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Disciplines
Manufacturing | Metallurgy

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Bulk motion for ultrasonic-assisted microforming using Terfenol-D

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ABSTRACT

Microforming requires high-precision motion due to scaling issues. A Terfenol-D transducer was considered to provide bulk motion for micro-extrusion. Because Terfenol-D cannot practically produce the necessary 2.5 mm displacement for this micro-extrusion experiment, a lever system was designed to amplify the output displacement. Compliant joints (flexures) were used to replace conventional bearings, resulting in a flexible, solid-state lever mechanism. By eliminating the backlash and static friction associated with conventional bearings, it should be possible to improve displacement precision as required to meet the geometric tolerance demands of microforming. A chief concern when designing flexure joints that see large amounts of axial loading is compliance, which leads to not only loss of motion but also loss of accuracy as the lever system responds differently under different loads. However, because Terfenol-D already has load-dependent response, this loss of accuracy is moot when coupled with a Terfenol-D prime mover, as it already requires load-dependent control. Preliminary FEM analysis has shown this design to have lever ratio losses of approximately 4% from half load to full load, with lower than predicted stress.

Keywords: microforming, Terfenol-D, flexure, ultrasonic, extrusion

1. INTRODUCTION

Micromanufacturing is a growing field with applications in medical devices, MEMS, electronics, and many other fields. Several new challenges become apparent as parts reach the sub-millimeter level, including material size effects, geometric tolerance and surface finish, friction, and repeatability1. Tool wear is also a very important consideration, as it is currently very expensive to make tooling at this scale. To highlight the importance of geometric tolerance, first consider that for a typical machining process, many modern machine shops are capable of maintaining a 0.03 mm tolerance. On a typical 30 cm long part, this tolerance would comprise 0.01% of the overall length, while on a 0.5 mm part, the same tolerance comprises 6% of the overall length. Material size effects become apparent when one or more part dimensions become small enough that the geometry is only a few grains wide, resulting in degraded surface finish and reduced repeatability as individual grain orientation diminishes anisotropy2.

Ultrasonic vibration has been used in macro-scale forming processes since the 1950s, and has been proven as an effective method of reducing material flow stress3. Naturally this reduces the force required for extrusion, which should also improve tool life. Ultrasonic vibration has been used in the wire drawing process to reduce drawing force, improve dimensional accuracy, and improve surface finish4. Similar results have also been seen in recent research on microforming5.

Most current ultrasonic transducers are piezoelectric, which adds several constraints to the system. First, piezoelectric materials lack the strength to handle the extrusion force, often requiring a more elaborate setup than simply placing the actuator in series with the extrusion die. Second, piezoelectric transducers typically have a very sharp resonance peak, requiring very careful frequency response considerations in die and die support design. Magnetostrictive Terfenol-D’s broader resonance peak will allow more flexibility in die design. This will provide the capability to truly optimize the design for any application.

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Preliminary micro-extrusion results using a simple screw drive are shown in Figure 1. These results were obtained with a 2 mm annealed 1100 aluminum sample with a 64% reduction ratio. As can be seen this extrusion requires an 1800 N load over a 2.5 mm displacement. This paper presents a detailed analysis of design considerations involved in building a system to provide this bulk motion and force using Terfenol-D.

Terfenol-D is a giant magnetostrictive alloy, meaning it strains in response to a magnetic field. It is composed of terbium, iron, and dysprosium, and works by taking advantage of the oblong magnetic dipoles of rare earth metals. While it has one of the highest strain responses of all magnetostrictive materials, and in simple rod form is quite capable of achieving the strains and forces required for ultrasonic vibration, it is not practical to produce a rod long enough to produce the 2.5 mm displacement required for the bulk motion of the forming process described above. This necessitates some sort of strain amplifier, possibly a lever-type system. Because Terfenol-D is a metal, it has a relatively high Young’s Modulus. Although it is not capable of directly producing levels of strain that are sufficient for bulk motion, this strain corresponds to a maximum force on the order of over 110 newtons per square millimeter of Terfenol-D cross-sectional area. This large force will allow the use of a lever type system to amplify the strain to provide adequate bulk motion for forming while still maintaining the forces needed for this process. Precise position control is possible with Terfenol-D, however adding a conventional lever system built with moving parts to amplify displacement will necessarily add errors due to compliance, backlash between components, and static friction. The proposed method to overcome these errors, and thus improve the precision of the process, is to design a lever system with no moving parts by replacing all rolling or sliding interfaces with compliant joints. By making the device solid-state, the system will be essentially backlash and friction free, which should provide additional improvement to geometric tolerance. A very similar strategy has been used in high-precision robots to achieve linear motion with 5 nm resolution.

