

Modeling Friction Stir Welding through Advanced Scaling Techniques

John A. Roubidoux

Colorado School of Mines

Patricio F. Mendez

Colorado School of Mines

Abstract: Materials of all types are processed using the same fundamentals. The different types of materials include metals, ceramics, polymers, electronic, and more, and their processing invariably involves heat transfer, fluid flow, solid mechanics, diffusion, chemical reactions, and other phenomena, often with two or three phenomena tightly coupled. Presented is a coupled model of the deformation and heat transfer in Friction Stir Welding (FSW). In the analysis of this problem, a threadless pin is considered and the effects of the pin and shoulder are separated. The model presented helps understand the torque, temperatures, and deformation history of the material near the rotating pin, but it does not address the mechanical mixing occurring behind the pin.

1. Methodology: Scaling principles include techniques such as dimensional analysis, similarity, asymptotics, scale models. Scaling principles have the following useful properties: 1) they provide design rules that can be used immediately by design engineers to conceive a process based on non-equilibrium phenomena; 2) they provide guidelines to extrapolate processes that are successful in one alloy system to another; 3) they provide guidelines to extrapolate a non-equilibrium process across size scales; and 4) they summarize the balance between dominant driving forces in non-equilibrium processes. By applying scaling principles we obtain scaling laws. Scaling laws have the functional form of a power law of the relevant problem parameters such as the following proposed scaling law for penetration in manual welding [20]

$$P = G I^{4/3} V^{-1/3} E^{-2/3} \quad (1)$$

Where G is a constant, I is the current, V is the travel speed, and E is the voltage. We observe in this power law that the parameters are raised to a constant power. Expressions where a constant is raised to a variable power are not power laws in this context; thus, if a is a constant, and P is a parameter, P^a is a power law, but a^P is not. As power laws are aimed to compare different welding processes, they are based

on the parameters, and not on the problem variables (space, time). Thus if L is a length in the x direction, L^a is a useful power law to compare welding alternatives, while x^a is not.

Power laws are a natural consequence of dimensional homogeneity [21], which states that all terms in an equation must have the same dimensions, and dimensions can only be formed as power laws of basic units such as m, kg, s. The fundamental nature of power laws is also evident in the engineering wisdom that “everything is a straight line when plotted in a log-log graph.” In mathematical terms, the straight line $y' = ax' + b$ in a log-log plot corresponds to the power law $y = 10^b x'^a$, where $y' = \log y$, and $x' = \log x$.

Power laws clearly indicate trends and can yield accurate predictions over several orders of magnitude, and they also convey much intuitive meaning: the sensitivity of a power law to a given welding parameter is directly proportional to the exponent of the parameter.

2. Scaling Today: The original and simplest approach to obtaining scaling laws from differential equations is inspectional analysis, which involves the construction of dimensionless groups from the governing equations. This approach was briefly presented by Bridgman [1], made explicit by Ruark [2], and is included in classic textbooks on Transport Phenomena such as Geankopolis [3], Bird, Stewart, and Lightfoot [4], and Szekely and Themelis [5]. More recently, authors devoted entire chapters or whole books to exploring deeper aspects of scaling. Among them Denn [6] and Deen [7] devoted a whole chapter to scaling, Kline [8] devoted a whole book, and Dantzig and Tucker [9] put emphasis on scaling throughout their whole book on modeling of materials processing. Bender and Orszag focused on simplification methods based on self-consistency and explain the “dominant balance” method for simplification of differential equations [10].

Although little in comparison to other modeling techniques, peer reviewed journals have published articles specific to scaling. Sides [11], Chen [12], and Astarita [13] focused on heuristics useful for scaling. All these articles aim at the manual obtention of unknown characteristic values, thus put emphasis on rough estimations of the differential expressions, and avoid considering unwieldy coupling between the equations. Yip [14] proposed an artificial intelligence approach based on an automated search for self-consistent balances, yet still using rough estimates for the differential expressions. The approach presented in this paper was first introduced in [15], followed by [16, 17, 18, 19].

3. Friction Stir Welding (FSW) of higher temperature metals: TWI invented the friction stir welding process in 1991. It is a solid-state process that joins metals through mechanical deformation. In this process a cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together, as shown in Figure 1.

