Non-thermal Micro Adjustment Using Ultrashort Laser Pulses

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In the field of micro technology highest accuracies have to be attained regarding position, angles and distances. To achieve this task within reasonable expenses roughly tolerated assembly followed by high-precision adjustment is often applied. As the final tolerances tend to get smaller in the same manner as the dimension of the devices common adjustment processes are reaching limits rapidly. To provide a better solution for this discrepancy the Bavarian Laser Centre investigates a new process of highly accurate, contact-free and time-efficient micro adjustment for a wide variety of materials using ultrashort laser pulses. The process mechanism is based on the effect that an ultrashort laser pulse of high intensity is able to produce plasma on the surface of the absorbing bulk material in nearly isochoric manner. The following expansion of the plasma into the confining medium excites shock waves propagating into the bulk material due to recoil effects. These shock waves, which rapidly decay to compressional waves, induce near-surface plastic deformation which results in bending the actuator's free end away from the laser beam. With suitable actuators this can be used for highly accurate adjustment. Results of previous investigations show that the bending angle can achieve accuracies in the scale of a few 10 µrad while allowing maximum deflections of a few degrees. Up to now copper, steel, silicon and pyrex-glass have been successfully deformed with this process.

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1. Introduction

The increasing miniaturization of micro-optical, micro-electromechanical systems (MEMS) or microoptomechanical systems (MOEMS) as used in hard disk drives, fiber optical devices, highly integrated sensors etc. demands highest accuracy in terms of positioning functional components among each other. Meeting these strict tolerances is still an up-to-date key assignment in micro-manufacturing. As high precision positioning and fastening during manufacture is only possible with enormous economic and technical effort, relative roughly tolerated assembly of the complete system followed by a precision adjustment of active elements holding critical parts as lenses or sensors, offers a more cost-efficient way of producing micro systems. Due to the limited access to certain components in a completely assembled system and furthermore the sensitivity of micro systems to mechanical loads or impacts, laser-based adjustment processes offering contact-free treatment have already established in numerous applications.

As a first approach to meet the stricter tolerances of micro systems macro adjustment processes may be adapted to the downscaled domain to a certain amount. E.g. the laser-based Temperature Gradient Mechanism (TGM), schematically shown in Fig. 1, has already been successfully adapted to a certain extent. The bending process induced by the TGM consists of three main steps. At first the laser, irradiating the surface of the actuator, is used to induce a temperature gradient and in succession also a compressional stress gradient and flow stress gradient along the cross section of the bulk material. As consequence material near the surface starts to plastically deform and expand. When the laser is shut off, all gradients disappear after a certain time due to heat conduction and the actuator starts to cool down. During this phase the deformed zone, which now possesses a higher flow stress compared to the heating phase, contracts and leads to a permanent bending of the actuator towards the irradiated surface. [1, 2]

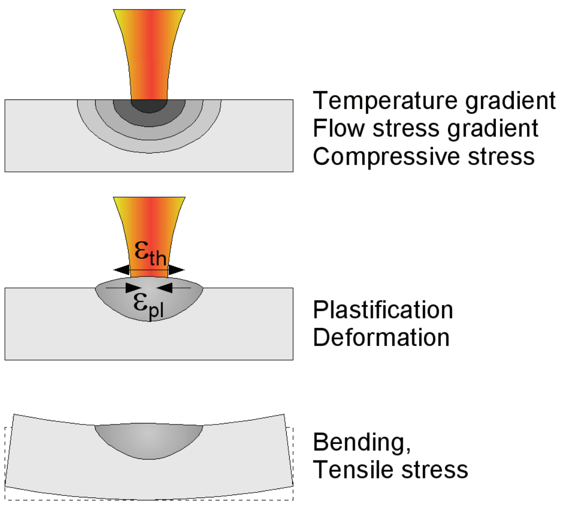

Fig. 1 Temperature Gradient Mechanism

This process mechanism has already been successfully introduced for a number of industrial applications and is widely gaining attention. Known industrial applications include the micro-adjustment of reed-contacts and drive actuator arms holding the read/write heads for computer hard drives. [1, 3] Although the process is a very good choice for specific tasks in micro technology disadvantages arise as a result of the thermal principle.