2. METHODOLOGY

The first step in designing the lever system to accomplish bulk motion was to select the best lever configuration. Given that (a) Terfenol-D is capable of 0.16% magnetostriction, (b) rods of Terfenol-D are commonly available in standard lengths of up to about 150 mm, and (c) 2.5 mm of output displacement is desired, lever ratios should be in the range of 10-15. Rod diameter was determined by desired output force, along with lever ratio and Young’s modulus of Terfenol-D in a blocked state. The following lever configurations (Figure 2) were selected for review: a conventional straight lever design, a two-section bent lever design, and a symmetric four-section bent lever design.
The basic designs were compared on the following bases: (1) linearity of motion, (2) size, (3) complexity, and (4) compliance. Linearity was chosen to ensure that lever ratios (or displacement gains) were relatively constant throughout the arc of travel. Size was considered because a large factor in the future marketability of this design is in the overall size of the unit, as shop floor space is always at a premium. Complexity was chosen since it generally affects both the cost and reliability of the unit. Cost was not directly considered due to the fact that because all designs had similar effective lever ratios, assuming rigid bodies, all designs could effectively use the same transducer which comprised the majority of the cost of the device.

Compliance was the most heavily weighted factor, as compliance not only leads to undesirable off-axis movement in the output section, but also results in an effective “loss” of motion, as a considerable portion of the total displacement could go into compressing the flexure joints. In effect, this would require a transducer with larger travel, increasing the cost. Note that the effect of compliance essentially serves to make the effective lever ratio dependent on force. While normally this would affect the accuracy of the system, Terfenol-D already has a non-linear response. Because of this, the system will require force-dependent control to obtain accurate displacement output. Therefore, compliance in the lever system can be accounted for through this control strategy and it will not affect the final accuracy of the device.

2.1 General joint design and modeling

For analysis, the flexure joints were modeled as rectangular cantilevered beams under axial loading, subjected to compressive axial loading and a known angular deflection that corresponds to one half of the angular travel of the system, as shown in Figure 3.
The assembly was designed to be manufactured as it would be in the center of its linear travel (position B), and assembled pre-loaded to position A. This way, if total angular travel for a particular joint is $\Theta$ degrees, and components are assembled to be in an initial state of $-\Theta/2$ (position A), then maximum travel will occur at $\Theta/2$ degrees (position C), thus effectively halving the angular deflection requirement of the joint. This scenario also maximizes linearity of motion for a consistent lever ratio.

Maximum stress was taken as the sum of axial and bending stress. Euler buckling was also considered in the design stage. A2 tool steel was chosen for the flexures due to its high strength, good fatigue life, and ability to be deep-hardened. Maximum allowable stress was determined using a factor of safety of 1.3 with respect to the endurance limit of high strength steels, resulting in a maximum allowable stress of 569 MPa.

The effects of bending moments on reducing the output force of the assembly were only calculated for the worst case to determine their significance. Joint height was fixed to 50 mm, while joint length and thickness were calculated to minimize compliance subject to stress and buckling constraints.

### 2.2 Linearity, size, and complexity

Linearity was analyzed by plotting output motion vs. input motion. Designs were evaluated by creating a linear fit trend line to these plots and comparing their R-squared values. A benchmark for size was developed by creating a worst-case scenario based on the length of a direct-acting actuator. Without any mechanical advantage, given the magnetostriction and displacement considerations above, this transducer would be over 2 meters long. Complexity was simply defined as the number of beams and joints in each design.

### 2.3 Compliance

In a compliant joint design, it is desirable to have bending compliance in one direction while maintaining stiffness in all other directions. This can be attained by designing joints with large aspect ratios\(^7\), but even these designs have a limit to their effectiveness. Therefore, for a given flexure joint, compliance is primarily determined by loading and angular travel. The rest of the mechanism has significantly more design flexibility that allows designs that are sufficiently overbuilt with regards to stiffness, so compliance was evaluated only in the flexure joints for comparison purposes.

Compliance was estimated by treating each joint as a simple beam in uniaxial compression using the following equation:

$$\delta = \frac{F\ell}{AE}$$

where $\delta$ is joint deflection, $F$ is the applied load, $\ell$ is the effective length of the joint, $A$ is the cross-sectional area of the joint, and $E$ is Young’s modulus. Total effective deflection for each design was calculated by taking the sum of every joint’s deflection times each joint location’s effective lever ratio, using the following equation:
\[ \delta_{total} = \sum_{j=1}^{n} \delta_j R_j \]

where \( \delta_{total} \) is total deflection, and \( \delta_j \) and \( R_j \) are the deflection and effective lever ratio at each joint location.

