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A BATCH WAFER SCALE LIGA ASSEMBLY AND PACKAGING TECHNIQUE VIA DIFFUSION BONDING

Todd R. Christenson[1] and Dave T. Schmale[2]
[1]Electromechanical Engineering Department
[2]Direct Fabrication Technologies Department
Sandia National Laboratories
Albuquerque, NM 87185-0329
e-mail: trchris@sandia.gov

ABSTRACT

A technique using diffusion bonding (or solid-state welding) has been used to achieve batch fabrication of two-level nickel LIGA structures. Interlayer alignment accuracy of less than 1 micron is achieved using press-fit gauge pins. A milli-scale torsion tester was built to measure the diffusion bond strength of LIGA formed specimens that has shown successful bonding at temperatures of 450°C at 7 ksi pressure with bond strength greater than 100 Mpa. Extensions to this basic process to allow for additional layers and thereby more complex assemblies as well as commensurate packaging are discussed.

INTRODUCTION

The fact that MEMS technology utilizes components that are many times desired to have three-dimensional geometry and at the same time employs fabrication techniques based on planar processing continues to present a challenge central to micromechanics. Equally troublesome, packaging of micro electro mechanical devices and systems remains the most costly addition for most applications. The three-dimensionality constraint has been alleviated somewhat by various high aspect-ratio processes based on additive thick photoresist techniques [1-5] as well as deep silicon etching [6,7]. The nature of high aspect-ratio microstructures, however, complicates further process integration which is exemplified by the increased difficulty in maintaining intercomponent tolerances. A journal bearing at several hundred micron thickness illustrates this problem. An additional problem area in LIGA (or deep x-ray lithography, DXRL) based metal microfabrication has been achieving planarization which is a need arising from non-uniform deposition processes associated with this additive molding technique. The implementation of precision diamond lapping and polishing has yielded excellent thickness control [8] and has revealed its utility in the same way CMP (chemo-mechanical polishing) has furthered surface micromachining (SMM) capability [9]. More complex LIGA device geometry has been necessarily implemented with the addition of microassembly [10]. Problems and costs associated with serial microassembly and packaging, however, have plagued the implementation of high aspect-ratio metal micromechanisms that have required individual component assembly. A technique is necessary, therefore, to provide batch assembly and packaging of LIGA fabricated mechanisms that inherently must provide for multi-level precision high aspect-ratio processing.

Previous work has recognized the above limitations that have been an issue in particular in arrayed high aspect-ratio vertical actuators [11]. This approach used successive DXRL, electroforming, and planarization steps using bonded PMMA techniques. Complications arise in this type of processing due to plating base integration and eventually photoresist stability. Other related batch wafer transfer techniques have been explored by integrating silicon micromachining with solder bump electroplating [12].

The batch diffusion bonding technique to be presented here is found to directly reconcile the aforementioned problems. The fact that diffusion bonding or solid-state welding takes place with insignificant creep, no melting, and thus no perturbation of the joined surfaces is perfectly suited to precision microfabrication. The smooth flat surface insisted by successful diffusion bonding is analogous to the requirements of silicon direct silicon-silicon bonding and is provided by precision diamond based planarization. The basic approach, alignment technique, two-level results and bond strength testing will be described.

BASIC PROCESS

Initial diffusion bonding tests were performed on individual DXRL defined parts electroformed from nickel. All electroplating work was carried out in a nickel sulfamate based bath at 50°C with a plating current density of 50 mA/cm^2. The 7-layer component depicted in Fig. 1 is exemplary of these

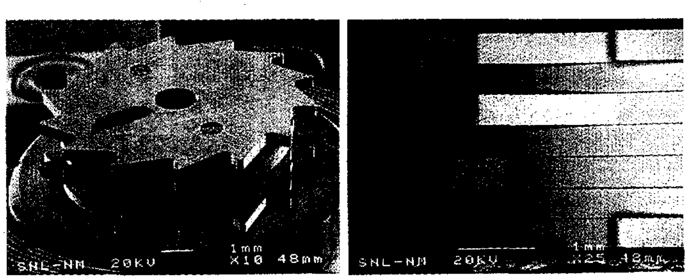


Fig.1 SEM photographs of 7-layer diffusion bonded all nickel component defined by DXRL. Individual layer thickness is 430 μm.

