An Experiment Towards Establishing the Tolerance of Micro-Scale Interference Fits

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LIGA technology is capable of producing high aspect ratio parts with sub-micron feature sizes out of a variety of metal alloys, ceramics, and thermoplastics. LIGA was invented in Germany, and the German acronym stands for lithography (Lithographie), electroforming (Galvanoformung) and molding (Abformung). LIGA fabricated parts have many unique properties. The lithographic process permits cost effective production of intricate components. High aspect ratios with smooth and straight sidewalls are hallmarks of LIGA fabricated parts while a wide variety of materials enable numerous applications[1,2].

A challenge with LIGA fabricated micromechanical parts is that they generally require some level of assembly to achieve functional mechanisms or devices. In order to assemble these devices, individual parts must be permanently attached to one another. One attachment method that has recently been demonstrated is forcing pins into holes in which the nominal diameter of the hole is smaller than that of the pin[3]. These interference fit assemblies are able to withstand harsh environmental conditions that would destroy adhesively bonded parts. A critical aspect relating to the performance of interference fit assemblies is the tolerances of the mating parts. Unfortunately, no standard for the tolerance of sub-millimeter nominal diameter interference fits currently exists. The applicable standard, ISO286 specifically excludes nominal diameters under 1 mm. Further, this standard evolved through the consensus of experts based on practical experience – not on theory[4], thus no experimental and little theoretical work appears in the literature.

Evolving sufficient practical experience to determine appropriate tolerances for micro-scale interference fits would be a daunting task. Thus, it would be more expedient to develop a scientific basis for establishing the tolerance of micro-scale interference fits. The work reported in this paper describes the classical analytical mathematical model to predict the performance of cylindrical interference fits. The classical model indicates that the geometry and material properties of the parts are the dominant parameters affecting the performance of the assembly. The material properties of LIGA materials are of significant interest and have been published for a handful of alloys[5]. The dimensional metrology of micro-scale parts used in the experiments poses unique challenges[6] and is described in this paper. To assess the performance of the interference fit, the axial insertion force can be measured during assembly and an apparatus to do so is presented. Finally, the experimental results are reviewed in relation to the theoretical model.

Theory

The force required to insert (or extract) the pin from the hole is a good performance metric for an inference fit. To determine the insertion force, Vallance and Doughtie assume a Coulomb friction model to obtain[7],

$$F = f \, \pi \, p_c \, d_c \, L \,. \tag{1}$$

Where F is the insertion force, f is the coefficient of friction, p_c is the contact pressure, d_c is the contact diameter, and L is the length of engagement between the pin and the hole. Equation (1) states that the contact pressure times the contact area gives the normal force, which is then multiplied by the coefficient of friction to obtain the axial insertion force. Vallance and Doughtie use thick walled cylinder stress theory to determine the contact pressure,

$$p_c = \frac{AE(d_c^2 - d_i^2)(d_o^2 - d_c^2)}{2d_c^3(d_o^2 - d_i^2)} \,. \tag{2}$$

Where A is the total shrinkage, E is the modulus, d_i inside diameter of the inner member, and d_o is the outside diameter of the outer member. Assuming that the inner member is a solid pin, the outer member is an infinite plate, substituting the difference between the pin and hole diameters for the total shrinkage, and the average of the pin and hole diameters for the contact diameter, equation (2) reduces to,

$$p_c = \frac{E(d_p - d_h)}{(d_p + d_h)}\,. \tag{3}$$

Where d_p is the diameter of the pin and d_h is the diameter of the hole. Note that this derivation assumes that the modulus (and Poisson's ratio which was previously reduced to obtain equation (2)) is the same for both the inner and outer members. In fact, this is a reasonable assumption for our work with steel pins and nickel alloy LIGA parts, each of which have a modulus of about 190GPa and a Poisson's ratio of about 0.3.

Part Metrology

Obtaining and measuring or confirming the dimensions of the mating parts proved a challenge in itself. The pins were fabricated from steel plug gages purchased from Deltronic whom also supplied metrological reports for the gages. An SEM image of a sharpened pin is shown in Figure 1. On occasion, surface asperities were detected on the surface of the gages, one of which is visible on the shaft of the gage shown in Figure 1. Thus, surface roughness was measured using a Wyco NT3300 optical profiler to assure no or only minor concave asperities existed on the gages. Measurements indicated the average roughness of the gages to be generally about 200nm RMS with occasional isolated regions exceeding 1µm.