### 3. RESULTS OF ANALYSIS, FINAL DESIGN DECISION

The first stage of analysis involved determining which factors were important. The effects of bending moments in the design with the largest bending moments, the straight lever system, resulted in a reduction of force of 0.1 N at the output stage; therefore the effects of bending moments in the flexures were neglected for the remaining studies. In the linearity study, all three designs had R-squared values greater than 0.999, so linearity was considered a non-determining factor. This is expected, as the relatively small overall travel resulted in angular travels of the flexure joints of well under 1 degree from the center of travel. The effects of the remaining factors--size, complexity, and compliance--were analyzed using a decision matrix with weightings of 20% for both size and complexity and 60% for compliance. Table 1 shows the raw values for each of these factors for each design.

<table>
<thead>
<tr>
<th>Design</th>
<th>Compliance (m)</th>
<th>Size (mm)</th>
<th>Complexity (# of features)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Lever</td>
<td>6.92E-05</td>
<td>300.0</td>
<td>5</td>
</tr>
<tr>
<td>Bent Lever</td>
<td>3.62E-04</td>
<td>261.7</td>
<td>11</td>
</tr>
<tr>
<td>Dual Bent Lever</td>
<td>2.23E-07</td>
<td>442.4</td>
<td>14</td>
</tr>
</tbody>
</table>

To get a final weighted score the results were scaled by their respective weighting factors such that a maximum of 10 points were available for a given design (0-6 for compliance, 0-2 for size, and 0-2 for complexity). For compliance, a score of 0 corresponded to a compliance equal to 5% of the overall travel, while 6 points corresponded to the lowest compliance of all designs which was less than 0.009%. Note that designs with greater than 5% compliance receive negative points. This simulates an additional cost criterion, as designs with excessive compliance will require a larger, more expensive Terfenol-D transducer to achieve the same motion. For size, a score of 0 corresponded to half of the overall length of a design with no mechanical advantage (1560 mm), while 2 corresponds with the smallest of all designs which was 262 mm. For complexity, the design with the highest number of features gets 0 points, while the one with the lowest number of features gets 2 points. Table 2 shows the final weighted scores for the designs, with the dual bent lever design as the highest rated design. One additional advantage of the dual bent lever design over the others is that despite being complex, it has symmetry over two planes, which should practically eliminate off-axis motion.

<table>
<thead>
<tr>
<th>Design</th>
<th>Compliance</th>
<th>Size</th>
<th>Complexity</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight Lever</td>
<td>2.7</td>
<td>1.9</td>
<td>2.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Bent Lever</td>
<td>-11.4</td>
<td>2.0</td>
<td>0.7</td>
<td>-8.7</td>
</tr>
<tr>
<td>Dual Bent Lever</td>
<td>6.0</td>
<td>1.3</td>
<td>0.0</td>
<td>7.3</td>
</tr>
</tbody>
</table>
4. **FINAL DESIGN AND VALIDATION**

After selecting the most appropriate lever configuration, the design was created in Solidworks, and strength, deflection, and buckling resistance were validated in COMSOL.

4.1 **Description of final design**

Figure 4 shows the layout of the various components for the first iteration of the bulk motion system. The “cantilevered beam” portion of the flexure joints are 2.4 mm long, 1 mm thick, and 50 mm wide. Rigid beam lengths are 150 mm, as measured from the centers of each flexure. The beams sit 85 degrees from the horizontal in their initial, pre-loaded state, and the flexures deflect approximately 0.5 degrees throughout the length of travel. The Terfenol-D transducer expands approximately 0.23 mm, resulting in an output displacement of 2.5 mm. Transducer force is 21.8 kN, and output force is 2 kN.

![Figure 4. Complete bulk motion assembly](image)

The principle of operation is as follows: The assembly is fixed at (A). The Terfenol-D transducer (B) expands longitudinally due to magnetostriction, causing the transducer end caps to move away from each other. The transfer rods (C) serve the purpose of changing the direction of the applied force from the transducer, as they are attached to opposite top/bottom caps (D). This, in turn, causes the top and bottom caps to move closer to each other, thus horizontally expanding the outer frame which is made up of rigid beams and flexure joints (E, F). Due to the geometry of the outer frame, displacement at the output (G) is increased by a factor of about 11.

Compliance and backlash from the system outside of the flexure joints has been minimized by ensuring all bolted connections are either axial or in double shear. Backlash is essentially eliminated in double-shear joints by using press-fit pins or centerless ground AN bolts in close-fit holes when required.

4.2 **FEM validation**

The lever system’s operation was validated via a 2D plane strain study using COMSOL. This ensured that not only was stress within allowable limits, but also that the flexure joints were behaving as expected. A linear buckling study was also performed to ensure the stability of the thin flexure joints under heavy compression.