DISCLAIMER

tests and is unique in the sense that all interfaces have identical overlap area which allows it to be diffusion bonded in one step while maintaining equal pressures at each interface. Copper wires have been press fit into two locating holes to provide interlayer alignment for the component. This preliminary work identified successful bonding parameters of temperatures near 500°C and pressures near 10 ksi with periods of several hours.

The basic batch wafer-scale diffusion bonding scheme is illustrated in Fig. 2. Two substrates are prepared, one with and one without a sacrificial layer, and are subsequently decorated with complementary DXRL formed and planarized geometry. If fully released two-layer components are desired, a sacrificial layer is applied to both substrates. For multiple layer released components, a titanium layer may be used to protect the second sacrificial layer until release. Typical substrate materials are nickel, alumina, or silicon. Copper at 1 μm thick serves as the sacrificial material for nickel structures and can be etched in wet chemistry that in no way attacks the mechanical nickel material. The copper sacrificial layer also must not interact with the mechanical material (nickel) in order to retain its etchability and not disturb the planarity of the mechanical material surface for subsequent diffusion bonding steps. Copper has been found to be suitable for this task and a diffusion barrier material has been found not to be necessary.

The substrates are also provided with DXRL patterned alignment structures to allow the press fitting of alignment pegs. The resulting alignment scheme uses commercially available precision circular gauge pins which have a diametrical tolerance of +1μm/-0μm. The pins are cut to length and press fit into one of the substrates which will be designated the foundation substrate without a sacrificial layer. The other substrate (the sacrificial substrate) is then press fit onto the foundation substrate. This step has been demonstrated without the assistance of any optical instruments and is aided by slightly beveling the end of the pins.

Prior to joining the substrates, the nickel is initially cleaned with an oxygen plasma followed by an ammonium hydroxide treatment to remove the nickel oxide [13]. The substrates are immediately placed in a hot press apparatus which is evacuated to the 10^{-6} Torr range and backfilled with argon prior to heating and pressing. The hot press accommodates 6-inch diameter subtrates and is capable of providing a 50 ton load at 1100°C. Since the bonding area will likely never be greater than 50% of the substrate area, this press is well suited for the 3 and 4 inch diameter substrates that are used here at 10 ksi pressures.

Subsequent to bonding, the substrates are removed from the hot press and placed in a liquid sacrificial layer etchant that releases the entire sacrificial substrate. Additional layers are processed in the same manner and it is evident that there is no limit on the number of levels that may be joined.

RESULTS

The test mask set that was used includes a layout with a variety of geometry which when mirrored and stacked constitutes a variety of overlapping structures. Two level nickel structures resulting from the batch alignment and diffusion bonding sequence are shown in Fig. 3. Interlayer alignment of less than 1 μm was achieved as revealed by the two level x-y vernier measurement fiducials shown in Fig. 4. These vernier patterns are placed near the outer edge of the 3 inch diameter pattern and co-located with the press fit pin alignment structures thereby ensuring even better than 1 μm alignment between these areas.

