Increasing the Durability of Ultrasonic Welding Tooling

by

Daniel W. Smith

Clarkson University

Increasing the Durability of Ultrasonic Welding Tooling

A Thesis Proposal by

Daniel W. Smith

Department of Mechanical and Aeronautical Engineering

Mentor: Dr. Daryush Aidun

Industrial Advisor: Daniel C. Hutchinson, General Motors

March 11, 2011

Introduction

In industry, there is a constant strive for innovative processes are economically advantageous and still maintain a high degree of quality for the product. This has led to the development of new technologies in process engineering. Process and manufacturing engineering includes the joining of materials in ways such as welding and soldering, which has received special interest, especially beyond conventional means such as arc or spot welding. In particular, ultrasonic welding has received special attention. Ultrasonic welding can be used to join metals as well polymers, and has found uses in the electronics and automotive industries, particularly in wiretapping and in the manufacture of batteries. However, several variables are involved with ultrasonic welding that, when changed even slightly, can have a drastic effect on the quality of the weld produced. Abundant research has been done involving the pressure applied, frequency, and energy applied during the weld in order to produce welds with high yield stresses. However, little research has been done on prolonging the life of the tools within the welder. This paper proposes a method used with previous success to determine the composition of steel tooling in ultrasonic welding that will produce high quality welds while having a lifetime of several thousand weld cycles.

Unlike most forms of welding, which involve large amounts of heat to be generate to fuse two pieces into one, ultrasonic welding works by using a high frequency to cause the materials to diffuse into one another. The materials are placed between two parts of the welder, which are called the anvil and the horn. The anvil serves as an anchor point, a stable surface that holds the materials in place during the welding step. The horn is the component of the welder which vibrates at a high frequency, causing frictional heat while clamping the two materials together. The two materials are first inserted between the anvil and horn. The horn then clamps down, pushing the materials together and pushing them against the anvil. Once this is done the horn vibrates, the frictional heat causing the materials to diffuse and become one piece. This way of joining with only 2 materials is why it is advantageous to use this form of welding in electronic applications.

Because this technology is relatively unexplored, the components are expensive to produce. Companies and corporations that use this technology have huge budgets devoted to this technology and are looking for ways to reduce this budget by spending less money on the tooling. In particular, the horn is very expensive and can cost several thousand dollars each to produce. Therefore, these are the first to be researched for better durability. However, increased durability cannot come at the cost of weld quality. A more durable horn must be found that does not compromise weld quality. Previous tooling durability studies show that manipulating the composition of the steel produces drastic changes in the tooling durability. The particular element of interest is vanadium, which shows an increase in durability, but decreases after a certain vertex point. This vertex point is the key point of interest. As such, the core question is what is the best composition of vanadium in steel to prolong tool life in ultrasonic welding without compromising weld quality and durability? An exploration of the mechanics behind ultrasonic welding and previous research will provide more information.

Background

The basic mechanics behind ultrasonic welding are relatively simple. The horn applies a constant pressure to the weld constituents while the anvil keeps the constituents in place. When the horn vibrates, it does so generally at a frequency in the range of 20-22 kHz. When it vibrates, the oxide layer on the surfaces of the materials is broken up, exposing the pure base metal beneath [1]. The metals diffuse into each other, producing the weld. The temperature of the weld constituents remains low with respect to the melting point of the metal, which is why this form of welding is referred to as solid state joining [1]. However, there are more, subtle mechanics going on as well. These complex mechanics are the surface and volume effects. The surface effect describes the motion of one piece of weld constituent across another. The motion can be characterized by two phases: a "sticking" phase and a "slipping" phase. During the "sticking" phase, frictional and shear forces overcome the vibration forces of the horn, and allow for diffusion and mingling of the metals, essentially developing the weld [2]. By contrast, the "slipping" phase is distinguished by a displacement of one weld metal relative to another. This causes plastic strain in the metal as well as the breaking up of the oxide film on the surface of the metals [2]. The volume effect assists in describing the plastic strain caused, as it is a result of the energy imparted to the material by the vibration. On the lattice level of the material, dislocations and other imperfections present in the material are provided energy via the vibration, which causes them to overcome the energy keeping them in place. The plastic strain caused by these shifting imperfections contributes to the plastic strain present during the "slipping" phase, as well as disrupting the oxide film layer [2]. As is expected, the welding takes a toll on the horn and anvil, causing wear which leads to decay in weld quality over time. Common practice in industry is to increase the composition of vanadium present in tool steel in order to increase tool durability and resistance to wear. Studies exist to support this action [3]. A similar set up has been used successfully to do preliminary testing with varying compositions of vanadium. This study will be an extension of the previous testing.

