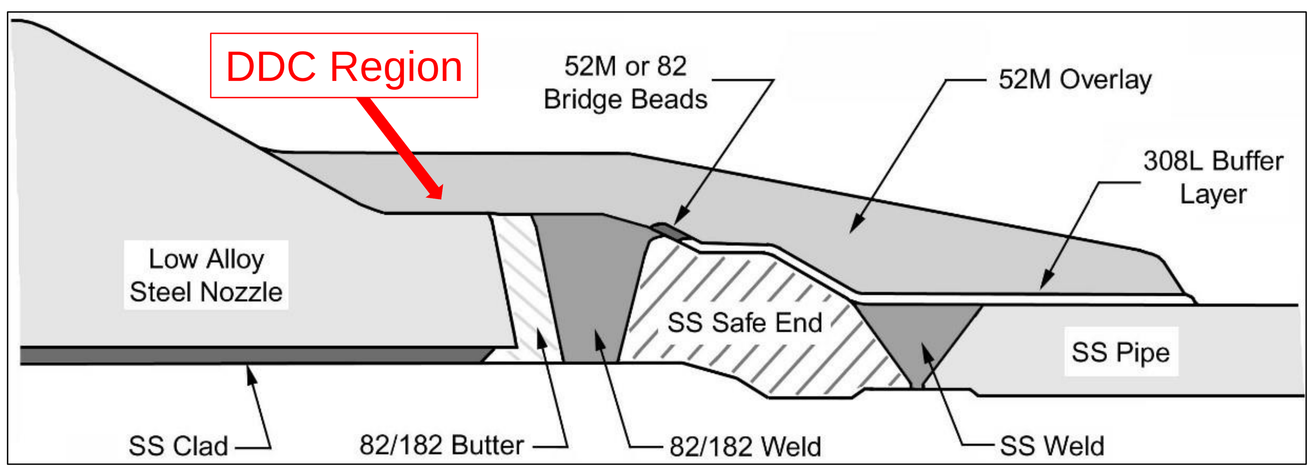

Figure 1: Schematic of multipass weld used in nuclear industry with DDC-susceptible region marked (52M Overlay) [1].

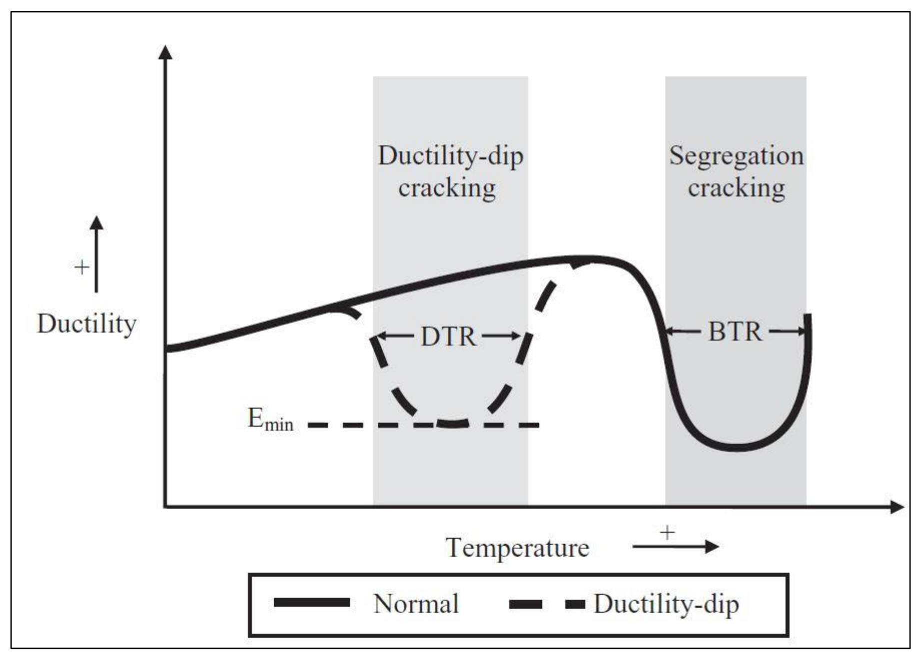

Figure 2: Ductility vs. temperature graph for a material prone to DDC [2].

