Friction Stir Welding Defects, Analysis and Correction:

History and Defects of Solid-state Welding

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Abstract

Friction stir welding is a reasonably new method for materials processing and fusing which enables the combination of dissimilar materials. The process as designed by The Welding Institute provides a unique approach to manufacturing where plastics and metals can be combined for any combination of designs and still retain similar tensile strengths or greater than other forms of welding. This process is not free of defects that can alter, limit, and occasionally render the resulting fusion of materials unusable.

Most popular amongst these defects is the wormhole defect that often goes un-noticed by the machinist. To correct these defects, this report presents a background to the process of friction stir welding, an examination of the defect's origins, and a potential method to determine at run time potential defects and implement correctional behavior to correct the weld.

Introduction

Background

Alterations in mechanical design, structure and implementation of various materials is constantly changing as new technologies are derived. With new materials to manufacture and components to develop, various methods of combining similar and dissimilar materials are in high demand, but none so much as Friction Stir Welding (FSW). This relatively new form of material fusing has wide ranging applications, but also possesses areas of concern when trying to develop defect free welds. Many such defects are hidden beneath the weld surface, creating a potentially dangerous scenario should a defective weld be implemented.

Objectives

The research presented is intended to broaden the reader's understanding of the process of FSW, provide insight in defects and potential reconciliation of the weld, and critically analyze the usefulness of a friction stir weld correctional unit in machining of future welds. To best engage these objectives, it is advisable that the reader keep the following in mind:

1. What is the process of friction stir welding and how does it differ from methods such as stick, arc, etc.? And are these differences intrinsically responsible for the defects?
2. What advantages does FSW hold for machining?
3. What other variables play a role in the formation of successful and defected welds?

Developmental Plan

This review will evaluate five key areas of focus:

1. Broader Impact: Extrapolation towards the technique of FSW as both versatile and structurally efficient as well as comparative analysis regarding good and bad welds.
2. Historical Overview: A brief description of instantiation of FSW and current usage.
3. Current Analysis and Technique: How variations in weld and material formations differ with regard to variables in the process and common defects.
4. Discussion of Technique: How analyzing the defects provide greater insight to correction.
5. Future Work: Development of Runtime-Assisted Control Systems: Evaluation of defect nature and potential for auto-correction of defects during a weld.

Broader Impact

Considerations for fusion, arc and other welding techniques have been a large part of general machining and manufacturing for some time. The development of solid state friction stir wielding presents many unique advantages over existing fusing techniques in that[1]:

1. Friction stir welding can fuse heterogeneous materials such as steel and aluminum, different alloys and non-metal materials such as plastics and plastics to metals [7, 8].
2. Versatile pin-tools and techniques can fuse hollow and solid materials at near similar efficiencies [10].
3. Fused materials generally contain less residual stress which inhibits tensile strength, tactile strength, etc. [5, 6].

This new technology is not without errors and defects as was its predecessors. The typical wormhole defect is often a hidden and vast influence of tensile and tactile strength. Where this procedure excels lies in its ability to fuse entire sections of materials rather than shallow surface joining.

These defects are likely directly correlated to key process parameters which when evaluated in a dynamic runtime system can be used to isolate critical points of their creation, expansion and termination. By creating a self-sustained system that can automatically adjust welds to maintain integrity, friction stir welding will become a more versatile and widely used system of material fusing.

History

Friction Stir Welding (FSW) was developed by Thomas et al. at the Welding Institute in Cambridge, England[11]. The Solid-State technique for plasticizing materials has rapidly become a popular method of fusing dissimilar materials and traditionally non-weldable materials alike [8]. By rotating a pin-tool across butted materials at speeds just quick enough to make the materials soft

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[1] Recommendations for further reading can be found on page 17

(Figure 1), a weld can be made [1, 2, 3] leaving a distinct weld pattern (Figure 2). The variations on weld formation have been heavily studied with regard to speed of the pin-tool's traversal and rotation speed as well as other manufacture-time variables such as heat, resulting crystallization of material [8], and shape of the pin-tool and it's threading [7].

