The Forge Phase of Friction Welding

A plastic model is designed to theoretically describe the movement of interfacial material during the forging phase of friction welding

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ABSTRACT. Even though the forging phase has been previously recognized as the time during which the majority of actual bonding occurs during friction welding, this current work represents the first theoretical investigation of the forging process. A model is constructed to represent the distinct rigid and plastic regions of the weld process which are present during forging. From this model with the application of the upper bound theory of plasticity, expressions for the velocity and displacement fields for material within the interfacial plastic zone are obtained. They require an upper bound forging stress equal to the average compressive yield stress of the plastic material at the weld interface.

The most significant result of the analysis is the derivation of a parameter which is a theoretical measure of the original abutting surface material to be expelled into the weld flash. This interfacial dispersion is postulated to be a potential parameter of weld quality optimization. Note that it is found to be proportional not only to the conventional upset but also to the initial characteristic length of the interfacial plastic zone at the onset of forging.

Introduction

Basic friction welding possesses distinct heating and forging phases. In the initial phase of the process, one weld piece is rotated while another axially aligned piece is held stationary. The pieces are brought together and an axial pressure is applied which is sufficient to cause frictional heat generation at the abutting surfaces. This initial phase constitutes the heating phase. When the weld juncture is adequately heated and softened, the relative surface speed is rapidly brought to zero. At the same moment the axial pressure is raised to the forging level. This is the

Part I—Theoretical Analyses

The forge phase of a friction weld between two cylindrical weld pieces of similar material. An analysis is developed for the deforming plastic interfacial region which results in corresponding velocity and displacement fields. From these fields is derived a relationship for the original interfacial cross sectional area at the onset of forging which will become expelled into the flash during forging. The ratio of this quantity to the original interfacial cross sectional area shall be referred to as the interfacial dispersion, \( q \). It ranges from a value of zero where no dispersion has taken place to a value of one where all of the original interfacial area has been dispersed into the flash. The interfacial dispersion is postulated to be a measure of the degree of removal of contamination, rough asperities, and voids from the weld interface and, therefore, provides a quantitative parameter which could be used to optimize weld quality.

Finally, the velocity field is employed in the development of a required forging load in the typical upper bound sense of plasticity and is seen to result in a forging load equal to the average yield stress in compression of the material in the plastic interfacial region. This result is quite reasonable and lends credibility to the conceived flow pattern.

Theoretical Analysis

Velocity Field

The analysis of the forging phase begins with the construction of a model to represent the deformation of the weld pieces during the forging. As represented in Fig. 1, plastic zones that have been prepared during the heating phase extend a distance, \( h \), on each side of the interface. During forging the rigid sections of the weld pieces act as platens to compress the plastic zones and cause the subsequent
plastic flow. It is assumed that throughout the forging phase the boundary between the rigid and plastic sectors of each weld piece remains flat and parallel to the interface. As forging ensues the rigid platens move towards the interface at some unknown constant velocity, $V_c$. However, $V_c$ can be related to the axial displacements of each weld piece, the upset:

$$u_p = V_c \cdot t'$$  \(1\)

and

$$h = h_0 - u_p$$  \(2\)

where $u_p$ is the upset of each weld piece; $t'$ is the time beginning at the onset of forging; $h$ is the instantaneous plastic zone size; and $h_0$, the plastic zone size at forging onset.

For the present model the plastic zone size at the onset of forging is postulated to be the axial distance from the interface where the average temperature equals the minimum necessary for compressive yielding at the forging stress level. The temperature distribution in the weld pieces at the time corresponding to forge initiation as predicted by a one dimensional temperature solution is suggested as a suitable aid in the theoretical estimation of $h_0$. This coupled with the temperature-compressive yield stress property of the weld material provides an analytical link between the heating and forging phases.

Figure 1 depicts a typical flash of two weld pieces joined by friction welding. At the onset of forging, line elements $OA$ and $OA'$ lay within the abutting interface while elements $AB$ and $A'B'$ lay along the lateral surfaces of the rods. The curved profile of the resulting flash, $AB$ and $A'B'$, indicates that the radial plastic flow velocity decreased from a maximum value along the abutting interfacial surfaces to essentially zero at the rigid-plastic boundaries, $y = \pm h$. Thus, the radial velocity at the boundary which could produce the typical curved flash is assumed to be linearly distributed from zero at $y = \pm h$ to $U_o$ at $y = 0$ as shown in Fig. 2.