First, the final deformation is reached after the actuator has cooled down to ambient temperature. Depending on the material and the actuator geometry, this cooling can take up to 30 seconds, which is a significant downtime concerning closed-loop controls and overall process time. Second, thermally induced residual stresses remain in the actuator after the adjustment is finished. These stresses reach the scale of the material's yield stress, inducing a certain risk of downgraded thermal and mechanical long term stability. Third, the thermal impact may damage sensible structures close to the laser interaction zone. Monocrystalline silicon or fused silica as standard substrates for MEMS and MOEMS are particularly sensitive to high temperature gradients, which can lead to cracks due to their brittleness.

As these disadvantages arise as a reason of the thermal process principle, adjustment based on non-thermal interactions may offer solutions for this discrepancy and allow time and cost efficient adjustment processes for up-to-date and also upcoming micro technology. Therefore two novel laser-based and non-thermal adjustment processes developed at the Bavarian Laser Centre (BLZ) are introduced and experimental results are presented.

2. Non-thermal laser micro adjustment

A well proven and subtle way to avoid thermal load in laser processing is to switch to shorter pulse lengths, in particular to ultrashort laser pulses below 10 ps pulse duration. The special way ultrashort light pulses interact with material accounts the superior processing quality achieved with femto- and picosecond laser sources. Whereas normal laser pulses within durations of ns or more affect the target mostly based on heat conduction, the interaction time of ultrashort pulses is far beyond the timescale of thermal interaction. The photon energy is absorbed by free or valence electrons which are instantly ionized. Before energy in terms of heat can be transferred to the lattice, molecular bonds are broken and the irradiated material is transformed into a state of plasma nearly with no generation of melt. The plasma usually expands and lifts off from the interaction zone instantly taking most of the excitation energy with it. Therefore, the thermal impact on the remaining material is significantly decreased whereas the processing accuracy is greatly improved. These non-thermal effects have been converted into exact micro-adjustment process mechanisms in two different ways at the BLZ.

2.1 Ablation of a pre-stressed coating

It is well known e.g. in semiconductor fabrication that certain coatings induce intrinsic or thermal stress to the substrate, thus deforming it. By locally ablating such a pre-stressed coating using ultrashort laser pulses, the substrate relaxes partially without inducing any additional effects allowing exact alignment processes. This mechanism, as shown in Fig. 2, can be used to accurately lower or raise the free end of an actuator. [4, 5]

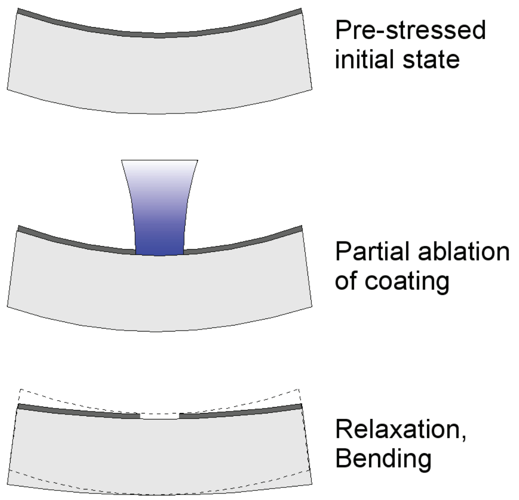

Fig. 2 Micro adjustment by ablation of pre-stressed coating

The intensity of the focused ultrashort laser pulses is set just above the ablation threshold of the coating material, so no damage to the substrate is applied. Due to the well defined pre-stress induced by the coating the achievable deviation angle per irradiation is only dependent on the ablated width or area respectively. Investigations were carried out using silicon wafers of different thickness coated with 500 nm Si_3N_4 resulting in a bending of the probe towards the coating mainly caused by intrinsic stress. Bending angles of approximately 80 µrad per irradiated track of 100 µm width have been achieved without any significant damage to the substrate.