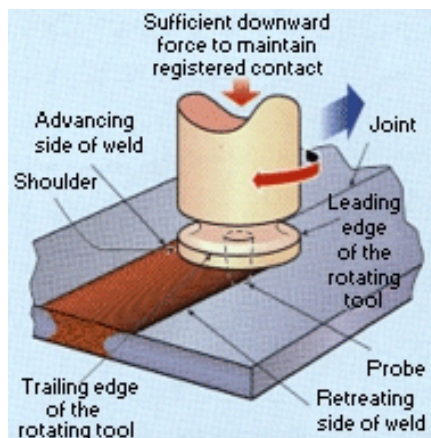


Figure 1: Schematic of Friction Stir Welding (courtesy of TWI)

This process can weld previously reported unweldable aluminum alloys such as the 2xxx and 7xxx series used in aircraft structures. The strength of the weld is 30-50% greater than with arc welding. The fatigue life is comparable to that of riveted panels. One of the current challenges for FSW is to weld higher melting temperature metals such as steel, titanium, and copper-based alloys. Some amount of success has been accomplished in these areas, as presented during the latest Trends in Welding Research conference this year, but their development is clearly behind that of aluminum.

Many of the challenges in FSW higher temperature alloys are intrinsic to the use of higher temperatures and stronger alloys. This increases tool

wear and complicates machine setup. Also, there still are significant process related challenges. For example, the rotation and translation speeds are still determined by trial and error for each new alloy. The vast amount of FSW knowledge of aluminum is of little help in setting up the conditions to FSW steel and titanium.

Scaling principles can help overcome these obstacles by generating universal laws and criteria that must be preserved across alloy systems. In modeling FSW, two challenging problems must be addressed: the mechanical deformation of the base metal in the vicinity of the tool, and dissipation of the generated heat to the rest of the material. These become especially complex if we consider that deformation happens in a corkscrew fashion trailing the rotating pin and in a flat manner under the shoulder of the pin. The pin might also incorporate a thread, which further complicates the modeling.

The following analysis was developed with the help of Tom Lienert from Los Alamos National Laboratory and Tony Reynolds from the University of South Carolina [30].

4. Coupled Thermal and Mechanical Analysis in FSW: Modeling of FSW is radically different than modeling of fusion welding processes, since it happens completely in the solid state. First, materials properties are not well known at the high temperatures, strain rates, and strains involved in FSW. Second, the process is inherently coupled, and softening in the Heat and Deformation Affected Zone (HDAZ) is directly related to the heating, and the heating is due to extreme plastic deformation.

Consider FSW using a pin without thread. The analysis considers the shear layer around the pin, close to the mid-thickness of a thick plate. In this case, the influence of the tool shoulder and of the back surface will be minimized and will be neglected. This shear layer resembles a thin cylindrical sheath around the pin. In this sheath the material is being deformed at a very fast rate, generating heat. We could call this region a “non-adiabatic shear band.”[30].

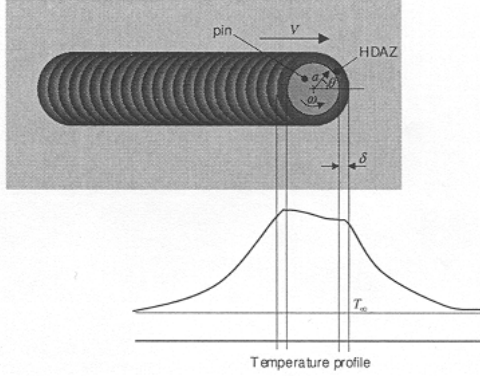


Figure 2: Temperature distribution along longitudinal axis [30].

5. Heat and Deformation in the HDAZ: The hypotheses stated imply that the properties in the HDAZ are relatively independent on the position θ around the perimeter of the pin. Thus, the analysis of the HDAZ can be further simplified as the one-dimensional problem of a semi-infinite solid whose face is being sheared away. The corresponding temperature and deformation profiles are illustrated in Figure 3 [30].

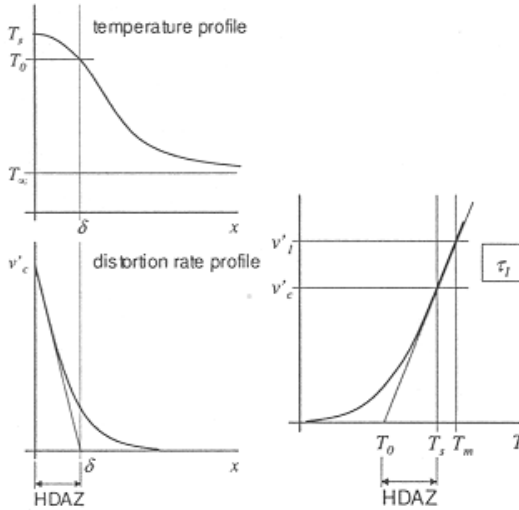


Figure 3: Left: Temperature and distortion rate profiles in the HDAZ. Right: Constitutive behavior of base metal.