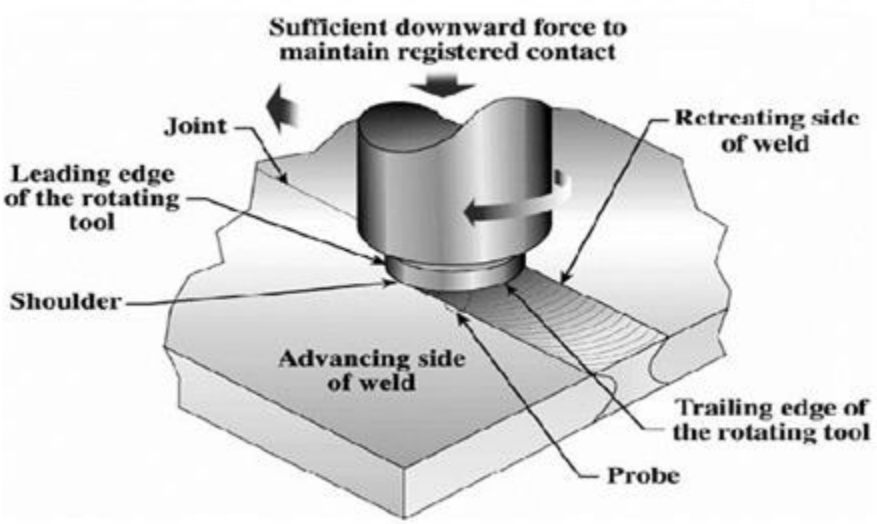


Fig. 1: Anatomy of A Weld in process [3]

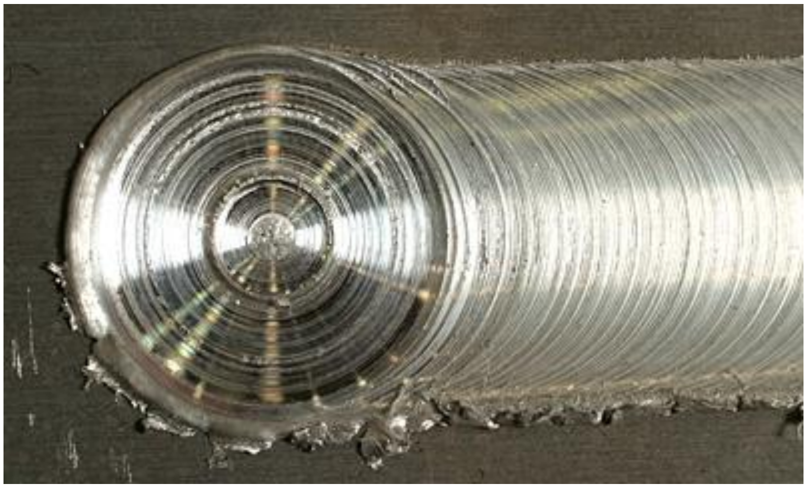


Fig. 2: Typical weld [12]

The research developed from these variations provided the basis for understanding of manufacturing welds with sufficient grain redistribution [8] and tensile strength for welds [7]. The standard has also been established for threaded pin-tool use; as Bilici observed, “Biggest tensile strength [was] obtained with [a] threaded tool. […] Pitch length of threaded pins [is] very important for the weld quality and the weld strength.”[7]. Unfortunately, until recently the method for creating a defect-free weld – or a weld with proper mixture of both materials and no voids – was centered on trial and error for speed of traversal as well as rotational velocity of the pin tool [1]. New hypothesis are emerging that suggest that though weld speed and rotational speed are important to help rectify the defects [2, 3], the cause of these defects are found in temperature and orthogonal forces to the pin-tool’s traversal.

Current Analysis and Technique

Modern technique for interpreting weld integrity has historically been analyzed by dissection, analysis and testing for the weld for proper tensile and tactile strength. A procedure such as this requires that the resulting weld be abandoned so the width of the bin tool (resulting fused material) can be subjected to a series of rigorous and ultimately destructive experiments to evaluate the effectiveness of the weld. During the early years of FSW, machinists and researchers started to look at flow patterns of the resulting weld with tracing materials that could be visually (and with microscopes)evaluated [9, 10]. Though this method provided an enhanced understanding of the reformation of the separate materials, the resulting bond is forever altered. As an alternative for tracing materials, micro-ct scanning technologies can be implemented to evaluate material flow, and any potential stress fractures or wormholes.

Tracer Materials

Among pioneering research efforts to determine material flow behavior were M. Guerra et al and Murr et al. Guera's focus on material's reformation behind the progressing weld pin provided some of the fundamental understanding of how the materials behaved with different materials [9]. Some of the initial welds of aluminum and copper illustrated the blending – "vortices" – were easily traceable by the naked eye [10], see figure 3.