Calling the velocities in the $r$, $y$, and $\theta$ directions $u$, $v$, and $w$ respectively, the linear expression for $u$ at any $r$ becomes:

$$u = h (1 - \frac{y}{h})$$  \(3\)

Application of continuity to the volume of material enclosed by $y = \pm h$ to $h$ and a radius $r$ results in a relationship between the radial velocity at any point on the interface, $\bar{u}$, and the platen velocity, $V_c$:

$$\bar{u} = \frac{r}{h} \cdot V_c$$  \(4\)

Thus the radial component of velocity can be written as:

$$u = \frac{r}{h} V_o \left(1 - \frac{y}{h}\right)$$  \(5\)

Next application of the volume consistency condition of plasticity yields the axial component:

$$\dot{e}_r + \dot{e}_\theta + \dot{e}_z = 0$$  \(6\)

where the expressions for the corresponding strain rates in cylindrical coordinates are:

$$\dot{e}_r = \frac{\partial u}{\partial r}$$  \(7\)

$$\dot{e}_\theta = \frac{u}{r} + \frac{1}{r} \frac{\partial w}{\partial \theta}$$  \(8\)

$$\dot{e}_z = \frac{\partial v}{\partial y}$$  \(9\)

Substitution of eq (5) into (6) through (7) to (9) results in:

noting that at $y = 0$, $v = 0$ and for forging without relative rotation between the weld pieces, $w = 0$. Thus, eq (5) and (10) provide a kinematically admissible velocity field within the deforming plastic zones.

Displacement Field

The next step is to find the final position of a material particle originally at the general position $(r_o, y_o)$ within the plastic zone after a forge to a given upset. Refer to Fig. 3. First, consider the axial displacements. Employing eqs (1), (2), and (10) in differential form results in a first order differential equation for $y$ in terms of $u_p$:

$$\frac{dy}{dt_p} = \left(\frac{y}{h_0 - u_p}\right)^2 - 2 \frac{y}{h_0 - u_p}$$  \(11\)

Equation (11) is solvable by the change of variable technique as demonstrated in the Appendix. Employing the initial condition that at $u_p = 0$, $y = y_o$, the axial displacements within the plastic zones during forging become

$$y = \frac{y_o (h_0 - u_p)^2}{h_o^3 - y_o u_p}$$  \(12\)

This equation can be written in dimensionless form as

$$y = \frac{y_o}{h_0} \left[\left(1 - \frac{u_p}{h_o}\right)^2 \right]$$  \(13\)

The above displacement solution can become indeterminate when the upset ratio, $\frac{u_p}{h_o}$ becomes 1 simultaneously with the initial particle position ratio, $\frac{y_o}{h_o}$.

This is the case where all of the plastic zone is expelled into the flash. The same situation is seen to arise for the radial displacements as derived from...
eq (5). Note the dependence of the radial velocity component on the axial coordinate. Substitution from eq (12) for \( y \) results in the following first order differential equation which is solvable by separation of variables and integration as shown in the Appendix.

\[
\frac{d r}{d u_p} = \frac{r}{h_o - u_p} \left( \frac{h_o^2 - y_o u_p}{h_o^2 - y_o u_p} \right)
\]

Employing the initial condition that at \( u_p = 0, \ r = r_0 \), the radial displacements within the plastic zone during forging become:

\[
r = r_0 \left[ 1 - \frac{y_o u_p}{h_o} \right] \left[ 1 - \frac{y_o u_p}{h_o} \right]
\]

(15)

The radial displacements also result in a form representable in a general dimensionless expression:

\[
\frac{r}{R} = \frac{r_0}{R} \left[ 1 - \frac{y_o u_p}{h_o} \right] \left[ 1 - \frac{y_o u_p}{h_o} \right]
\]

(16)

where \( R \) equals the original radius of the weld pieces.