4.3 **COMSOL setup and loading**

Figure 5 shows the model of the lever system as loaded in COMSOL as well as the meshing used. For simplicity, the entire body was modeled as solid A2 tool steel. A “fixed” boundary condition was applied to the fixed end (A), and transducer force was applied to the top and bottom caps (B). Output force was applied at the output end (C).
Initially, transducer and output forces were applied as simple loads. However, this resulted in system instability, as the entire assembly would tend to contract instead of expand. Reducing output force was ineffective at solving this imbalance. It was then decided that it would be more realistic to model the output force as a linear spring, as this is much closer to the force vs. displacement reactions encountered during extrusion as seen in Figure 1. The output force was then modeled as a linear spring, with a spring rate determined to provide the desired 2 kN of force over 2.5 mm of travel. Because the system was modeled starting in its mid-travel state, the spring was given a corresponding pre-load of 1 kN. Therefore the overall FEM study concentrated on the last half of total travel.

4.4 FEM results, first iteration

Figure 6 displays the results of the first round of the stress/strain study. The outline represents the shape of the lever system before deformation. Note that deflection is exaggerated for clarity. Stress in pascals is shown in the scale, while the axes show position in meters. The FEM predicted stress was about half of that predicted by treating the flexure as a rectangular cantilevered beam, and the linear buckling study validated the system’s stability.

Figure 7 displays the FEM deflections in both the horizontal and vertical directions. The plot on the left shows x-displacement from the center position of travel, while the plot on the right shows y-displacement from the center position of travel. Note that because this study focuses on the last half of travel, the expected displacement in the x-direction is...
1.25 mm. The expected lever ratio was 10.9, while the FEM predicted lever ratio was 10.26. There are likely two principle causes for this difference: First, motion in the flexure joints does not occur by rotation about precise points as assumed in the cantilever approximation, but is distributed along the length of the flexure joint. Second, compliance could also play a role in reduction of effective lever ratio.

![Displacements from FEM study: X-direction shown on left, Y-direction shown on right](image)

Figure 7. Displacements from FEM study: X-direction shown on left, Y-direction shown on right

To separate the effects of compliance and lever ratio inaccuracy, the simulation was re-run with half of the design load. Theoretically, this should also halve any displacement loss to compliance. Therefore, with reduced loading, if the effective lever ratio is closer to the predicted lever ratio, the error can be attributed to compliance. With the FEM conducted at half loading (same displacement), the effective lever ratio increased from 10.26 to 10.87; much closer to the predicted lever ratio of 10.90.

In all, the FEM model showed approximately half the predicted stress and significantly more compliance; about 6% of total travel. Clearly the FEM does not match the analytical design. At this point one previous assumption becomes glaringly false: For the initial design, only the rectangular beam portions of the flexure were considered to be flexible; all other material, including the fillets where the beam portions meet the larger beam portions, were considered rigid. The fault in this assumption becomes obvious when looking at the fillet areas in Figure 6. Note that on the inset, the portion contained within the dotted lines represents the rectangular beam used in the cantilever approximation.

4.5 Second iteration, FEM results

While the first iteration design meets stress requirements, there is much to be gained; it is desirable to push the materials closer to maximum allowable stress to reduce compliance. To accomplish this, the rectangular area was shortened drastically and the fillet radius was reduced to one third of the original amount. From here the joint was thickened until the bending moment of the joint became large enough to affect output force.

Figure 8 shows the changes made for the second design and von Mises stress for the fully loaded condition. FEM stress was much closer to the maximum allowable stress, and the lever ratio under full load increased from 10.23 to 10.44, resulting in compliance equal to about 4% of total travel. This is a 30% improvement over the first iteration. Half load FEM lever ratio for the second design is 10.88, compared to 10.87 for the first design, and 10.90 for the analytical rigid body case.
5. CONCLUSIONS

This design has met the requirements to provide bulk-motion for a micro-extrusion device. Predicted stress is also well within allowable limits, and displacement lost to compliance is acceptably small. The design could be further optimized by modeling both the fillets and the rectangular portion of the flexure as a variable cross section beam.

Beyond microforming, this assembly could be used to provide precision motion for other manufacturing processes or robotics applications that could benefit from the fast response and large force generation of Terfenol-D. This design could also very easily be modified for a pull configuration by eliminating the transfer rods and directly mounting the transducer to the top and bottom caps of the lever assembly.

The next step in this study will involve building a prototype to make a more direct comparison between using Terfenol-D bulk motion versus more conventional methods. This study will compare the tolerance capabilities, energy efficiency, and estimated overall cost effectiveness of both systems. Further research will focus on designing and testing a Terfenol-D transducer to provide ultrasonic vibration for ultrasonic micro-extrusion.

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