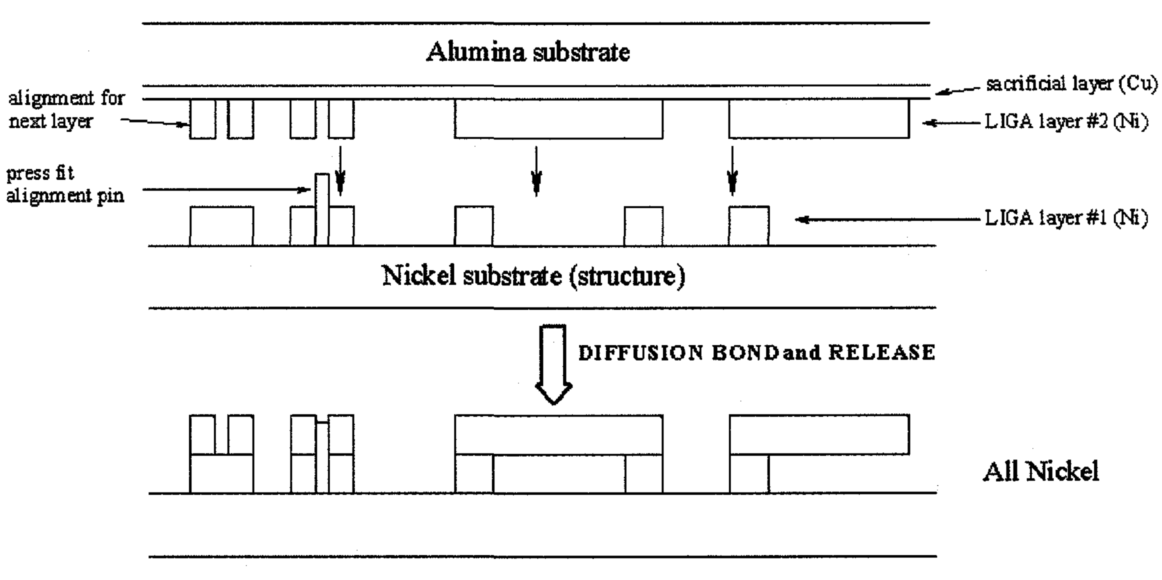
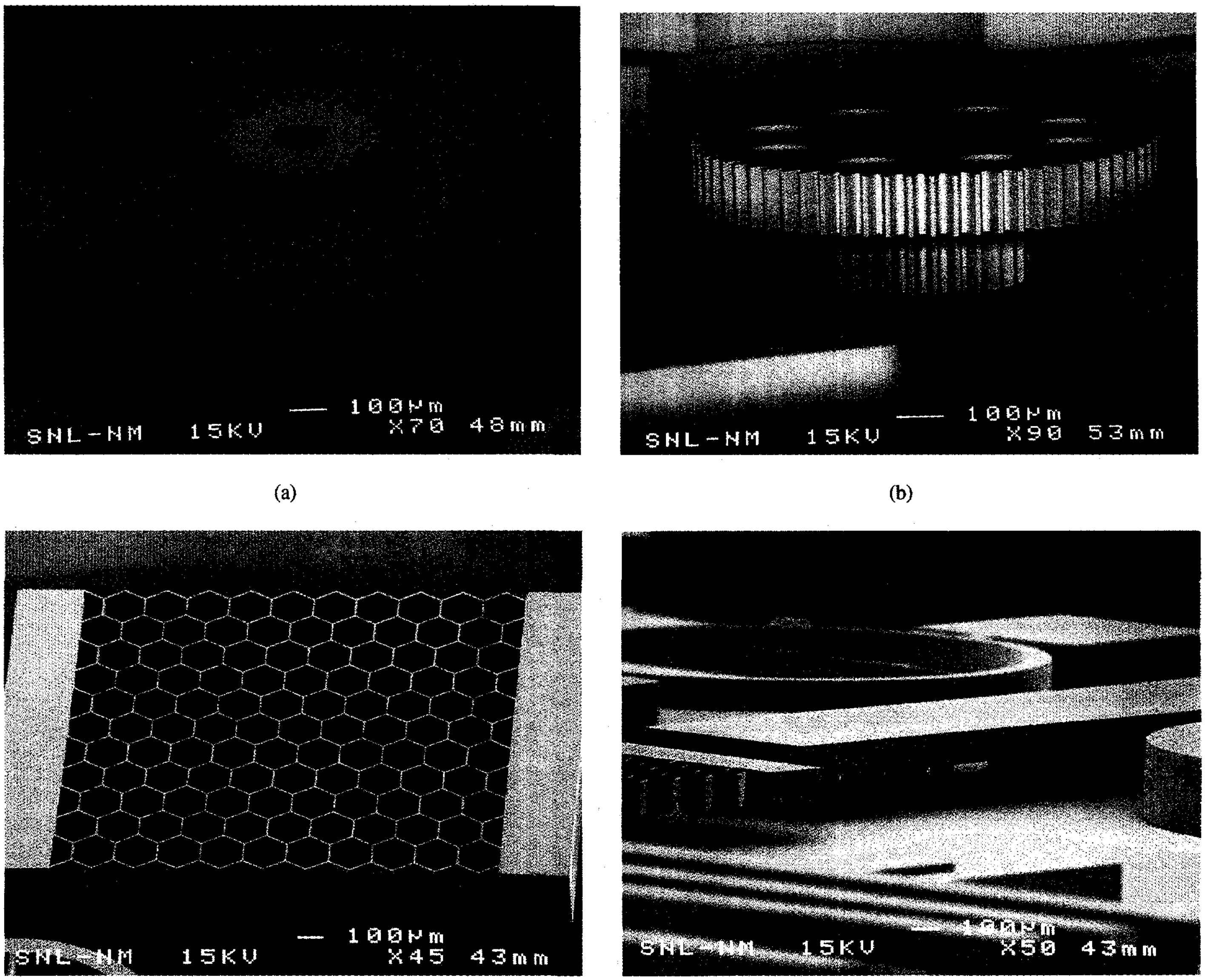