**Interfacial Dispersion**

When \( y_o = 0 \), the radial displacements of eq (15) refer to the movement of particles at the weld interface during forging. The final interfacial position of particles comprising a ring originally at \( r_0 \) can be employed to estimate the amount of original interfacial material which becomes dispersed into the flash. For the ring of particles which at the completion of forging comes to rest on the original outer circumference of the interface, \( r = R \) and eq (15) becomes

\[
R = \frac{r_{0 R}}{1 - \frac{y_o u_p}{h_o}}
\]

(17)

where \( r_{0 R} \) is the original position of the ring moved to \( R \). Thus inversely:

\[
r_{0 R} = R \left( 1 - \frac{y_o u_p}{h_o} \right)
\]

(18)

It then follows that the original interfacial material remaining dispersed throughout the interface after the forge will be that which was initially at \( r \leq r_{0 R} \). This represents an area of:

\[
A_{R} = \pi R^2 - \pi R^2 \left( 1 - \frac{y_o u_p}{h_o} \right)^2
\]

(19)

or in terms of the fraction of original interfacial material expelled into the flash, i.e., the interfacial dispersion:

\[
\eta = \frac{A_R - A_{R}}{A_R} = 1 - \left( 1 - \frac{y_o u_p}{h_o} \right)^2
\]

(20)

**Upper Bound Forging Load**

By employing the upper bound theorem of plasticity, an evaluation is made of the conceived kinematically admissible velocity field to determine the required forging load. Through this theorem the power expended by the unknown forging load is set equal to that required to produce the rate of energy dissipation reflected by the velocity field. If the actual velocity field for the forge has been selected, the actual forging load will be derived. In general, however, a velocity field which does not exactly match that taken by nature will be conceived. This field requires more power than actually needed and results in a forging load greater than demanded; thus, an upper bound. For the purpose of this analysis, the entire plastic zone is idealized to be a perfectly plastic, Mises material region. Furthermore, the effective compressive yield stress of the plastic material is assumed constant, \( \sigma_o \), throughout the zone. In the actual case, the yield stress would vary within the plastic zone according to the initial temperature distribution as the forge is first applied and then to whatever distribution develops as the material begins to deform plastically. Here, \( \sigma_o \), is assumed to be some weighted averaged value of the high temperature-compressive yield property.

The power expended by the external forging force is:

\[
W_p = 2PV_o
\]

(21)

remembering that \( P \) is advancing at a velocity \( V_o \) across both plastic zone boundaries, \( \pm h \).

This power is ideally spent as the internal work of deformation which for a Mises material is:

\[
\dot{W}_1 = 2 \sigma_o \int_{vol.} \sqrt{\frac{1}{2}} \left[ \epsilon_1^2 + \epsilon_2^2 + \epsilon_{12}^2 \right]^3 d vol.
\]

(22)

where \( \epsilon_1, \epsilon_2, \epsilon_{12} \) are the principal strain rates; \( vol. \) represents a volume integration.

For this case the principal strain rates are given by eq (7), (8), and (9). Employing the velocity expressions (5) and (10) the internal work of deformation becomes

\[
\dot{W}_1 = 2 \sigma_o \int_{vol.} \sqrt{\frac{1}{2}} \int 1 d r dy
\]

(23)

By employing the symmetry in \( \theta \), an elemental volume can be written as:

\[
\ d vol. = 2 \pi r d r dy
\]

(24)

Hence, considering integration of half the total plastic volume:

\[
\dot{W}_1 = 2 \sigma_o \int_{R}^{R} \int \sqrt{\frac{1}{2}} \left( \frac{V_o y}{r} - \frac{V_o y}{h} \right) \int 2 \pi r d r dy
\]

(25)

\[
\dot{W}_1 = 2 \sigma_o \int_{R}^{R} V_o
\]

(26)

Equating the power supplied to the internal work of deformation results in the average pressure required to produce the conceived velocity distribution.

\[
\frac{P}{\pi R^2} = \sigma_o
\]

(27)

Because the upper bound forging load results in the average compressive yield stress of the plastic zone, a very reasonable conclusion, support is given to the postulated flow field as a representation of the actual material movement in the interface region during the forging phase.

**Conclusions**

This analysis represents the first attempt to theoretically describe the movement of interfacial material during the forging phase of a friction weld. An instantaneous velocity field has been presented which is compatible with the observed shape of the expelled flash of typical friction welded pieces. From this velocity field, the displacement field has been derived and presented along with a relationship giving the fraction of original interfacial...
material expelled into the flash during the forging phase. It is upon this interfacial dispersion which an optimization of the friction welding process may ultimately be based. Finally, the temperature field when applied to the upsetting bound theorem of plasticity resulted in a required average forging pressure which is reasonable in light of standard uniaxial compression tests.