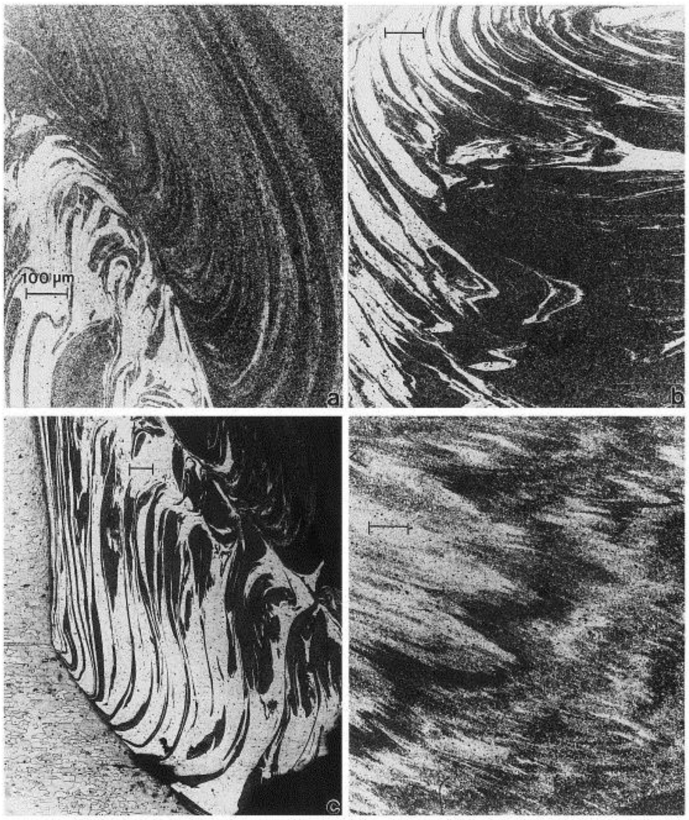


Figure 3, Dissimilar Material Vortices [9]

Further analysis as variable speeds of pin-tool rotation and weld traversal provided a distinct estimation of flow variability, but only with respect to copper and aluminum; a new test would be devised using steel balls as tracing materials [9]. Such resulting traces though harder to detect without imaging equipment appear readily when scanned using an X-ray machine, figure 4 [9].

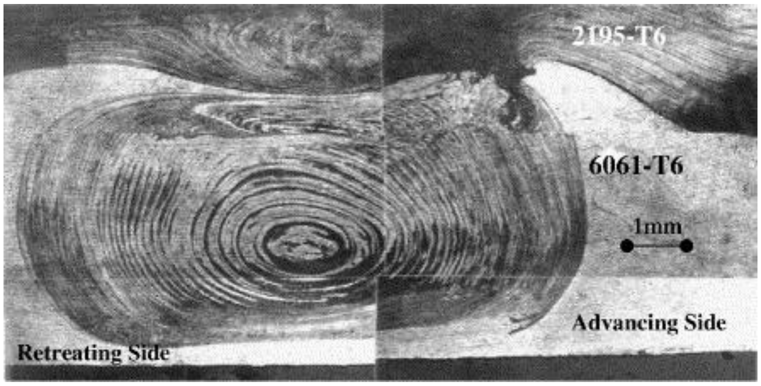


Figure 4, Bead Tracers, [9]

Alternate Analysis

Implications can be made about the use of tracing materials in functional welded materials such as the impact on weld integrity, resulting crystallization deformations and limitations to tensile strength.

As an alternate method to tracer materials, computational methods are being implemented to evaluate the efficiency of the weld without the use of tracers. These are based on analysis of the weld signal data as provided by South Dakota School of Mines and Technologies' (SDSM&T) ISTIR [3] welding machine and the Xradia micro-XCT imaging machine with VSG Avizo Fire.

Sensor Observations

The ISTIR machine at SDSM&T is capable of running welds with sensor data updates between 60 and 1024 updates per second. Each signal captured can contain more than forty parameters from pin-tool torque to distance traveled. Through signal analysis with relation to defective welds, Boldsaikhan, et al. have found a seeming correlation with relation to movement orthogonal to the direction of the welded material (X Force) and the force of the forge (Z Force) which will hence be referred to as the Y-Force [1] – illustrated in figure 5.

Discussion of Technique

Weld sensor data indicates that as the pin tool progresses along the X direction, material flow causes slight movement into one or the other material in a cyclic manner [2]. This behavior is not in itself an indication of a defective weld. Rather the rate of change or first derivative of the Y-Force, can indicate a less than ideal flow of material behind the tool, yielding possible defects [1, 3]. Phase space analysis of the weld tool is the fundamental principle behind this mapping of Y-Force variance. Figure 6 illustrates, if at a given rotational position a point is mapped to a weld location as a plane, and a second point is mapped after one full rotation, the distance between the two points provides insight to the underlying flow [3].