2. Experimental Method

Table 1: Nickel-based filler metal 52M composition.

Nickel 52M Chemical Composition (wt%)																	
Ni	Al	B	C	Co	Cr	Cu	Fe	Mn	Mo	Nb	P	S	Si	Ti	W	Zr	Others
57.9	0.059	<0.0001	0.034	0.018	30.1	0.22	9.47	0.76	0.15	0.83	0.007	0.015	0.09	0.22	0.071	0.002	0.056

- The chemical composition of Nickel-based filler metal 52M used in Gleeble testing and Sysweld FEA modeling is shown above in Table 1.
- Stress-strain curves are absolute-value-integrated via trapezoidal area in the DDC temperature range to provide IME, which quantifies combined DDC stress/strain due to the thermomechanical effects of welding.
- Gleeble testing consisted of simulated strain ratcheting (SSR), a process where stress and strain are accumulated on the sample using welding thermomechanical histories and high restraint. This process has been shown to reproduce DDC.
- The Sysweld FEA model describes the stress-strain behavior of a high-restraint, narrow-groove multipass weld. Areas of high strain accumulation often show DDC.
- Stress-strain curves are obtained from Gleeble testing and the Sysweld model [3].
- Nodes in the model are chosen which represent areas where cracking is likely (L), plausible (P), unlikely (U), and highly unlikely (HU). These categories are qualitative and chosen based on experience and literature information [3]. Figure 3 shows this node selection.

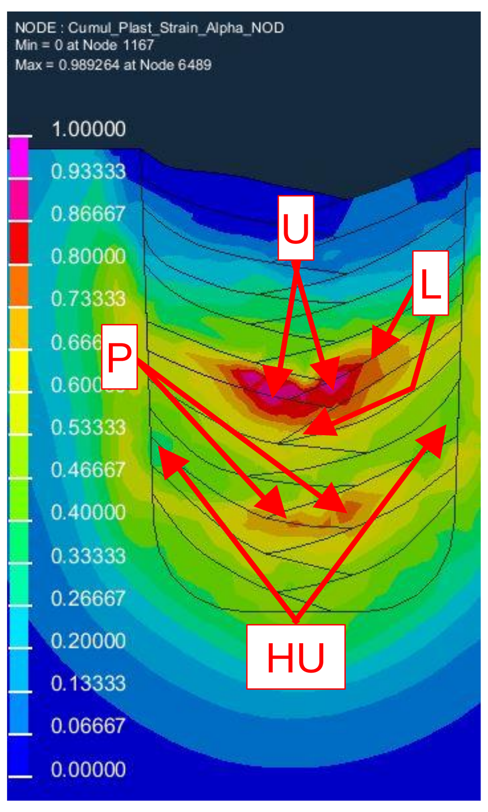

Figure 3: Cumulative plastic strain map in Sysweld FEA model showing approximate crack category locations.

3. Results

Gleeble Test IME Calculation Results

Table 2: Selected Gleeble Samples for Comparison to Sysweld.

Sample	IME, MJ	# of Cycles
1	23.2733	10
2	19.5568	10
3	19.5719	10
4	16.0772	10

- Table 2 shows the IME results from a selection of alloy 52M SSR tests which all were subject to 10 thermal cycles.
- Figure 4 shows an example stress and temperature vs. time plot taken from Sample 1. Green lines show DDC range.
- Each sample was found to contain DDC verified by visible light and electron microscopy.