It should be observed that the interfacial dispersion proves not to be a function of axial upset alone as shown by eq (20), but rather a function of the ratio of upset to the initial plastic zone size. Therefore, in a general sense, upset alone is not sufficient for controlling the removal of oxides, contamination and voids from the weld interface as earlier suggested by Vill. In other words, depending upon the size of the plastic zone, and thus the amount of deformable material, a given upset can remove a varying percentage of available plastic material into the flash. When applied to the material at the interfacial surface, the result is a different dispersion of contamination for the same upset. This case arises even when the controlling parameters of speed, heating and forging pressures are identical, but the heating time varies producing different plastic zone sizes.

Finally, special consideration should be made noting the assumption of a flat cylindrical shape for the plastic zone in the theoretical model. This assumption has a definite bearing on the form of an allowable velocity field for forging. In Part II of this investigation, experimental evidence is presented evaluating the influence of the plastic zone shape on material flow during forging, and therefore, assessing the shape assumed in the theoretical model. The experimental study also presents information on the relationship between the heating phase and the forging phase as reflected through the temperature distribution at the onset of forging and the resulting plastic zone shape. In a third major segment of the experimental work, verification is obtained on the applicability of the derived displacement eq (12) and (15) in predicting movement of interfacial material during forging.

Part II—Experimental Investigation

ABSTRACT. In conjunction with the theoretical analysis of Part I, an experimental study was undertaken to gain knowledge of the forging phase and its influence on weld quality. Specifically, three avenues of interest were pursued. First, temperature indicating, gridred, plexiglass specimens were friction welded and showed the distinct correlation between the isotherms at the onset of forging and the interfacial plastic zone shape. Second, these same specimens revealed the significant effect which the plastic zone shape has on the plastic flow field during the forge. Third, other laboratory cast plexiglass rods containing internal nylon grids verified the theoretical flow field as a fair means of estimating displacements and interfacial dispersion during forging.

Introduction

An experimental investigation was undertaken to gain information about the nature of the forging phase of basic friction welding. While previous research was aimed at the importance of forging during friction welding with respect to weld formation and quality, virtually no results of related studies have been published. Thus this work along with the theoretical analysis of Part I provides the first steps toward the understanding of forging's role in the movement of material at the weld interface and subsequent weld quality.

As mentioned in Part I, the heating phase occurs in friction welding while relative rotation exists between the weld pieces. At this time frictional heat generation causes elevated temperatures adjacent to the abutting weld surfaces. The higher temperatures in this interfacial region are reflected by a lower resistance to plastic yielding. Therefore, at the onset of the forging phase the higher axial forging pressure creates a zone of plastically deforming interfacial material in each weld piece. Of special interest is the manner in which this softened material flows into the flash during forging. Specifically, this experimental investigation was concerned with the governing factors which influence the plastic flow patterns and the subsequent removal of contamination, oxides and voids from the abutting surfaces. The overriding idea is that exact determination and control of these factors would lead to the control of weld quality.

Three main aspects of experimental study were established in conjunction with the theoretical analysis of Part I. First, a correlation was sought between the temperature distribution at the onset of forging and the ensuing profile of the rigid-plastic boundary between the rigid and softened sectors of the weld pieces. Second, the influence of the shape of the resulting plastic zone as determined by the rigid-plastic profile was investigated with respect to material flow patterns during forging. Finally, the actual displacement field for the plastic zone after forging to a given upset was determined for comparison with that predicted by the theoretical analysis.

Experimental Investigation

Experimental Welding Unit and Specimens

Three-quarter inch polymethyl methacrylate rod was chosen for test specimen material because it was easily welded at low axial loads and because its transparency enabled visualization of the final interfacial flow characteristics. To weld this material, a lightweight experimental friction welding machine was built and employed as shown in Fig. 4. It consisted of a combined modified drill press and a loading frame with a releasable base chuck. The welding unit operated in the conventional friction welding manner with speeds up to 5000 rpm and axial loads up to 100 psi. Previous work suggested that this should be a reasonable range for the friction welding of plexiglass-like polymers.

A unique and important feature of this experimental welding machine was the upset control. This positive stop on the loading frame permitted the forge to be halted at any desired degree of axial upset. Thus deformations in the interfacial plastic zone were attainable for observation at intermittent stages of the forging phase. The three control parameters continuously monitored during welding were the axial load (Baldwin 1000 lb load cell), the axial displacements, specifically the total burn-off and upset (dial indicator), and the heating time (electric clock). The rotational speed was pre-set on the machine.