A review of the literature pertaining to the proposed study reveals a wide diversity of testing that has been done with respect to ultrasonic welding. However, a large portion of it was deemed irrelevant because it had to do with plastic welding rather than joining of metals. Out of the articles left, many are dealing with welding foils. This is useful in terms of background, but not indicative of results expected from the welding proposed in this study. The foils studied had thicknesses up to 1mm, whereas the proposed study deals with thicker materials [2],[4], [5]. Also, extensive research has been done on the weld parameters such as amplitude of vibration, energy input, and weld duration [5]. This is not useful in the frame of this study, as these parameters have been predetermined. Vast research has also been done on making the welds durable. These studies show that the weld itself can become stronger than the constituents it was welded from [4]. There are also computational models which are useful in describing at a level between that of a layman and that of a scientist the mechanics behind ultrasonic welding [6]. Some results of previous studies are also surprising, indicating temperatures of welding reaching 30-80% of the melting point of the constituent metals [7]. Those results are questionable, as this author has had no experience of the constituent metals reaching those sorts of temperatures. After reviewing the literature, it was found that there were no studies directly pertaining to durability of ultrasonic weld tooling.

This gap in the research of ultrasonic weld tooling durability is a serious gap. No research exists testing the durability of either anvils or horns. However, this could be because what research has been done remains in the corporate realm. However, the methods proposed for this study exist independently, and this study is essentially a combination of those methods, which will be described [2], [3].

Research Methodology

The process for this study will be as follows. The horns that will be tested will be made of steel with compositions of vanadium ranging from 11% to 14% by increments of 1%. This means that there will be 4 horns to test. Each horn will be subjected to a null test with pressure paper and welding test coupons. Pressure paper is a type of paper that when subjected to compression acts similar to carbon paper. It changes to different colors based on the pressure applied to the paper, and the color can vary across the paper. This paper will be used to determine wear rates of the horns. Test coupons are small pieces of weld constituent that are run through a weld sequence so that they are welded together. These will be pull-tested to determine the yield stress of the weld, which can be used to determine the quality of the weld. After these tests, the horn will be run through 500 welds, and these tests will be repeated. The welding followed by testing will be done until the horn reaches 3000 welds. The tests will be run again at 3000 welds as an end point. The process of repeating of the welds and taking data will be repeated for each of the horns. The data across the weld points will be plotted against each other, with one plot for the wear rates and another for the yield stress of the test coupons. These plots will also have the data for the horns with 10% and 15% composition vanadium. The horn with the best wear rate along with the best yield stress in the welds will have the optimal composition for use in tooling.