For typical tool rotating speeds, conduction heat transfer is dominant radially, and the rotating motion of the metal creates a uniform temperature circumferentially (this can be verified using the Peclet number with the tangential velocity of the tool and the thickness of the shear layer). With these considerations the problem can be considered one-

dimensional and steady state. The following equation captures the heat transfer problem:

$$\alpha \frac{d^2 T}{dx^2} + v_N \frac{dT}{dx} + \frac{\alpha}{k} \bar{q} = 0$$

$$T(0) = T_{\max}, \quad \frac{dT}{dx}(0) = 0$$

Where T is temperature, α is thermal diffusivity, x is the distance from the pin-base metal interface, v_N is the velocity of the tool head, k is thermal conductivity and \bar{q} is heat flux. The shearing velocity is related to the shear rate in the solid by

$$v_T = \int_0^\infty \frac{dv}{dx} dx$$

Where $\frac{dv}{dx} = \dot{\gamma}$ is the shear rate of the plastic deformation. These equations capture the solid mechanics problem in a simplified way. The coupling between these two equations is given by the behavior of the solid. Very little information is available for the high temperatures and shear rates typical of FSW. Extrapolation from available data [31] suggests the following constitutive equation is a good approximation

$$\dot{\gamma} = A \tau_s^n \exp\left(-\frac{B}{T}\right)$$

Where A and B are empirical constants, τ_s is shear stress, and T is absolute temperature. Proper normalization involves dividing the heat transfer problem into a region of deformation and heat generation, and another region of heat transfer without deformation.

6. Preliminary Results: Foregoing the algebraic manipulations, estimates for the thickness of the shear layer, δ_v , and the maximum temperature in the shear layer T_{\max} can be obtained using the following power laws:

$$\delta_v = 2 \left(\frac{\alpha \Delta T_{1/2} v_T}{v_{1/2} v_N \Delta T_T} \right)^{1/2} \left(\frac{2 \alpha v_T \tau_{1/2}}{v_N \Delta T_T k} \right)^{n/2}$$

$$\Delta T_v = \left(\frac{\Delta T_T \Delta T_m v_T v_N}{\alpha C} \right)^{1/2} \left(\frac{2 v_T \tau_{1/2} \alpha}{v_N \Delta T_T k} \right)^{n/2}$$

Where the subscript $1/2$ indicates a temperature half way between melting and the beginning of thermal softening, v_T is the circumferential velocity on the surface of the pin. C is an empirical constant related to A and B .

For aluminum 6061, these equations predict a shear layer thickness of 0.83 mm and a maximum temperature of 514 °C for 250 mm/min welding velocity, and a tool of 5 mm diameter rotating at 300 rpm. For 500 mm/min and 800 rpm, the predicted shear layer thickness is 0.72 mm and the maximum temperature is 525 °C. These values are of the right order of magnitude for typical friction stir welds.

7. Discussion: The formulas presented are a reasonable starting point to compare FSW of different alloys, or of the same alloy under different conditions. If proven right, these formulas could also be used to make inferences about the unknown mechanical behavior of the material by measuring torque and temperature during FSW. This way some unknown materials properties could be compiled as approximated values until they are measured with specific tests.

In the work to be developed, the scaling principles described will be tested experimentally with the assistance of Tom Lienert from Los Alamos National Laboratory. They will also be extended to consider the effect of different pin configurations, such as threaded pins, the effect of the shoulder, and the effect of the complex swirling metal motion behind the rotating pin.