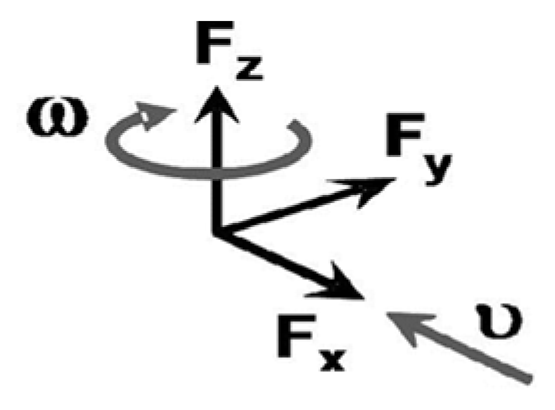


Figure 5. Force Representation [1]

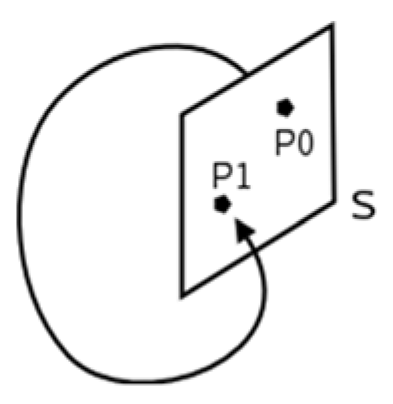


Figure 6: Phase Space mapping [3]

Further analysis done by Janes, Corwin, and Logar have suggested that as different materials have different temperatures needed to achieve a plastic flow, the focus of correction will likely lie in monitoring the Y-Force[3]. It was also proposed that a system to use the Y-Forces cyclic nature to map against its derivative to achieve representative graphs of sectional behavior [3]. These mappings as shown in figure 7 illustrate how a sensor's Y-Force data can be represented as good or defected weld sections.

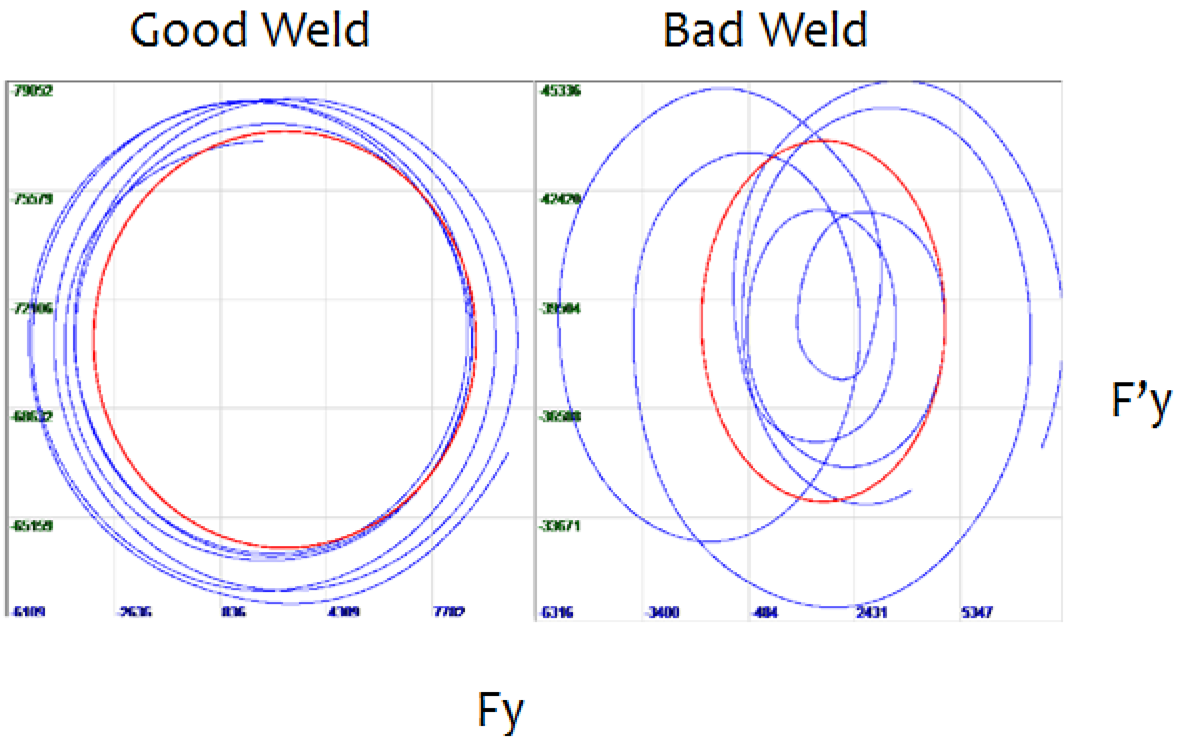
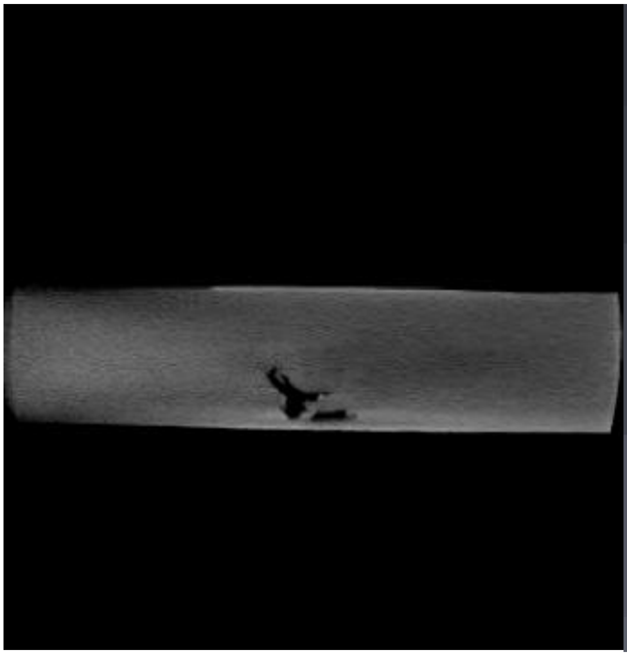