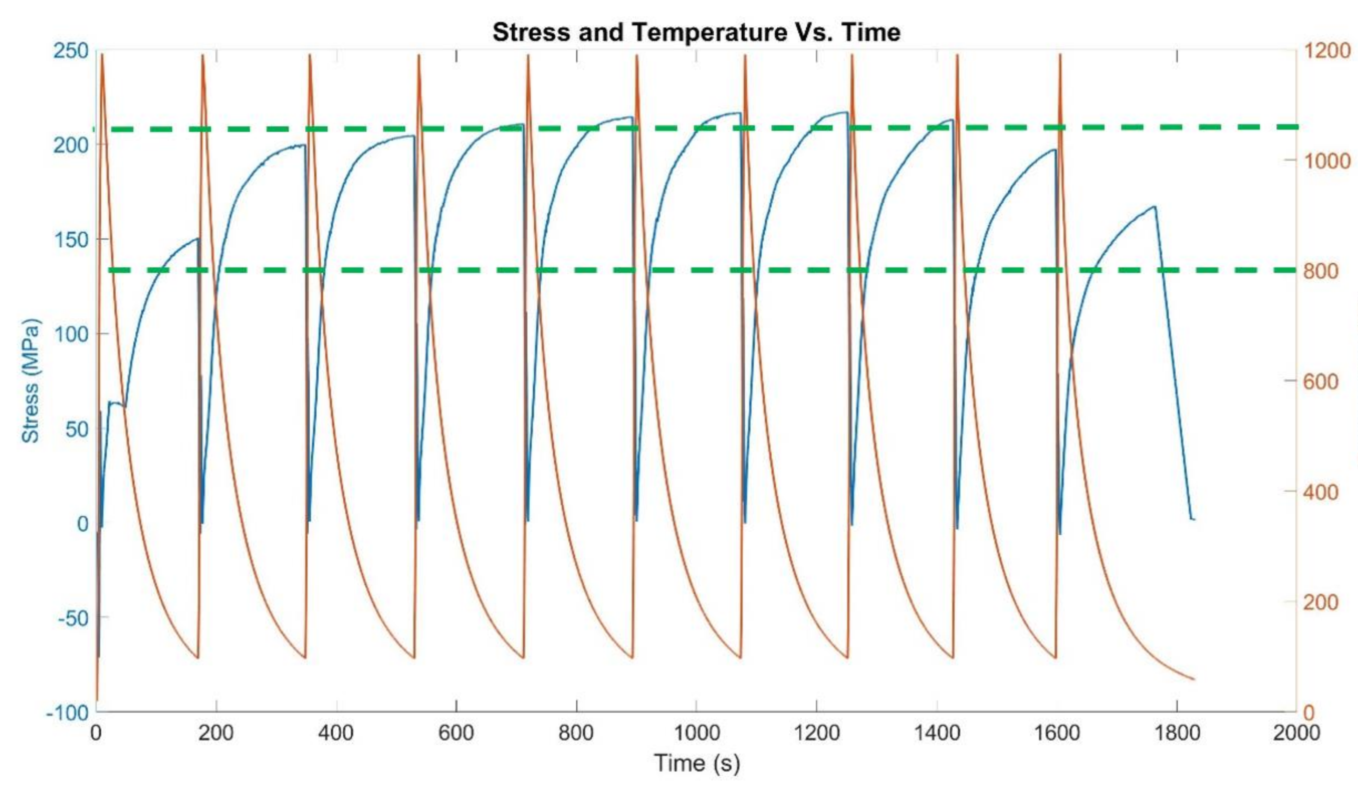

Figure 4: Example of Stress/Temperature vs. Time for Gleeble test – Sample 1.

Sysweld FEA Model IME Calculation Results

Table 3: Selected Sysweld Nodes with IME Calculations.

Cat.	Likely		Plausible		Unlikely		Highly Unlikely	
Node ID	6523	6595	6626	6634	6489	6846	6609	6786
# of Cycles	10	12	11	11	14	13	10	10
IME, MJ	21.933	31.668	45.052	64.274	44.736	61.662	31.488	25.440