Although this process mechanism allows highly accurate, non-thermal and very fast micro adjustment compared to the TGM, disadvantages arise. First, due to the limited pre-stress that may be induced to the substrate without the danger of a delaminating coating, achievable bending angles are limited. Moreover and also limiting the bending angle, the same area can not be irradiated repeatedly to increase the bending angle as the coating can only be ablated once. Representing the second drawback, if not already done in prior process steps, the coating has to be applied in an additional step and the actuator design and manufacture may need to be adapted. Despite these disadvantages highest accuracies are achievable as already single pulses ablating the coating within a minimal radius of approximately 50 µm lead to a deformation of the actuator.

2.2 Laser-induced micro-shockwaves

Within the investigations of ablating pre-stressed coatings a second process mechanism has been identified as a novel possibility for micro adjustment. As laser pulse intensity increases distinctly above the ablation limit, a deviation of the substrate away from the irradiated area can be observed although no pre-stress is applicated. Further investigations of this effect led to the process mechanism as illustrated in Fig. 3.

As the ultrashort laser pulse hits the target, near-surface electrons absorb the energy. By transmitting this absorbed energy to the lattice within a few 10 ps plasma is formed in nearly isochoric manner. This highly pressurized plasma expands into the atmosphere and a shockwave is induced into the material due to recoil effects. [6, 7] The shockwave plastically deforms near-surface material before it decays to a normal compressional wave transmitting the material without further significant interaction. The deformation results in a deviation of the substrate away from the irradiated surface. [8]

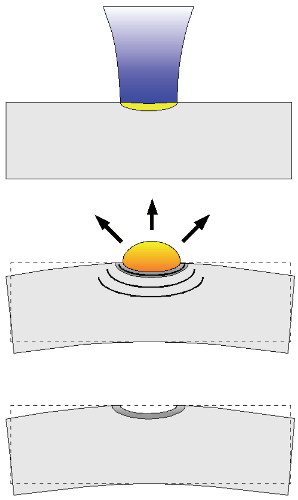

Fig. 3 Micro adjustment by laser induced shockwave

The micro-adjustment process by laser induced shockwaves possesses the same advantages as the micro-adjustment by ablation of pre-stressed coatings and furthermore overcomes the mentioned drawbacks as higher bending angles and repeatability on already irradiated areas are possible. In addition, no specific treatment of the actuator is needed due to the fact, that the bulk material itself is deformed. Therefore, the novel process mechanism is very promising as fast and highly accurate micro adjustment is feasible for applications in micro system technology. To sum up achievable values over a range of different parameters as material, pulse energy etc., experimental results are presented in the following.

3. Experimental results of micro adjustment by laser-induced micro-shockwaves

All experimental investigations were performed as schematically shown in Fig. 4. As adjustment by laser-induced micro-shockwaves results in a bending away from the irradiated area, this angle is indicated positive. The lowering of the actor's free end is acquired by a fiberoptical distance sensor allowing resolutions as low as 20 nm. Within one experiment the laser beam travels once across the actuator (broadness 6 mm) perpendicular to the main axis with a defined feed speed of v_L. After the irradiation of one complete track the bending angle is calculated with the value of the free ends lowering and the distance between laser beam track and free end. The laser used in all experiments is a Coherent "Libra" with 800 nm central wavelength, 100 fs pulse duration, 1 kHz repetition rate and a maximum pulse energy of 950 µJ focused onto the probe using an 800 nm wavelength best-form lens of 10 mm focal length.