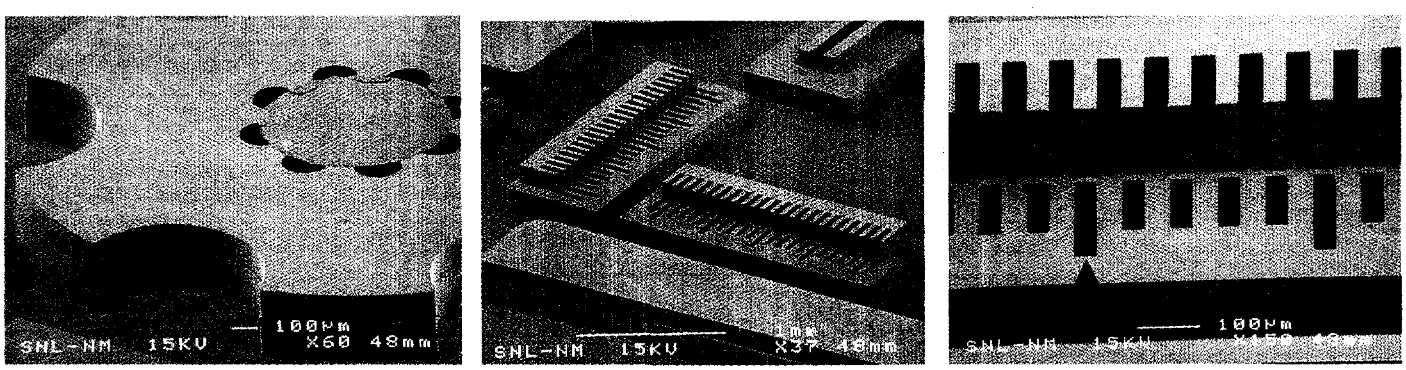