Figure 7, Circle Mapping [3]

When this behavior is combined with our understanding of weld material flow, it would seem that the materials being welded are not hot enough to flow smoothly behind the pin-tool, which in turn causes the orthogonal movement into one of the two materials.

To further evaluate the behavior of the defects, samples of defective welds were made with 6061 aluminum and were then imaged with technologies such as the Xradia Micro-XCT and Avizo Fire. These samples were run over a range of eight to twelve inches where the main controlled parameter was the variation in weld speed or X-Force. The sample's various accelerations displayed expected circle mapping results when above twelve inches per minute and would return to a good weld's mapping after reducing speed to ten or below. These samples were then cut into three lengths along the weld and imaged separately with the Xradia Micro-XCT (Figure 8).



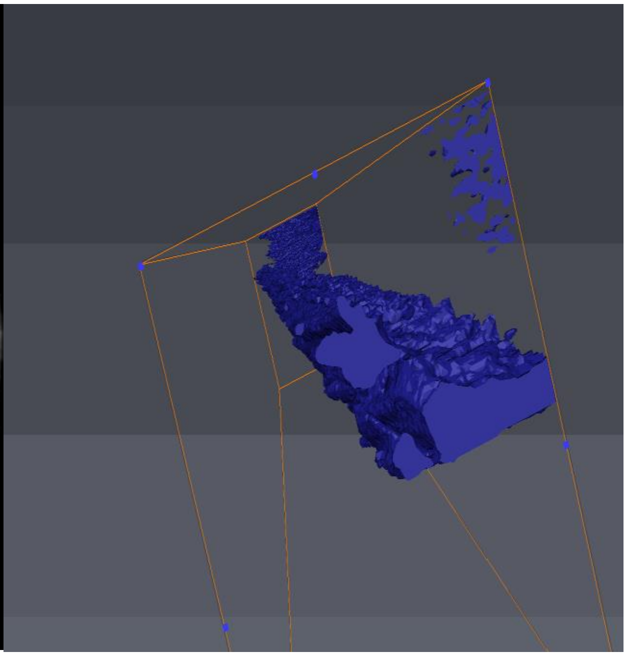


Figure 8A, Defective Weld (Xray)

Figure 8B, Weld Defect (Avizo)

To assist the correlation efforts of defect inception, expansion, and termination, Avizo Fire is used to negate the material and expose the defect as a three dimensional solid (figure 9). These extrapolated defects provide insight to the nature of the defect as weld speed varies. The rendering in figure 9A is a good example of the hypothesis of cyclic expansion of defect due to material being too cool to fully fill the weld after the pin has displaced the material. As the weld from this sample slows, the defect reduces in size and splits into two smaller pieces which terminate in the third piece of this sample.