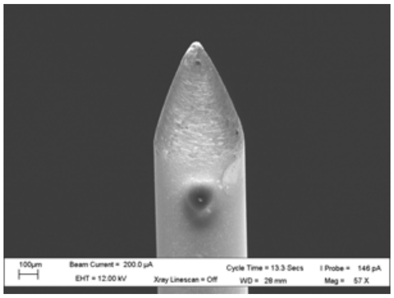

Figure 1. Sharpened Plug Gage

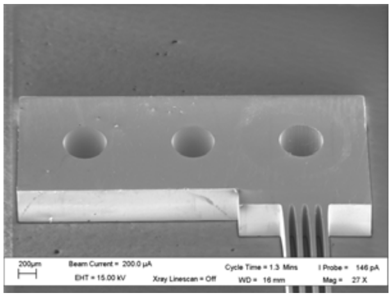

Figure 2. LIGA part

The parts possessing holes were fabricated by electroplating NiMn into LIGA molds. Top and bottom hole diameters were measured with a VIEW Engineering Voyager V6x12 optical microscope which has a measurement uncertainty of ±1.5µm. Side wall roughness was measured using the Wyco profiler and were generally less than 100nm with occasional regions up to 150nm average surface roughness. The roughness was measured on accessible sidewalls of the part and it was assumed that the sidewall roughness inside the holes was very similar.

Experimental Apparatus

The experimental apparatus consists of a Physik F-206 hexapod robot with controller that inserts the pin, an Eppendorf linear stage to position the LIGA part (hole), an ATI Nano17 load cell to measure insertion forces, and a Watec CCD camera with Navitar 5X lenses to align the parts, along with video monitor, personal computer, custom fixtures, tooling, and software. The apparatus is shown in Figure 3. Figure 4 shows a close up of the Physik platform, load cell with pin holder, and LIGA sample holder.

Figure 3. Experimental Apparatus

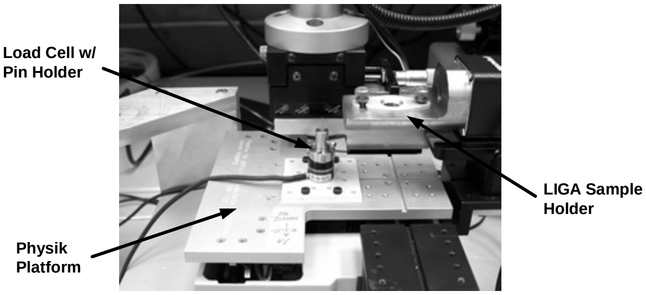

Figure 4. Close up

The load cell was calibrated using mass balance weights. The motion of the Physik was calibrated using a Starrett digital indicator which was calibrated though its full scale using gage blocks. In addition, experiments were performed to characterize and compensate for the compliance of the system.

To perform an insertion experiment, the pin and hole are aligned by viewing the overhead microscope while manually commanding the Physik and Eppendorf motion stages. Once coarsely aligned, the Physik moves the pin up until the hole in the LIGA part self centers on the point of the pin. After centering, a restraining plug is inserted over the LIGA part to prevent the part from moving vertically during pin insertion, but permits lateral part movement to compensate for any minor misalignment between the pin and hole. An experiment is performed by commanding the Physik to move upward, thereby inserting the pin into the hole while the force and displacement are recorded on the computer.

Results

Figure 5 shows the results of two experiments compared with the theoretical model. The tests consisted of inserting a 497.5µm diameter pin into an estimated 494.4µm diameter hole. Singer® sewing machine oil was used as a lubricant to assure a consistent coefficient of friction. Test 1 and test 2 were conducted in succession using the same pin and hole, the difference being that in test 2 the pin was inserted further through the approximately 500µm deep through hole to investigate the extent of the constant force region. There is excellent correlation between test 1 and 2, which indicates that the experiment is repeatable and no permanent deformation occurs to either the pin or the hole. However, the experimental results do not correlate with theory. The experimental results show that the insertion force initially increases and then decreases to about half of the peak force. In addition, the peak force occurs prior to full insertion of the pin and the insertion force does not become linear until the pin is well through the hole.