Fig. 2 Batch wafer-scale DXRL based diffusion bonding procedure.



(a) (b) (c) (d)

Fig. 3 Various two-level batch diffusion bonded nickel LIGA components. The bottom and top layer thicknesses are 200 µm and 150 µm respectively. Fig. (a) small gear on large gear, Fig. (b) large gear on small gear (backscatter image reveals second layer surface topology due to relief of alumina substrate roughness) Fig. (c) cantilevered grid, Fig. (d) covered channels.



(a) (b) (c)

Fig. 4 Alignment scheme (a) showing 32.0 mil diameter pin press-fit into alignment structure after release of 2nd layer sacrificial substrate. X and y directional alignment verniers (b) indicating less than 1 micron alignment accuracy (c). Each vernier indicates 0.5 micron misalignment.

In this example, the foundation substrate material was alumina which has a much lower thermal expansion coefficient than nickel. This situation is believed to be responsible for a tensile strain in the nickel bonded layers and has been revealed by the use of ring and beam buckling structures [14] via the two-level diffusion bonding process. Internal strain as great as 0.05% has been measured in this way. Figure 5 shows a two-level ring and beam structure which has buckled. The use of metal substrates and in particular nickel with more closely matched thermal expansion to the electroplated nickel reduces this bonding induced strain.

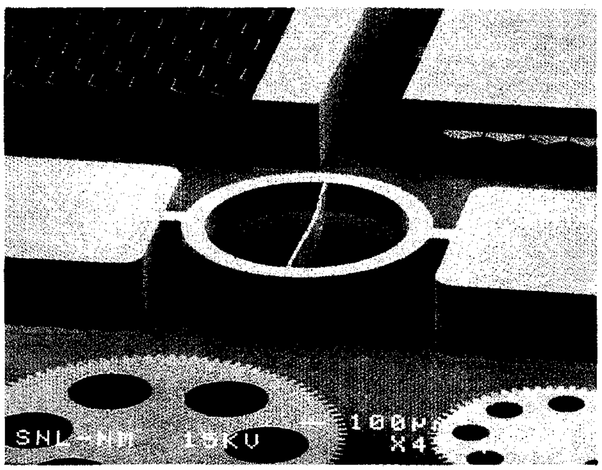


Fig. 5 Second level buckled ring and beam structure revealing a tensile strain in the diffusion bonded nickel layer. The substrate material is 99.6% alumina.

The Ni-Ni diffusion bonding should ideally be accomplished at the lowest temperature and pressure possible while maintaining an acceptable bond strength. An interlayer low melting temperature metal [15] or eutectic system [16] is commonly used in metal bonding to lower the bonding temperature. This approach was avoided due to the added process integration complexity as well as the attractiveness of single material components. Reinforcement of this position was obtained through the finding that excellent bond strength is achieved at bond temperatures as low as 450°C at 7 ksi pressures. This is well less than half (690°C) the absolute melting temperature of nickel and it is common to require two thirds of the absolute melting point temperature to achieve a good bond. This surprising result is believed to be due in part to the very fine grain structure of as-electrodeposited metals and is significant since higher temperature treatments (>600°C) substantially degrade the mechanical properties of electrodeposited nickel [17]. Thus energy from grain boundary motion encourages coalescence of grains at the diffusion bond interface. Surface treatment and substrate parallelism also play a large role and typical parallelism after lapping is near 0.1 mil over a 3" substrate area. Metallography results of the diffusion bond interface are shown in Fig. 6.

In order to better quantify diffusion bond strength and characterize the temperature – pressure – time tradeoffs, a milli-scale LIGA torsion tester was designed and built. Figure 7 shows photographs of the torsion tester that enables testing of local shear strength across the entire substrate area using arrayed specimen shapes representative in size of actual components. The torsion specimen shape is shown in Fig. 8

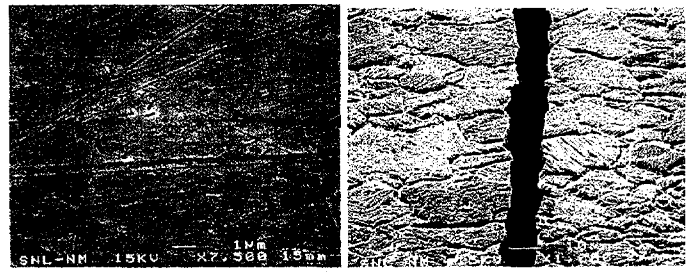
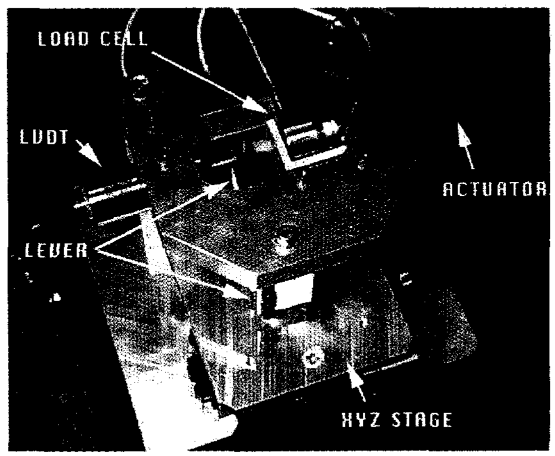
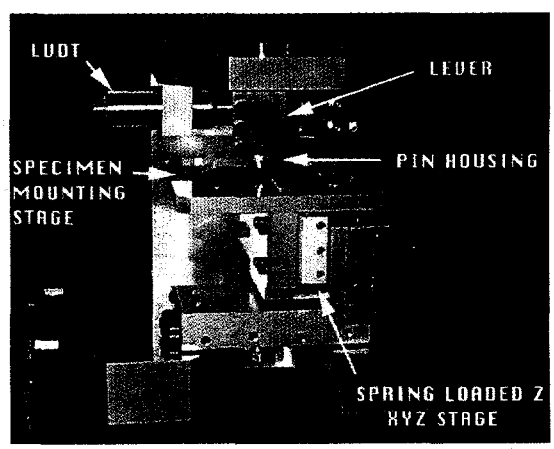