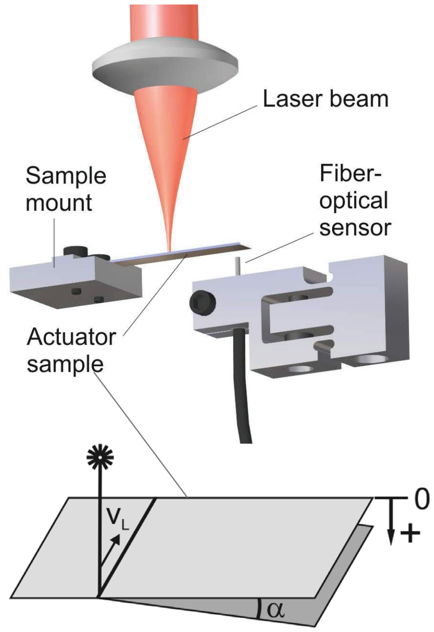

Fig. 4 Experimental setup

The diagram in Fig. 5 shows the bending angles achieved for copper, steel and silicon samples in comparison. Although pyrex glass as an amorphous material has been successfully deformed with this process, results are not presented as only a few experiments were accomplished up to now. In general, all investigated materials show an identical behaviour, only on a different scale. Copper and steel even reach significantly higher bending angles than silicon. The dependency of the bending ranges on the actuator material can be explained by regarding the material characteristics (Table 1).

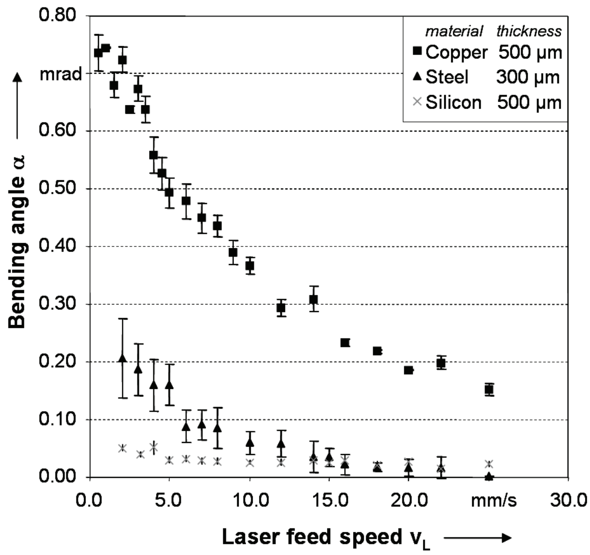

Fig. 5 Bending angle in dependency to laser feed speed for copper, steel and silicon, pulse energy 750 µJ

As copper features the lowest coefficient of elasticity of all investigated materials as well as the lowest flow limit, its resistance to plastic deformation is comparatively low and the highest bending angles can be achieved. Moreover, due to its high thermal conductivity, it is least sensitive to thermal re-bending due to temperature gradient mechanism. Steel is much harder to deform and more susceptible to thermal influences. Finally, monocrystalline silicon shows the highest resistance against plastic deformation as no dislocations or grain boundaries exist which could facilitate material flow.

Table 1 Material characteristics

Material	Young's Modulus [N/mm²]	Flow limit [N/mm²]	Thermal conductivity [W/m·K]
Copper (C17410HT)	129000	110	398
Steel (X5CrNi1018)	190000	186	16
Silicon	170000	n.a.	157

The process mechanism is repeatable on already irradiated areas as the plastic deformation of near-surface material can be cumulated up to a certain amount. So the achievable bending angle is only limited by the depth of material deformation and the applicable maximum plastic strain. This results in an asymptotic run of the bending angle curve in dependency of the number of repeated irradiations, as shown in Fig. 6.

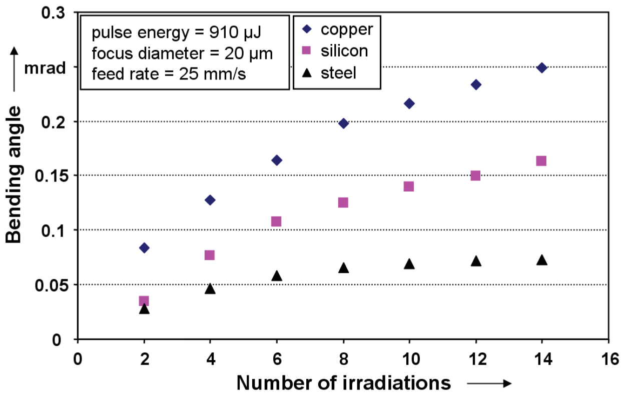

Fig. 6 Bending angle in dependency to repeated irradiation for copper, steel and silicon probes of 500 µm thickness, pulse energy 910 µJ