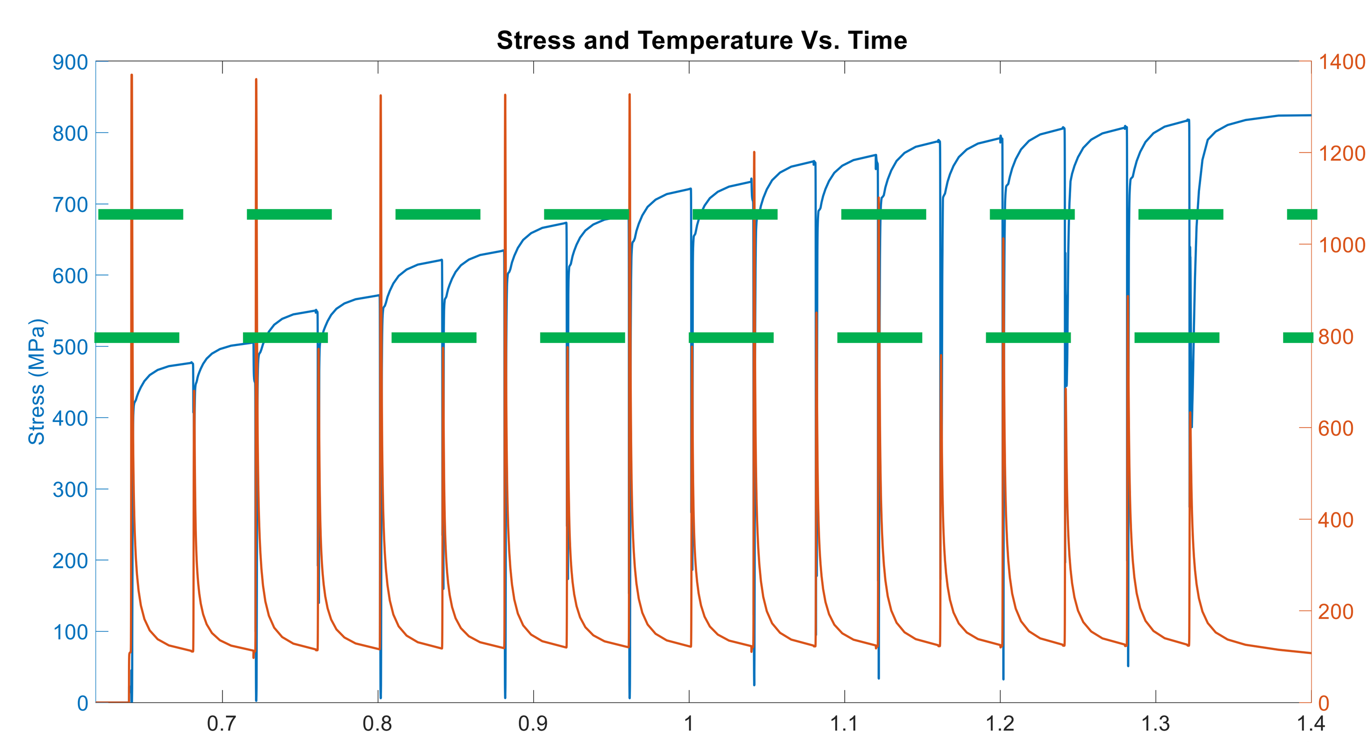

Figure 5: Example of Stress/Temperature vs. Time for Sysweld – Node 6523.

- Table 3 shows the IME values and number of thermal cycles for each node. Note this number of cycles counts only those which enter the DDC temperature range. Refer to Figure 3 for node category locations.
- Figure 5 is the stress and temperature vs. time for Node 6523. Cracks were found here on a weld mockup that was simulated using this Sysweld model.
- The same general trends apply to this data, only there are more thermal cycles and higher stresses than Gleeble testing.
- The magnitude of strain accumulated varies from node to node according to the color shading shown in Figure 3.

4. Discussion

- The cracking regions do not necessarily have higher IME. Sometimes, they even have a lower stress and strain.
- It is suspected this is due to the lack of recrystallization present in the cracking regions. This mechanism is only active with high levels of IME and temperatures.
- Overall, trends in graphs similar between Gleeble and Sysweld, but much higher stresses shown in simulation.