The welding machine was employed to join plexiglass specimens which were of different size of the plastic zone were attainable for observation at intermittent stages of the forging phase. The three control parameters continuously monitored during welding were the axial load (Baldwin 1000 lb load cell), the axial displacements, specifically the total burn-off and upset (dial indicator), and the heating time (electric clock). The rotational speed was pre-set on the machine.

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plexiglass which had reached the indicating temperatures. Thus, at the completion of welding, each grid consisted of a portion which, as initially, appeared dull and powdered. In the portion where the indicating temperature had been reached, each grid appeared melted, bright and glossy. A sharp line usually divided these regions. Therefore, the measurement of the maximum distance from the interface to a point where the indicating temperature was reached for a given grid's radial position was attainable.

Also during forging, the temperature grids deformed in the plastic interfacial zone while remaining undeformed in the rigid portion of the weld piece. The demarcation between the deformed and the undeformed grid sections provided a profile of the final plastic zone shape. Figure 6 exhibits the definition of both the indicating temperature demarcation and the distinct plastic zone shape, rigid-plastic boundary, as observed in the welded specimens.

Concurrently, the nylon grid configuration enabled accurate measurements to be made of the displacement field within the plastic zone due to forging. In order to obtain the nylon gridded specimens, a glass tubed molding rig was employed in which six lb test nylon monofilament was prestrung axially along a single diametric axis. The cylindrical specimens were then cast from polymethyl methacrylate in its monomer state, machined, cut, and faced to the final desired dimensions. The resulting radial position of any one grid strand was not found to vary more than 0.001 in. per inch length of cast rod. A solid grid-free rod was also cast to provide a similar material upon which to weld the nylon gridded specimens.

Upon completion of both tempil and nylon gridded weldments, the flash was machined away, and each specimen was polished. To cut out reflections from the cylindrical specimens' surfaces, they were individually placed in a clear plastic box filled with mineral oil. A traveling microscope was then employed to take measurements of the deformed gridwork. The microscope was graduated down to 0.0001 in.

**Isotherms and Plastic Zone Shapes**

Tempil grid specimens, which were welded at 3550 rpm and under the conditions described in Table 1, indicated an apparent link between the contours of the isotherms at forging and the resulting plastic zone shape. This can be observed in the photos of Fig. 6 for two specific cases where the indicating temperature was constant throughout the grid pattern. For these welds the isotherms indicated by the melted-powdered demarcations possess the same general profile as the rigid-plastic boundary. The plastic zone shapes in Fig. 6 are termed concave since, if removed from the weld pieces, they would appear similar in shape to a concave lens. In contrast, a plastic zone whose rigid-plastic boundary is dished away from the interface is termed convex.

### Table 1—Tempil Grid Specimens

<table>
<thead>
<tr>
<th>Speed rpm</th>
<th>Heating load, psi</th>
<th>Forging load, psi</th>
<th>Heating time, sec</th>
<th>Burn-off ( u_b ) (X .001 in.)</th>
<th>Total upset ( u_t + u_p ) (X .001 in.)</th>
<th>Number of specimens</th>
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<tbody>
<tr>
<td>3550</td>
<td>103 ± 5 constant</td>
<td>1090 ± 11</td>
<td>7.4</td>
<td>2.5</td>
<td>30</td>
<td>3</td>
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<td>1120 ± 2</td>
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**Fig. 4**—Experimental friction welding machine

**Fig. 5**—Plexiglass specimen configurations

**Fig. 6**—Friction welded specimens with tempil grids. Top—150°F tempil grid; bottom—200°F tempil grid
A compilation of measurements taken from all the tempil data of the 3550 rpm welds is shown on Fig. 7. At 3550 rpm a state of uniform wear was observed at the interface during the heating phase. Also in the plexiglass specimens, the rate at which the isotherms traveled down the specimens matched the rate at which burn-off progressed. Therefore, over the entire range of burn-offs employed, 0.0025-0.025 in., identical final plastic zone shapes and sizes were observed. For this reason the isotherm profiles measured for these various burn-offs are comparable. With an observed typical scatter of ±0.008 in., the plotted average isotherms reveal the same distinct concave shape as the final plastic zone. This helps to substantiate a postulated link between the heating and forging phases of friction welding—namely, the rigid-plastic boundary of the interfacial plastic zone is determined by that isotherm or band of isotherms which corresponds to the minimum temperature at which welding occurs for the weld material employed and at the given forging level and rate of straining. As shown in the ensuing paragraphs, the shape of the rigid-plastic boundary greatly affects the plastic flow pattern during forging and consequently the resulting weld quality.