Fig. 6 Metallography of the nickel-nickel diffusion bond interface resulting from 450°C, 7ksi bond. A barely perceptible bond line is indicated by the arrows (a) which is revealed after a grain boundary etch (b).



(a)



(b)

Fig. 7 Photographs of the LIGA torsion tester. (a) shows the actuator drive screw which contacts the load cel that is free to move against the lever and engage the LVDT. The LVDT measures the lever arm displacement at a point directly opposite the load cell nylon lever contact button which in this position eliminates errors from load cell compliance. (b) shows the pin housing extending from the lever arm and the 3 inch specimen holding platen which can be positioned via 4 ball slides.

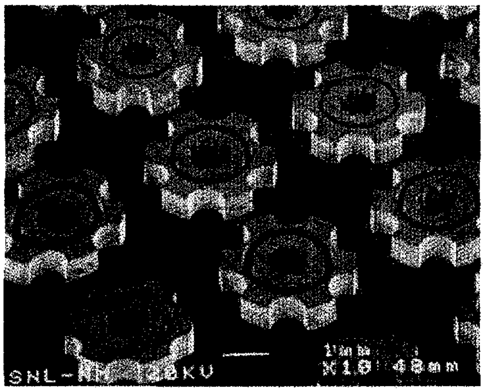
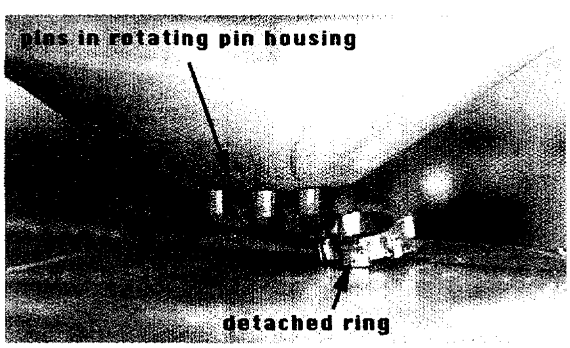


Fig. 8 Nickel substrate with diffusion bonded torsion test specimen array. The inner ring was provided to allow press fitting of an alignment pin if necessary.

and consists of a scalloped outer ring which accepts a hexagonal pattern of 800 μm diameter pins on a 3 mm bolt circle. The pins are press-fit into a LIGA fabricated disc that is then bonded into the pin housing with high strength epoxy. The pin housing rotates on precision bearings and is fixed in the lever arm which applies torque to the ring specimen thereby shearing the ring from the substrate. A motorized micrometer with 7mm travel applies the load at the end of the 2 inch lever arm and displaces a load cell mounted on a ball slide which is driven into a spring loaded LVDT. The moment arm length changes less than 0.5% over the 5-7° total rotation of the lever due to the normal direction of the applied load. Data are graphically prepared real time using a PC and a Validyne signal conditioner which provides calibrated load and displacement signals. The specimen engagement and sheared ring are shown in Fig. 9.