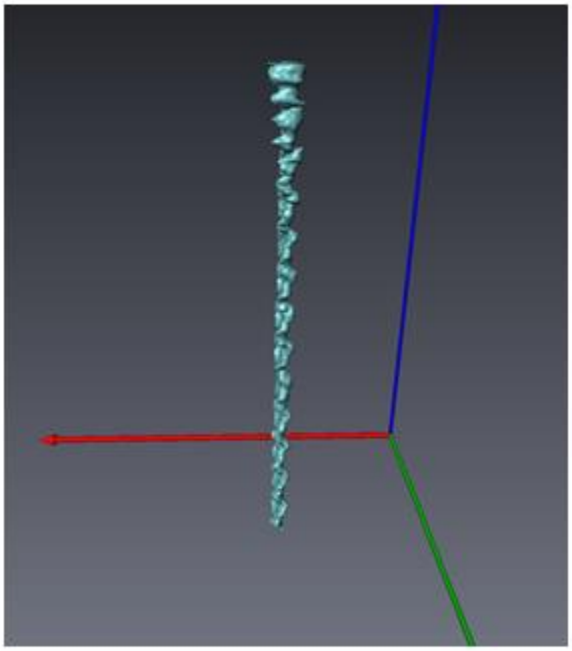


Figure 9A, Fast

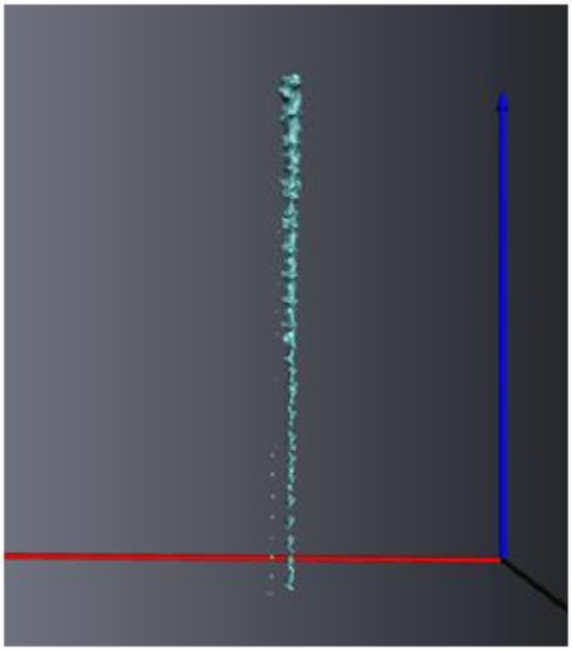
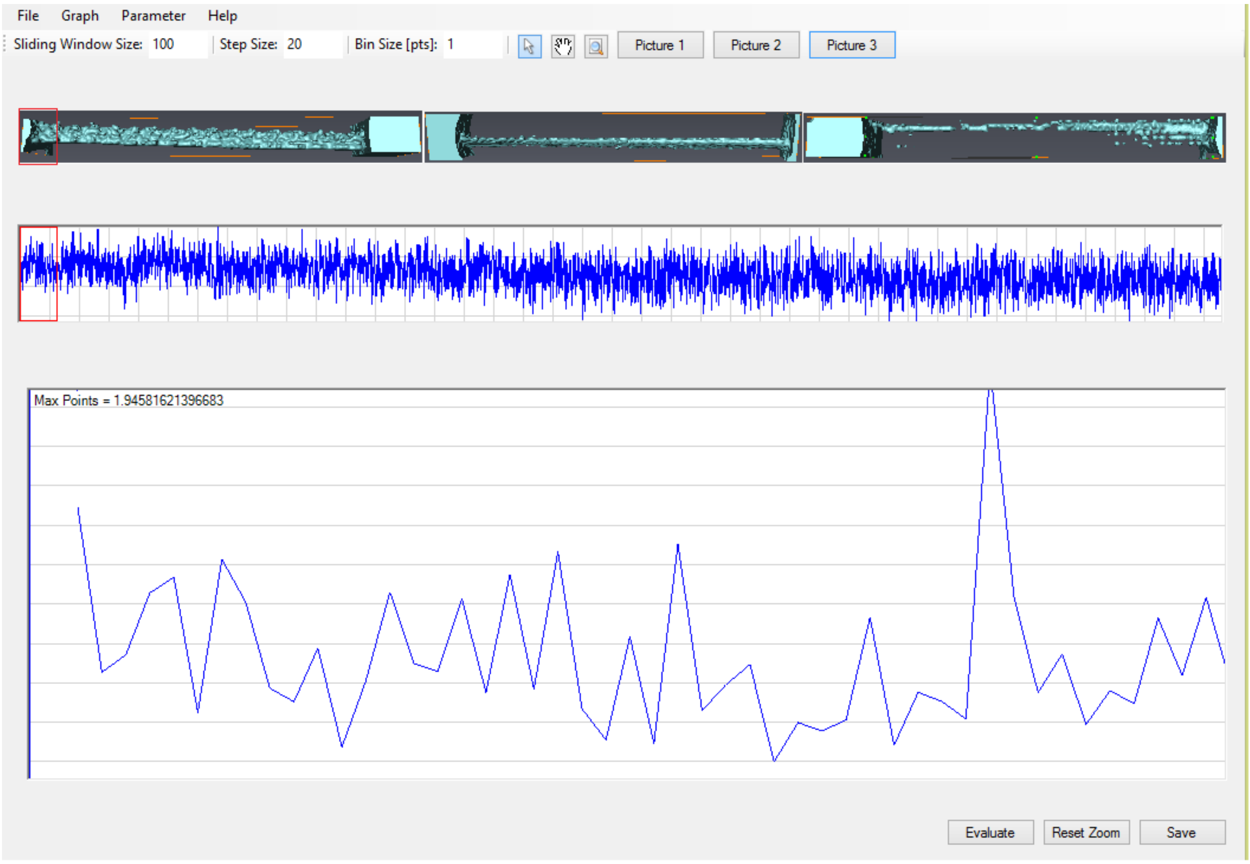