The theoretical investigation of Part I was based on an assumed flat rigid-plastic boundary. Welds made at 650 rpm revealed that when the wearing of material at the interface was at a low enough rate to permit the ensuing temperature distributions to equalize during the heating phase, the plastic zone shapes progressed from concave to flat to convex shapes. However, as soon as the wearing rate increased as reflected by rapid rises in burn-off, the isotherms and plastic zone stabilized to the concave shape as was exhibited by the 3550 rpm welds. This phenomenon can be seen in Fig. 8 from friction welds made under the conditions indicated in Table 1 at 650 rpm. Note that for the highly insulating material, plexiglass, the minimized wearing could only be achieved by a decreasing loading arrangement which initially restricted burn-off. For more conductive materials, such as metals, temperature equalization and inversion has been experimentally observed under normal welding conditions. A leveling off of plastic zone shapes has also been observed in metal welds for increased heating times. Therefore, the patterns of plastic flow as influenced by the plastic zone shape for the plexiglass specimens can be extended in considering other materials.

As shown in Table 1, under conditions of minimum wear an occasional balk occurred in the forging of the weld pieces. This is reflected by the relatively low degree of upset in comparison to that achieved for equivalent conditions and heating times for normal welds. These balks were associated with little plastic deformation at the interface and severely convex plastic zone shapes (see Fig. 9). Perhaps the acute convexity of the plastic zones can be attributed to an unusually high rate of heat generation at the central portion of the interface. This case could have been caused by a slight high spot at the center of one of the abutting surfaces, which because of the minimum wear con-

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**Fig. 7**—Contour similarity of plastic zone boundary and isotherms for 3550 rpm welds

**Fig. 8**—Initial plastic zone shapes at the onset of forging at 650 rpm
a concave zone where the particles were forced out into the flash.

This connection between plastic zone shape and the concept of weld quality and interfacial dispersion of contamination, oxides and voids is of considerable practical importance. Concave plastic zone shapes enhance dispersion, whereas convex shapes inhibit it. The shape of the resultant flash, or collar, was observed to directly reflect the internal plastic zone shape and corresponding plastic flow pattern. Thus, a means of qualitatively estimating flow characteristics for friction welds of opaque materials is available. As illustrated in Fig. 11, concave plastic zones forged into gradually flaring collars. Convex zones forged into flat edged, pinched collars. Excessive heating and/or higher forging loads on convex zones leads to the characteristic split collar. Here the forging level is sufficient to break down the outer rim of cooler material and force plastic material outward. In any case, the radially inward velocities imposed at the rigid plastic boundary are detrimental to final weld quality.

Plastic Flow Field Displacements

Resultant measurements of deformed nylon gridwork for friction welded specimens verified the applicability of the theoretical plastic flow analysis to estimate displacements within the plastic zone. The nylon gridded specimens were all welded under identical speeds, loads, and burn-offs as indicated in Table 2. The upset control was employed to stop the forge at specific intermediate upset positions for each specimen. Thus by viewing an entire set of specimens a verification was obtained of the sequential progression of displacements during forging. Figures 12-15 show this progression from the experimental measurements made on the individual grid lines for the 3550 rpm set of welds. All measurements were made to various points along the centerline of each grid filament from the lateral surface and free end surface of each weld specimen. This data was then converted to grid positions relative to the axial centerline and interface for the comparative plots.

Also shown on the figures are theoretical displacements within the plastic zone, which were based upon averaged initial radial positions ($r_0$), averaged initial plastic zone size ($h_0$), and averaged upset ($u_p$) of each weld piece during forging. These averaged values were made for the two experimental welds at each upset level. For the concave zones the initial characteristic plastic zone size at the onset of forging was established as the average height of the final plastic profile plus the total welding upset minus the burnoff. All were taken on a per weld piece basis. The average height of the final plastic zone was that height for a flat zone which would encompass the same amount of plastic material as found under the concave profile—Table 2. Note that the theoretical displacements were previously derived as:

$$ y = \frac{y_0(h_0 - u_p)}{h_0^2 - y_0 u_p} $$

Table 2—Nylon Grid Specimens

<table>
<thead>
<tr>
<th>Burn-off, $u_p$ (x .001 in.)</th>
<th>Heating time, sec</th>
<th>Upset $u_p$ (x .001 in.)</th>
<th>$u_p$ (avg) (x .001 in.)</th>
<th>$h_0$ (x .001 in.)</th>
<th>$h_0$ (avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9.4</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>7.2</td>
<td>11</td>
<td>15</td>
<td>13</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>5.4</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>7.0</td>
<td>36</td>
<td>37</td>
<td>37</td>
<td>89</td>
</tr>
</tbody>
</table>

$h_0$ (avg) = .083 in.