As one can see in Fig. 6, bending angles up to 0.25 mrad or even more are achievable on one repeatedly irradiated track. Whereas copper and steel samples show nearly no observable damage even after repeated irradiation, silicon as an extremely susceptible and brittle material can be used to visualize the microstructural changes induced by the process. Analogical Fig. 7 shows a SEM image on the left and on the right the according etched grinding pattern of silicon irradiated 14 times at full pulse energy. As seen in Fig. 6 steel already reaches the maximum bending angle after approximately 8 irradiations and keeps constant further on, accordingly structural changes are maxed out already before the viewed state. In silicon dislocations and micro cracks, which are localized approximately 50 µm around the irradiated track, can be observed and validate the impact and the residual stresses induced by the micro shockwaves. Damages like this can negatively affect mechanical long-term stability, so, according to the requirements, repeated irradiation in brittle materials like silicon should be limited to a number of 4 or below, where nearly no observable damage appears.

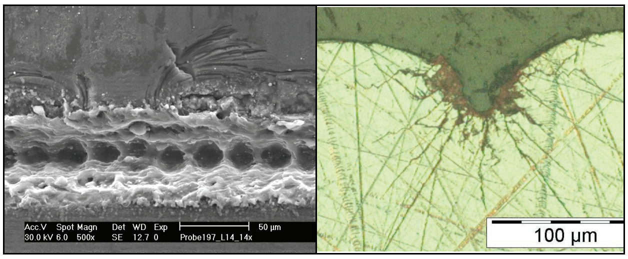

Fig. 7 SEM picture and etched grinding pattern of silicon after 14 irradiations, feed rate 25 mm/s, pulse energy 910 mW

To study the effect of vacuum on the bending process, copper samples were processed in a sealed chamber at ambient atmosphere and after evacuation in different focal positions. Fig. 8 shows the resulting bending angles as well as the corresponding power densities which were derived from the spot diameter of ablated material and the pulse peak power. Positively indicated focal positions are located above the material surface. Obviously, the bending angle is significantly increased by vacuum processing if the focal position is correctly adapted. High laser power densities and low heat dissipation encourage the bending mechanism.

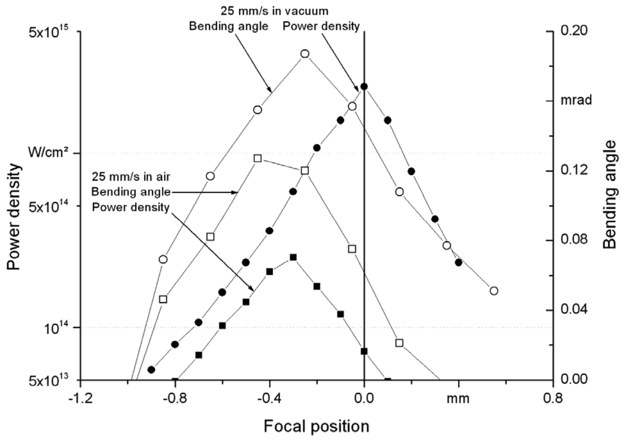

Fig. 8 Bending angle and power density in air and vacuum for copper (500 µm thickness), pulse energy 910 µJ

Due to the absence of any beam profile deforming air plasma better focusing conditions in the vacuum respectively higher power concentration lead to a more efficient ablation process and to a more powerful plasma expansion. The deviation in vacuum between the points of highest bending angle and peak power density arises from the fact, that due to the small focus diameters the ablation traces on the surface stop to overlap at a focal position of - 0.2 mm. The bending process benefits from overlapping pulses, as the material is already a little preheated from previous pulses which lowers its mechanical strength and its yield point. This argumentation is also capable to explain the increase in bending at lower laser feed rates (cf. Fig. 5).