8. Acknowledgements: This work is sponsored by NSF's Design & Manufacturing Program. Grant Number: DMI-0547649.

References

- [1] P.W. Bridgmann. *Dimensional Analysis*. Yale University Press, New Haven, first edition, 1922.
- [2] A.E. Ruark. Inspectional Analysis: A Method which Supplements Dimensional Analysis. *Journal of the Mitchell Society*. 51:127-133, 1935.
- [3] Christie J. Geankoplis. *Transport Processes and separation process principles: (includes unit operations)*. Prentice Hall Professional Technical Reference, Upper Saddle River, NJ, 4th edition, 2003.
- [4] R. Byron, Warren E. Stewart, and Edwin N. Lightfoot. *Transport Phenomena*. J. Wiley, New York, 2nd, Wiley international edition, 2002.
- [5] Julian Szekely and Nickolas J. Themelis. *Rate Phenomena in Process Metallurgy*. Wiley-Interscience, New York, 1971.
- [6] M.M. Denn. *Process Fluid Mechanics*. Prentice-Hall International Series in the Physical and Chemical Engineering Series. Prentice-Hall, Englewood Cliffs, NJ, 1st edition, 1980.
- [7] William M. Deen. *Analysis of transport phenomena*. Oxford University Press, New York, 1998.
- [8] S. J. Kline, Similitude and Approximation Theory, Springer-Verlag, New York, (1986).
- [9] J.A. Dantzig and Charles L. Tucker. *Modeling in materials processing*. Cambridge University Press, Cambridge England; New York, 2001.
- [10] C. M. Bender, S. A. Orszag, Advanced Mathematical Methods for Scientists and Engineers, McGraw-Hill, New York, (1978).
- [11] P.J. Sides. Scaling of differential equations. "analysis of the fourth kind". *Chemical Engineering Education*, (summer): 232-235, 2002.
- [12] M. M. Chen, Scales, Similitude, and Asymptotic Considerations in Convective Heat Transfer, in: Annual Review of Heat Transfer, C. L. Tien (Ed.), 3, Hemisphere Pub. Corp., New York, (1990).
- [13] G. Astarita, Chemical Engineering Science, 52, 4681-98 (1997).
- [14] K. M. K. Yip. Model Simplification by Asymptotic Order of Magnitude Reasoning. *Artificial Intelligence*, 80(2): 309-348, 1996.
- [15] P. F. Mendez, Order of Magnitude Scaling of Complex Engineering Problems, and its Application to High Productivity Arc Welding, Doctor of Philosophy Department of Materials Science and Engineering, Massachusetts Institute of Technology, (1999).
- [16] P. F. Mendez, T. W. Eagar, in Proceedings of Seventeenth Symposium on Energy Engineering Sciences, Argonne, IL, 106-13 (1999).
- [17] P. F. Mendez, T. W. Eagar, in Proceedings of International Conference on Modeling and Simulation of Metal Technologies, MMT-2000, Ariel, Israel, 636-45 (2000).
- [18] P. F. Mendez, T. W. Eagar. The matrix of coefficients in order of magnitude scaling. *In Fourth*

International Workshop on Similarity Methods, pages 51-67, Stuttgart, Germany, 2001. University of Stuttgart.

[19] P. F. Mendez, T. W. Eagar. Modeling of materials processing using dimensional analysis and asymptotic considerations. *Journal of Materials Processing Technology*, 117(3): CD-ROM, Section B9: Modeling, 2001.

[20] R. Gunnert, *Welding Journal*, 542- (1948).

[21] P. W. Bridgman, *Dimensional Analysis*, Yale University Press, New Haven, (1922).

[22] J. F. Lancaster, *The Physics of Welding*, Pergamon Press, (1986).

[23] J. F. Lancaster, *The Physics of Welding*, Pergamon Press, (1986).

[24] S. Kou, *Metallurgical Transactions A-Physical Metallurgy And Materials Science*, 13, 363-71 (1982).

[25] Y. H. Wang, S. Kou, in *Proceedings of Modeling and Control of Casting and Welding Processes*, Santa Barbara, CA, 197-209 (1986).

[26] W. Zhang, C. H. Kim, T. DebRoy, *Journal Of Applied Physics*, 95, 5220-9 (2004).

[27] W. Zhang, G. G. Roy, J. W. Elmer, T. DebRoy, *Journal Of Applied Physics*, 93, 3022-33 (2003).

[28] T. Debroy, S. A. David, *Reviews of Modern Physics*, 67, 85-112 (1995).

[29] P. F. Mendez, in *Proceedings of Trends in Welding Research*, Pine Mountain, GA, (2005).

[30] P.F. Mendez and T.J. Lienert. Non-adiabatic shearing in Friction Stir Welding. *TMS Letters*, 2006.

[31] Y. V. R. K. Prasad, S. Sasidhara, *Hot Working Guide, A Compendium of Processing Maps*, ASM, (1997).