* Speed—3550 rpm; heating load—106 ± 4.5 psi (constant); forging load—1115 ± .5 psi.
Convenient values of initial axial positions with respect to the weld interface \( y_o \) were chosen for each computed grid line. The results show general agreement between the analytical displacement fields and the measured ones, particularly at the lower upset ratios where the concave zone profile is not fully developed. For higher ratios the analytical flow fields predicted greater movement of material in the outer regions of the interface than was actually observed. Thus the interfacial dispersion \( \eta \) as derived in Part I from eq (2) may be an over-estimation of the removal of oxides, voids and contamination from the interface:

\[
\eta = 1 - \left( 1 - \frac{u_p}{h_o} \right)^2
\]  

Conclusions

The experimental study presented here revealed several important facts about the nature of forging during friction welding. The patterns of plastic flow during the forge were seen to be greatly influenced by the shape of the rigid-plastic boundary at the weld interface. In turn this rigid-plastic boundary shape appeared to correlate well with the isotherms developed during the heating phase of the process. Finally in affecting the plastic flow characteristics, both the isotherms and resulting plastic zone shape had a primary influence on the dispersion of original interfacial surface material. Thus, they are a key to the control of both weld quality and the resulting flash formation.

The value of concave and flat plastic zone shapes in deference to convex zones to the dispersion of interfacial material is of practical importance. This is particularly useful since it was shown to be qualitatively indicated by the shape of the resulting collar. Also of practical importance is the knowledge that control of the isotherms during the heating phase could lead to control of the plastic flow fields to produce a desired flash pattern and modes of dispersion considered most useful for a particular joint configuration.

The experimental study verified the potential applicability of the flat zone analytical plastic flow model of Part I for estimating displacements and the interfacial dispersion. It also pointed out the need for a theoretical heat transfer solution enabling prediction of concave or convex isotherms. This in turn coupled with a velocity field compatible with the corresponding contoured rigid-plastic boundary would provide refinement to the present solution. Perhaps of equal importance is the need for both theoretical and experimental information to further evaluate the interfacial dispersion in terms of optimization of weld quality. Greater under-
standing of its role in estimating weld quality could provide a powerful analytical tool in future design of friction welded joints.

Acknowledgement

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References


Appendix

Axial Displacements

The axial displacements of particles within the plastic zones adjacent to the interface during forging are derivable from the velocity expression, eq (5):

\[ y = d \frac{dy}{dr} = V_0 \left( \frac{h_0^2 - 2 h}{h_0} \right) \]  

(A1)

Employing relationships (1) and (2) yields:

\[ d y = d u_p \left[ \left( \frac{y}{h_0 - u_p} \right)^2 - \frac{y}{h_0 - u_p} \right] \]  

(A2)

Call:

\[ \xi = h_0 - u_p; \quad d \xi = -d u_p \]  

\[ d y = \left[ \frac{2 \xi \left( \frac{y}{\xi} \right)^2 \xi}{\xi^3} \right] d \xi \]  

(A3)

Call:

\[ \chi = y; \quad \frac{\xi}{\xi} \]  

\[ y = \chi \]  

Thus:

\[ d y = \chi d \xi + \xi d \chi \]  

(A4)

Substitution back into eq (A3) results in the following separable first order differential equation:

\[ \chi d \xi + \xi d \chi = (2 \chi - \chi^2) d \xi \]  

(A5)

\[ \frac{d \chi}{\chi - x^2} = \frac{d \xi}{\xi} \]  

(A6)

Integration of eq (A6) results in:

\[ \ln \frac{\chi}{x - 1} = \ln \frac{\chi}{\xi} + c \]  

(A7)

or:

\[ \frac{\chi}{x - 1} = \xi \]  

(A8)

Substitution back for \( \chi \) and then \( \xi \) results in the final form of the solution:

\[ y = \frac{c(h_0 - u_p)^2}{h_0 - y_0 u_p} - 1 \]  