The correlation of the bending angle to the amount of deposited laser energy per length unit becomes apparent in Fig. 9. Copper samples were processed in ambient air with different laser scanning speeds and pulse energies. Obviously, the energy input per length unit is the most relevant parameter affecting the bending angle, the pulse energy itself only has a comparatively small effect. However, if the pulse energy is to low (cf. 85 µJ, 150 µJ in Fig. 9), no bending at all can be observed, regardless of the scanning speed and the energy input. Metallographic examinations of the samples show that with low pulse energies of 85 µJ and 150 µJ the ablation threshold of the material is barely reached and nearly no ablation groove is formed. Anyhow this result points out that the usage of lower-cost ultrashort laser sources is feasible as long as the pulse peak power lies distinctly above the ablation limit of the material.

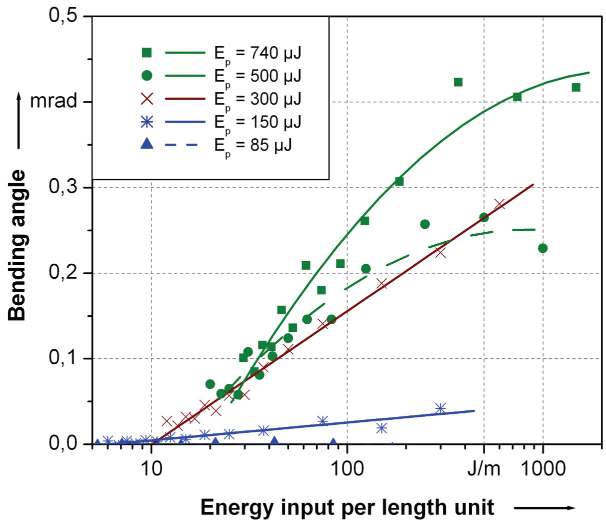

Fig. 9 Bending angles achieved with different pulse energies in copper (500 µm thickness)

Planned experiments include variation of pulse duration, beam deviation, focussing strategy, irradiation geometry and further actuator materials. The declared aim of these researches is to create the most cost- and time-effective process strategy feasible. After identifying this, applicable actuator strategies and materials are used to create a demonstrator system for an industrial application. As knowledge about long-term stability and robustness is most important for successful implementation in micro-fabrication, these demonstrator systems will be used to qualify this novel process mechanism.

4. Conclusion

Laser micro-adjustment offers a variety of advantages in comparison to classical adjustment processes. Anyhow already established process mechanisms, as the TGM, can only be downgraded to a certain dimension of miniaturization and furthermore are restricted to thermally insensible materials as a reason of the thermal process principle. Micro adjustment without any thermal interaction using ultrashort laser pulses avoids these disadvantages and offers extremely precise process guiding. One possibility is the ablation of pre-stressed coatings from substrates, anyhow achievable bending angles are very limited due to danger of delaminating coatings. By inducing micro-shockwaves into the material with high-energy ultrashort laser pulses both non-thermal interaction and applicable bending angles are feasible offering a promising novel process mechanism.

In overall adjustment with micro-shockwaves induced by ultrashort laser pulses works with a wide range of materials without special pretreatment, practically with any accuracy desired, as single laser pulses already cause a tiny deformation. One drawback of the new technique is the relatively high cost of the laser system, although typical prices for ultrashort pulse laser systems constantly decline since years.

The main application area for ultrashort pulse laser bending is expected to become the field of mechanical and optical micro-systems, where delicate components and materials have to be positioned with highest accuracy and lowest material strain available. Although the process mechanism is not limited to a specific actuator material, the use of silicon or fused silica based actuators offers a fundamental advantage: it allows the direct on-chip integration of position-critical components together with their micro-positioning devices without a further need for additional parts, manufacturing and assembly steps.

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