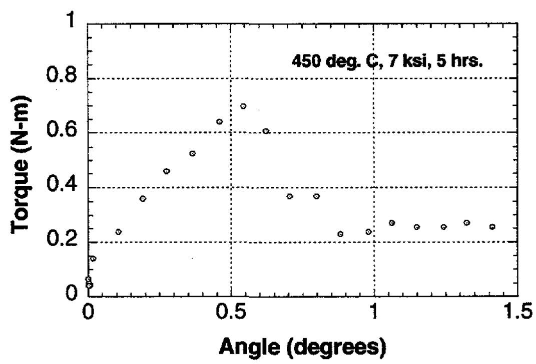
(a)



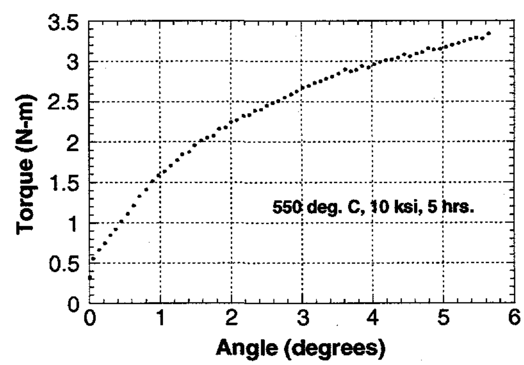
(b)

Fig. 9 Close-up photographs showing pin engagement with specimen (a) and completed test with detached ring after being ejected from between the pins.

A variety of bond strengths have been measured which have been found to be most sensitive to surface preparation and temperature and not as sensitive to pressure and time of bonding. A typical torque-angle curve for the scalloped specimen measurement is shown in Fig. 10(a). This sample was bonded at 450°C and a pressure of 7 ksi with an unoptimized surface treatment. The shear strength of the bond averages 130 MPa which is slightly less than half of the yield strength of the nickel material. The nickel tensile curves for various plating densities are shown in Fig. 11 [17]. A torsion test curve for a 550°C, 10 ksi Ni-Ni bond is shown in Fig. 10(b) which indicates a maximum shear stress of greater than 600 MPa. The test was not able to shear the specimen ring off as it began to yield the specimen near the maximum displacement. Thus, a bonding temperature near 480°C at a pressure of 7 ksi has been chosen to achieve an acceptable bond strength. An unanticipated benefit of this testing method is the ability to test adhesion of plating base layers. The Ti/Cu plating base used for nickel has been found to have an adhesion strength to alumina for example of near 250 Mpa.



(a)



(b)

Fig. 10 Torsion test curves for two different nickel-nickel diffusion bond conditions.

CONCLUSIONS

The work outlined here forms the basis for a highly desired outcome in metal microfabrication of MEMS which takes advantage of the unique qualities of deep x-ray lithography based fabrication including the attributes of additive processing as well as the advantages associated with

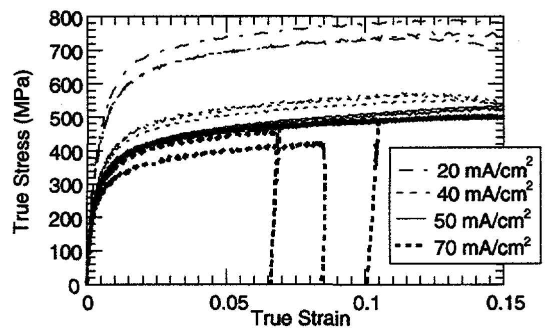


Fig. 11 Tensile pull data for as-electrodeposited nickel.

batch planar processing. The inherent batch assembly associated with this approach may be extended to include a process similar in nature to polysilicon surface micromachining but with the substitution of metal for polysilicon and several hundred micron structural heights in place of a few microns. For example, with the addition of one patterned sacrificial layer and an additional LIGA layer to the two-layer process, a pin joint may be formed. The fact that a metal package may be formed directly surrounding the mechanical system is desirable for some devices. Integration of magnetic metals such as permalloy along with copper which are readily accommodated in LIGA also will extend the application possibilities.

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