(A9)

Application of the initial condition that at \( u_p = 0, y = y_0 \), leads to the determination of the constant of integration:

\[ c = \frac{y_0}{y_0 h_0 - h_0^2} \]  

(A10)

Therefore, the solution for the axial displacements within the plastic zone proves to be:

\[ y = \frac{y_0 (h_0 - u_p)^2}{h_0^2 - y_0 u_p} \]  

(A11)

Radial Displacements

The radial displacements are derivable from the velocity expression, eq (5):

\[ u = \frac{d}{dr} V_0 \left( \frac{h_0^2 - 2 h}{h_0} \right) \]  

(A12)

Substitution of the solution for axial displacements, equation (A11), into eq (A12) results in the following differential equation:

\[ \frac{dr}{r} = u_p \left[ \frac{-h_0^2 - y_0 h_0}{(h_0 - u_p)(h_0^2 - y_0 u_p)} \right] \]  

(A13)

Note again that the relationships (1) and (2) have been employed. Equation (A13) can then be written as:

\[ \frac{dr}{r} = \frac{(h_0^2 - y_0 h_0)}{h_0^2 - y_0 u_p} \left[ \frac{d u_p}{u_p} \right] \]  

(A14)

\[ \left[ \frac{y_0 u_p}{u_p} - \frac{(y_0 h_0 + h_0 u_p + h_0^2)}{u_p} \right] \]  

The right hand side of equation (A14) upon integration is of the form \( \int \frac{dx}{x^2 + bx + c} \). For this problem the conditions on the integral are:

\[ b^2 - 4 ac = h_0^2(h_0 - y_0)^2 \geq 0 \]  

(A15)

Under conditions (A15) the general solution of the integral eq (A14) is:

\[ \int \frac{dx}{x^2 + bx + c} = \frac{1}{a(p - q) ln} \left| \frac{x - p}{x - q} \right| \]  

(A16)

as shown in (7) where \( p \) and \( q \) are the roots of \( ax^2 + bx + c \). In terms of eq (A14) the roots in terms of dimensionless ratios are:

\[ p = \frac{h_0}{y_0}; \quad q = \frac{y_0}{y_0} \]  

(A17)

Taking the positive root of the radical, \( 1 - \frac{y_0}{h_0} \), leads to the following values of \( p \) and \( q \). Note that taking the negative root, \( \frac{y_0}{h_0} - 1 \), has the same effect as switching the expressions for \( p \) and \( q \) which results in the same final solution:

\[ p = \frac{h_0}{y_0}; \quad q = \frac{y_0}{y_0} \]  

(A19)

Employing the results of (A19) to eq (A14) through the general solution (A16) yields:

\[ ln r = ln \left| \frac{u_p - h_0}{u_p - y_0} \right| + c \]  

(A20)

or

\[ r = \frac{u_p}{y_0} \left( \frac{h_0}{h_0} \right) - 1 \]  

(A21)

Applying the initial condition that at \( u_p = 0, r = r_0 \), leads to the determination of the constant of integration:

\[ c = r_0 \]  

(A22)

Thus the final solution for the radial displacements within the plastic zone becomes:

\[ r = \frac{1 - \frac{y_0 u_p}{h_0 h_0}}{1 - \frac{u_p}{h_0}} \]  

(A23)

The High Alloys Committee of the Welding Research Council will sponsor a symposium on the following topic on April 29:

“Characteristics of Nickel-Base Alloy Weldments”

The symposium is being held in conjunction with the 52nd Annual Meeting of the AMERICAN WELDING SOCIETY between 9:30 A.M. and 12:00 noon in Room 104 of Civic Auditorium, San Francisco, California. Included will be the presentation of the following short papers:


“A Mechanism for Cracking During Postwelding Heat Treatment of Nickel-Base Alloys” by M. Prager, Copper Development Association, and G. Sines, University of California at Los Angeles

“Methods for Improving the Weldability of High Strength Super-Alloys” by D. S. Duvall and W. A. Owczarski, Pratt and Whitney Aircraft

“Some Welding Problems with Inconel 718” by J. Gordine, Canadian Department of Energy, Mines and Resources

“Progress in the Welding of 50% Cr—50% Ni for Elevated Temperature Service” by E. P. Sadowski, International Nickel Co., Inc.

All are invited to attend and to participate in the audience discussion which is expected to ensue.