- The IME values in Sysweld are of a similar magnitude as the Gleeble, but often higher. This is due to the higher stresses involved.
- Figure 6 shows a side-by-side comparison of the IME values obtained both from the Gleeble and from the Sysweld model at each selected location.

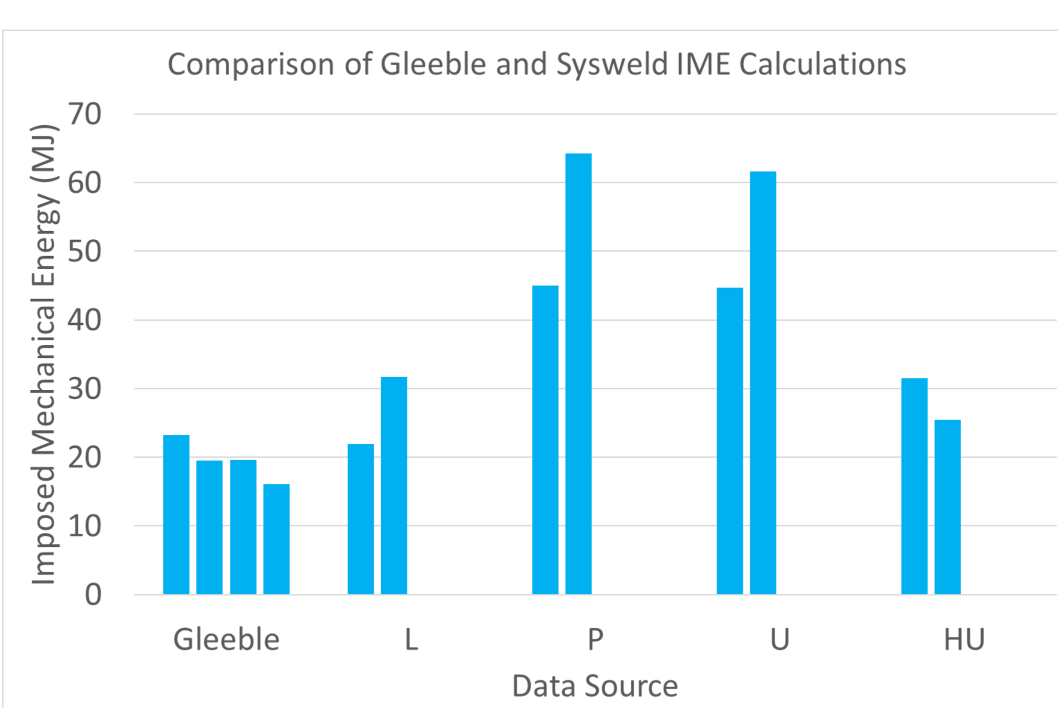

Figure 6: Graphical comparison of IME values.

5. Conclusions

- There is an observable similarity between Sysweld and Gleeble IME calculations, both qualitative and quantitative.
- IME shows potential as a quantity used to evaluate weld metal susceptibility to DDC under processing conditions and weld design when using Sysweld.
- More rigorous statistical analysis/calculations are needed to better establish this similarity and to further explore IME as a comparative metric between FEA model and Gleeble simulation.

References: [1] S. McCracken and R. Smith, "Evaluation of Filler Metal 52M Hot Cracking When Welding on Cast Austenitic Stainless Steel Base Materials," in Proceedings ASME PVP Conference, Baltimore, 2011. [2] J. DuPont, et al., *Welding Metallurgy and Weldability of Nickel-Base Alloys*, Hoboken, NJ: Wiley, 2013. [3] S. McCracken and J. Tatman, "Comparison Of Ductility-Dip Cracking To Computer Modeling With Sysweld™ In A Narrow Groove Multi-Pass Weld," in Pressure Vessels and Piping Conference, Vancouver, Canada, 2016. [4] S. Luther and B. Alexandrov, "Recreating Thermo-Mechanical Histories Causing Ductility-Dip Cracking Using Simulated Strain Ratcheting," *The Welding Journal*, Accepted June 2020.

Acknowledgements

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