Figure 9B, Transition

Current correlation methods include an adaptation of the software designed by Janes, Corwin, and Logar to include a detailed signal listing, defects, and images of the defect for easy comparisons as in figure 10. Though a good understanding of the cause and the expansion are understood, there is still little known about how a defect develops its shape or directions of expansion. The focus on this correlation is equally split amongst the defected weld's sensor information just before a defect is created and just after one is eliminated. Once weld sensor data can be correlated to defect shape, an automated correctional utility will be integrated into the system to preserve weld integrity.



Sliding Window Size: 100
Step Size: 20
Bin Size [pts]: 1

Max Points = 1.94581621396683

Figure 10, Correlation Software, Michael Janes

Future Work: Development of Runtime-Assisted Control Systems

Proposed Control Systems

As correlation of defect behavior to weld sensor data become established (especially defect formation and termination), integration of an automated control feedback system will create a virtual safety net for future welds. A model for hardware interaction and control will be a fairly simple task to integrate.

If the ISTIR had very few parameters, then attaching a feedback control system to it could consist of a series of relays and simplistic computational devices could drive the desired behaviors. Two simplistic computational processors could be employed to react to the behaviors of the ISTIR; the first as a "monitor" of the sensor-data output from the ISTIR and executor of any commands to the ISTIR. The second would be an "investigator" of the data and react if needed see Figure 11.