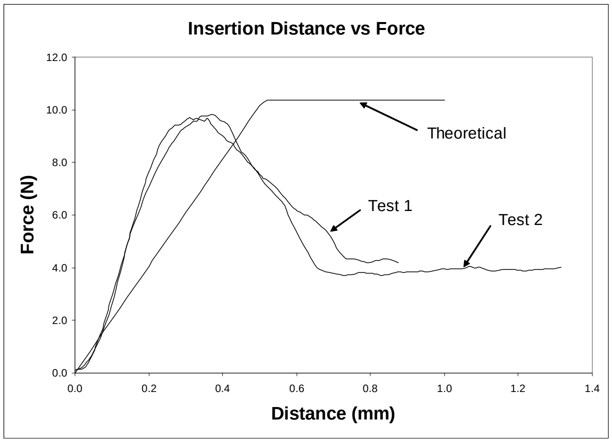

Figure 5. Experimental & Theoretical Results

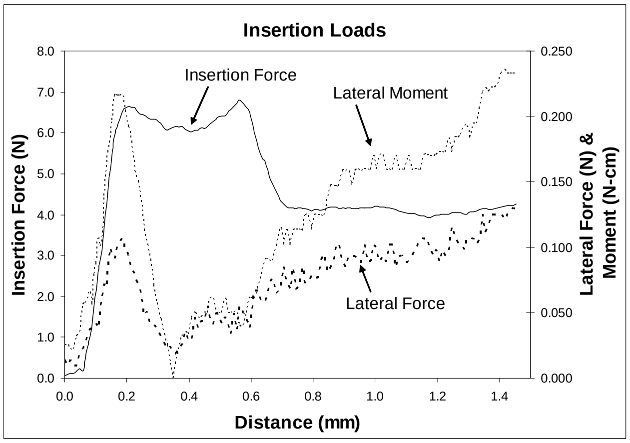

Figure 6. Insertion and Lateral Loads

Equation (3) shows that the contact pressure is a constant value for given geometries and material properties. Equation (1) states that the insertion force varies only as a function of insertion distance, thus the theoretical curve shown in Figure 5 reflects what the classical mechanics theory predicts. The magnitude of the insertion force that the theory predicts is subject to various assumptions, but none of the assumptions can account for the dramatic difference in the shape of the curves. The issue then becomes is the experiment or the classical theory in error.

Initially, it was hypothesized that the lubrication could be causing some sort of creeping effect. Thus, another set of experiments was run without lubricating the parts. The non-lubricated tests reviled the same characteristic curve as shown in Figure 5 with the exception of increased insertion force, which is to be expected. To further investigate this discrepancy, a simplified experiment was constructed that did not employ robotic systems to determine if the robot controllers were affecting the results. The simplified experiment again displayed similar behavior to that of tests 1 and 2. From this series of experiments we concluded that the original experiments were accurately depicting the insertion process. Another set of experiments was conducted in which the pin was inserted initially from the top and then from the bottom to determine if a slight taper in the hole could be causing the effect; however, the same result was obtained regardless of the direction of insertion.

Next we began investigating other theoretical models to explain the phenomenon. One possible explanation is that the classical model which is based on bi-axial strain is inadequate at this scale. The hypothesis was that the increasing axial load may cause a non-uniform bulge along the axis of the pin. To explore this possibility, we developed a simple finite element model based on tri-axial strain theory. Experiments with the model did display a slight drop in peak insertion force, but in general the tri-axial model more closely resembled the classical theory.

After more in depth considerations we realized that the shape of the curve is reminiscent of the force curve described by Whitney in his work on compliant insertion for clearance fits[8]. Thus, it is plausible that even though great care was taken to align the parts prior to insertion, some slight misalignment did exist and caused forces in addition to the force due to the interference fit. To evaluate this hypothesis, experiments were conducted that monitored the lateral forces and moments during insertions. The most dramatic instance is depicted in Figure 6 which shows insertion force and lateral forces and moments measured during insertion of a 497.5µm diameter pin into an estimated 494.8µm diameter hole. Note that insertion force is plotted against the left scale while both lateral force and moment are plotted against the right scale. In this experiment the peak force is less than that measured for the experiment in Figure 5, which seems reasonable given that parts having slightly less inference were used for this experiment. This experiment was unique because there appears to have been an initial misalignment that became aligned at about 0.35mm insertion distance, indicated by the lateral force and moment becoming nearly zero and possibly resulting in the plateau in the insertion force. Other experiments did not experience a dip in lateral force and displayed an insertion force curve similar to that in Figure 5. After 0.35mm insertion, the lateral loads gradually increase while the insertion force eventually drops to a steady state value. These experiments indicate that lateral loads do have an effect on the insertion force, but do not explain the unexpected shape of the insertion force curve.

Discussion

For the experiments conducted, the axial insertion force as a function of insertion distance displays unexpected nonlinear behavior. This behavior is repeatable and appears at odds with the classical theory describing insertion force of interference fits. Additional experiments confirmed that this behavior is not an artifact of the experimental procedure, due to effects from variation in dynamic and static friction, due to tapered holes, explainable with tri-axial strain theory, or due to extraneous lateral forces or moments.

It is possible that the behavior is a superposition of the effects mentioned above. It is also plausible that the behavior is caused, at least in part, due to a stress concentration between the tapering shoulder of the sharpened pin and the hole sidewall. It is even conceivable that the behavior is cause by the nature of the LIGA material or due to some sort of surface interaction effect. Several experiments were conducted with 500µm nominal diameter fits all of approximately the same magnitude of interference. Future work will explore this behavior for significantly different magnitudes of interference and nominal diameters. An experiment of particular interest would be to conduct an experiment at the macro scale to determine if this behavior is solely micro in nature.

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