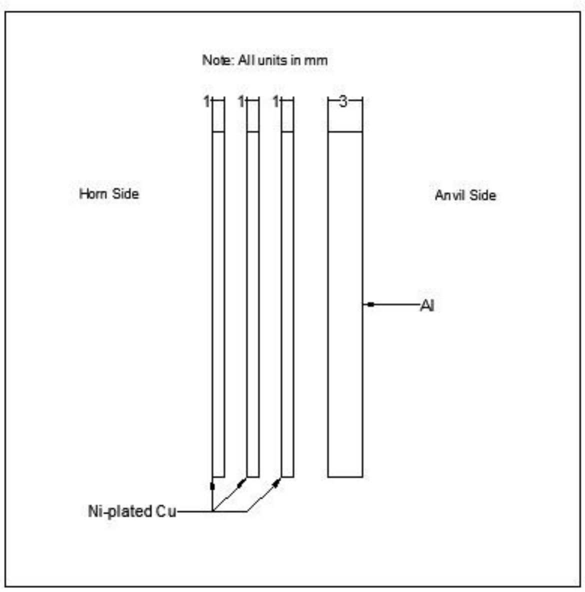


Figure 1

The materials used as the weld constituents will be three strips of 1mm thick nickel-plated copper as well as one strip of 3mm thick aluminum in the welder. The test coupons for the pull-testing will have the same constituents in the same order. The horn will be on the side of the nickel-plated copper, and the anvil will stay on the side of the aluminum, as shown in Figure 1. The welder controller which controls other physical variables of the weld process will have the following weld settings. The frequency of the horn will be 20 kHz, the amplitude of the horn vibration will be 8 µm, and the energy applied will be 3300 W ± 500 W. The energy applied will be more of a guideline, as it will vary from weld to weld and may stray outside the tolerance window. A weld outside this window will be comparable to welds within the tolerance window based on running this experiment previously. This means the tooling will not bear any excess or reduction in wear, which will not skew data.

Preliminary Data

Research using the outlined method was done during the summer of 2010. The horns studied included horns containing 2, 5, 10, and 15% vanadium, denoted by the prefix CPM, which pertains to the manufacturing process used to forge the horns. The general trends, as Figure 2 shows, for the change in volume over the number of trial welds, there is an improvement as the composition of vanadium increases from 2% to 10%. However, the wear increases when the composition is at 15%. Also, for the weld strength data, shown in Figure 3, the welds become stronger in general as the composition of vanadium increases. These trends imply the presence of a peak effectiveness of increasing the composition of vanadium between 5% and 10%. This peak will by hypothesized to be between 10% and 15%, which is why the experimental method will use horns with compositions from 10%-15%. If the peak is found to be within the experimental range, then the peak will have been found. If the peak is not found to be within the experimental range, then the peak exists between 5% and 10%. Figure 4 shows qualitatively the difference in wear between the CPM-2V horn that was used as a baseline and the CPM-10V which was determined to have the best wear rate out of the tested horns. The pictures of individual knurls are at 50x magnification.

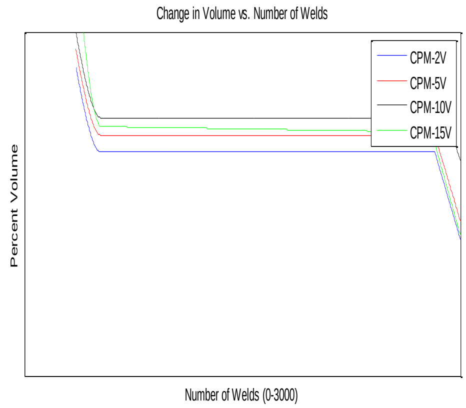


Figure 2

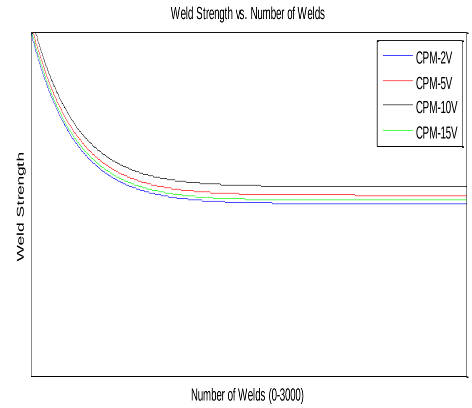
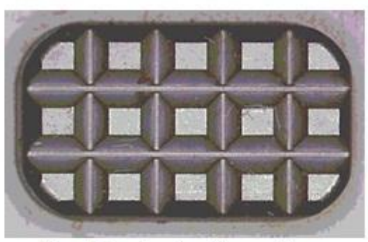
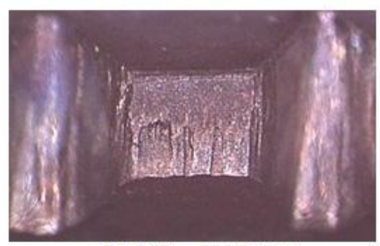