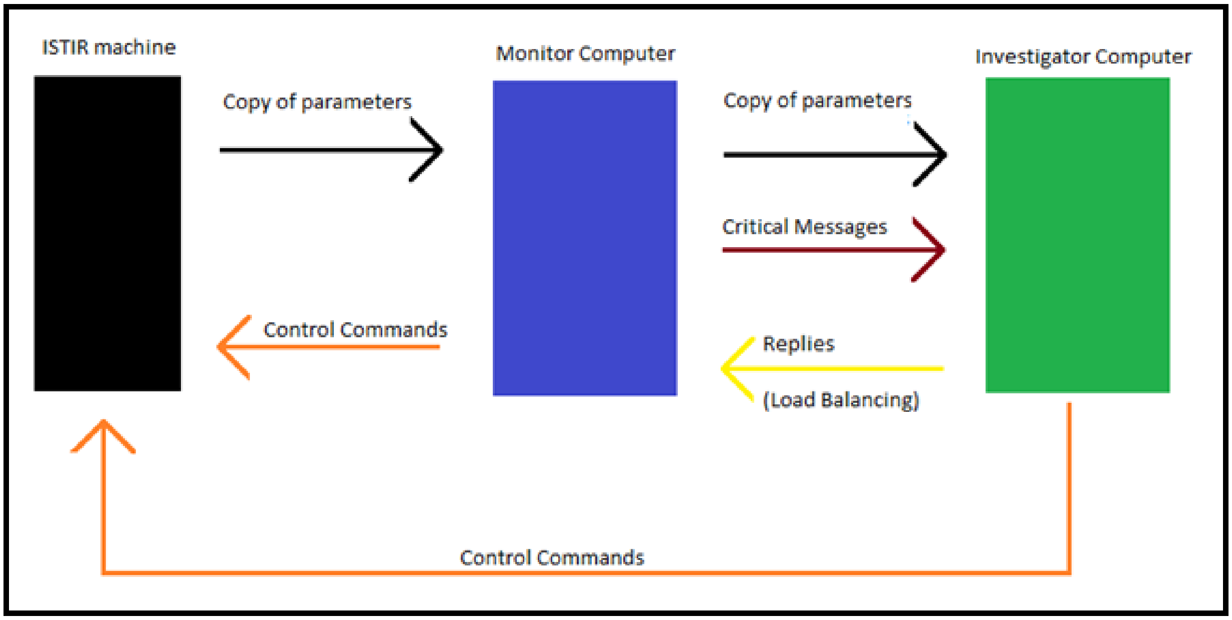


Figure 11, Architecture of Communication

The monitoring processor would have the task of immediate evaluation of all parameters. Should anyone parameter be indicative of a defect, the monitor would need to send a message identifying the parameter and its value to the investigative processor. All other data would be relayed to the Investigator for further analysis. This monitor processor should be able to assist in control commands directly should the Investigator be busy with needed calculations or transmission of control commands to the ISTIR.

The investigator processor would evaluate averages of time-distributed data and calculate the changes between each time-step's parameter values ($\frac{dy}{dx}$ or first derivative) and the rate of change between these ($\frac{d^2y}{dx^2}$ or second derivative). Once this is calculated and evaluated against threshold tables, an evaluation can be made as to corrective action, and to what extent. The investigator would have to be able to carry out execution of this task if it should receive a message identified as critical from the monitor. The provided parameter that is immediately identified as out of balance can be paired against its table value and the resulting command would execute.

Simple linear-feedback systems require a significant amount of math and table lookups to execute properly on a small number of variables. As mentioned, the ISTIR machine provides more than forty signals per time step, and would require many more computer systems working in parallel to perform as described. A potential approach to automated control can be handled in a new adaptive control system using a pure-feedback system as proposed by Na, Ren and Zheng [4]. This new system significantly limits the evaluations and back-stepping inherent in the described system.

A pure-feedback system uses the non-linear behavior of a particular system and applies the "mean value theorem on the non-affine functions [that represent behavior of the system] such that a pure-feedback system is represented in a strict-feedback form" [4]. When utilizing this system, two neural controllers will be required [4]. The first evaluates an approximation of the error associated with the non-affine function calculation, and the second functions like the previously defined example to reduce computation time and help handle "unknown nonlinearities" [4]. Though the construction of such a system would be a challenge programmatically, the resulting efficiency could be as high as $40^n * h$ where n represents the number of potential table look-ups and k represents the frequency per second of the sample data.

Conclusion

Summary

Evaluation of friction stir welding suggests a dynamic and versatile method for combining materials similar or dissimilar. The dynamic nature of this system, however, does allow for significant diversity in defects and requires significant attention to rectify. Though direct correlations have not been made to define tool and defect behavior, new imaging and sensor tracking techniques are narrowing the gap. As defect development becomes mapped simple correctional mechanisms will be employed to alleviate any defects before formation.

Recommendations for Further Reading

Heterogeneous Material Fusing:

M.K. Bilici – Effect of tool geometry on friction stir spot welding of polypropylene sheets. Found in Express Polymer Letters, 6(10), 805-813.

L. E. Murr, G. Liu, & J. C. McClure – A tem study of precipitation and related microstructures in friciton stir welded 6061 aluminium. From Journal of Materials Science, 33(58312/12), 1243-1251.

Established Practices and Pin-tools of FSW:

L. E. Murr, Ying Li, R.D. Flores , Elizabeth Trillo, & J. C. McClure – Intercalation cortices and related microstructural features in the friction-stir welding of dissimilar materials. Materials Res. Innovations, 2(3), 150.

Stress and Recrystallization:

N. Sun, North, T. H., D. R. Chen , & Y. H. Yin – Science and technology of welding and joining. From Influences of Welding Parameters on Mechanical Properties of AZ31 friction, 17(4), 304 - 309.

K. Deplus, A. Simar, W. Van Haver, & B. de Meester – Residual stresses in aluminum alloy friction stir welds. Found in International Journal of Advanced Mnaufacturing Technology, 2011(56), 493 - 505.

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