Figure 3

CPM-2V (Baseline) – 3000 Welds



Stapla Production Horn - New



CPM 10V – 3000 Welds

Figure 4

Timeline

This proposed research is very involved, considering its connection to General Motors, under whom the initial research was done. There will be many logistical situations that will need to be addressed. Acquiring materials will be the biggest issue to attend to, as both the horns and the weld materials are expensive. Also, welders with the ability to do this testing are in short supply. A current timeline of events is shown in Table 1.

Table 1

Date/Time period	**Event/Goal**
May 1st, 2011	Proposal accepted, horns and materials ordered
Early August 2011	Complete testing/data acquisition
October 1st, 2011	Complete data analysis, start writing thesis report
End of Fall Semester, 2011	Have completed most, if not all, of thesis report
Spring Semester 2012	Revise thesis report, prepare presentation
April 2012	Present results

To go into detail, by May 1st, 2011, the end of the Spring 2011 semester, the logistics for ordering materials will be completed. This way, there is leeway in case this deadline is not met, or if there is a delay in the shipping or receiving of the materials so that testing can begin promptly. Due to summer employment plans, the data acquisition which requires actually welding will most likely have to be held off until the end of the summer. Currently a welder is available for use with certainty in Michigan at a General Motors facility. However, ultrasonic welding manufacturers are being queried to determine whether a more local facility can be used. Based on previous experience, in an 8-hour workday, up to 1500 welds can be completed. Therefore, spending 5 days in Michigan working 10-12 hours daily as required would give enough time to complete the required 12000 welds and data collection. After this testing is completed, the data collected will be plotted as a part of HP400 in the Fall of 2011. By October 1st, 2011, the plots will be organized and completed, at which point the data analysis can be done and the thesis report itself can be started. By the end of the Fall semester of 2011, most if not all of the thesis report will be written, and the presentation can be started. During the Spring semester of 2012, the thesis report will be touched up and the presentation will be made and presented.

References

[1] L. Jeffus, "Ultrasonic Welding (USW)" in *Welding: Principles and Applications*, Fourth Edition, Albany: Delmar Publishers, 1999, 686-687.

[2] C.Y. Kong, R.C. Soar, P.M. Dickens, “A model for weld strength in ultrasonically consolidated components,” *Proceedings of the Institution of Mechanical Engineers. Part C, Mechanical engineering science,* vol. 219, no. 1, pp. 83-91, April 2005.

[3] R. M. M. Riofano, R. C. Casteletti, L. C. F. Canale, G. E. Totten, "Improved wear resistance of P/M tool steel alloy with different vanadium contents after ion nitriding," *Wear*, vol. 265, pp. 57-64, 2008

[4] T. Watanabe, D. Miyajima, A. Yanagisawa, “Effect of weld tip geometry on ultrasonic welding of A6061 aluminum alloy,” *Welding International*, vol. 24, no. 5, pp. 336-342, May 2010.

[5] S. Elangovan, K. Prakasan, V. Jaiganesh, “Optimization of ultrasonic weld parameters for copper to copper joints using design of experiments,” *International Journal Advancing Manufacturing Engineering*, vol. 51, pp. 163-171, March 2010.

[6] C. Zhang, L. Li, “A coupled thermo-mechanical analysis of ultrasonic bonding mechanism,” *Metallurgical and Materials Transactions*, vol. 40B, pp. 196-207, April 2009.

[7] H. Goto, M. Ashida, “Wear behaviour of a carbon steel subjected to an ultrasonic vibration effect superimposed on a static contact load,” *Wear*, vol. 110, no. 2, pp. 169-181, July 1986.