Ultrashort Pulse Laser Bending

Manfred DIRSCHERL[*], Gerd ESSER[*]and Michael SCHMIDT[*]

[*]*Bavarian Laser Centre, Konrad-Zuse-Str. 2-6, 91052 Erlangen, Germany*
E-mail: m.dirscherl@blz.org

Accurate positioning of smallest components represents an up-to-date key assignment in micro-manufacturing. It has proven to be most time and cost efficient to initially assemble the components with widened tolerances before precisely micro-adjusting them in a second step. The use of laser induced contact-free deformations for micro-adjustment of functional components such as recording heads or sensors has already been established for several industrial applications. The fact, however, that laser bending or shrinking processes normally rest upon thermal tensions has been found unfavorable. To overcome the drawbacks of thermal laser bending, such as time consuming cooling periods or thermally induced damage, a new laser micro-adjustment method, based on a fundamentally different mechanism is currently being researched and qualified. Instead of temperature gradients, specific effects achievable by surface structuring with ultrafast laser systems are utilized to achieve highly accurate micro-deformations. To explain the background of this novel technique, fundamental particularities of ultrashort-pulse laser material interactions are discussed using both theoretical models and practical observations. Results from extensive experimental studies are presented, revealing the potential of micro-adjustment with ultrafast lasers, concerning its precision, range and positioning speed.

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1. Introduction

The functionality of many micro system devices such as computer hard drives or micro-optical systems crucially depends on the accurate geometrical adjustment of specific lenses, sensors or other functional devices. The problem of meeting the ever stricter positioning tolerances represents an up-to-date key assignment in micro-manufacturing. Instead of high-precision manufacturing of each individual component and high-accuracy assembly it has turned out much cheaper and easier to perform production and mounting quick and roughly tolerated and to micro-adjust the critical components in a second step using specially designed actuators. As mounted micro components are typically difficult to access and highly sensitive to mechanical forces and impacts, contact-free laser adjustment processes offer a great potential for accurate manipulation of micro devices.

As, due to the continued strive towards miniaturization and integration, the need for a non-contact, automated positioning method became clearly identifiable, the first approach was to adept the macro process of thermal laser forming to the domain of micro systems. The process is typically based on laser induced temperature gradients. The so called "Temperature Gradient Mechanism [1] (TGM)" is shown in Fig. 1. The bending process following the TGM consists of three steps. First, the laser beam irradiating the actuator surface creates a temperature profile in the material which exponentially declines with progressing depth. After a certain time, the surface area starts to deform and expand. After the laser beam is turned off, the material cools back down and contracts, leading to a permanent, plastic bending towards the laser beam [2].

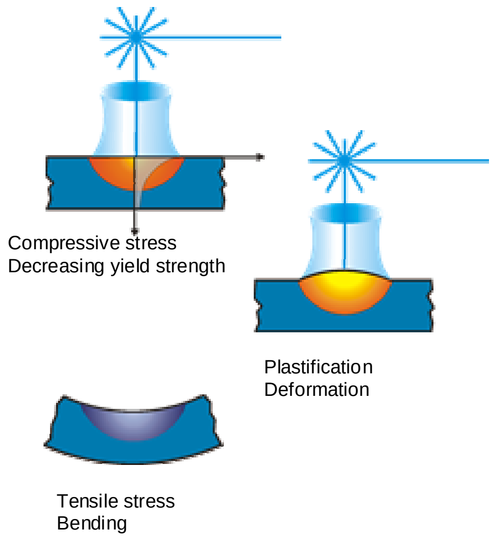


Fig. 1 Temperature Gradient Mechanism

This technique has already been successfully introduced for a number of high-precision 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 [3].

However thermally induced laser adjustment may be the process of choice for quite a number of applications in a dimensional range of some millimeters and with tolerances down to one micron, there are two fundamental problems arising from thermal tensions in general which prevent this technique from being applicable for further miniaturized tasks and many common substrate materials.

First, the final deformation is only reached after the actuator has been given a certain time to cool down. Depending on the material and the actuator geometry, this cooling can take 1-30 seconds, a significant downtime, especially in iterative control loops. Second, residual tensions remain in the actuator after the adjustment is finished. Near the surface, these tensions often reach the scale of the material's yield stress. This represents a certain risk, as the actuator then is more susceptible to mechanical or thermal loads. Also, the long-term position stability of an exceedingly pre-stressed material is by far less reliable than that of a system without prior exposure to high temperatures.

Especially concerning the field of integrated micro systems, thermal impact may also damage sensible structures close to the laser interaction zone. Mono-crystalline silicon, the overall standard substrate for semiconductor and micro electromechanical systems (MEMS) is particularly damageable by high temperature gradients, which can easily induce cracks due to its brittleness.

2. Non-thermal laser micro-adjustment

As MEMS and MOEMS are constantly gaining importance and are about to continually replace a wide number of conventional assemblies in the near future, the need for a new micro-adjustment method, allowing even smaller tolerances without the drawbacks of thermal tensions can clearly be derived. Our new approach is therefore based on the concept to obtain micro-deformations by utilizing the mostly non-thermal laser-material interaction phenomena caused by ultrashort pulses.

2.1 Initial approach

In order to convert the non-thermal surface effects into an exact micro-deformation of the irradiated sample, a completely new process mechanism is required. Fig. 2 shows our initial approach: An initially pre-stressed mechanical system is micro-deformed by gradually relaxing its elastic tensions.

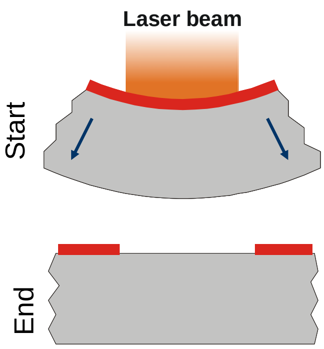


Fig. 2 Micro-adjustment by ultrashort pulse ablation of pre-stressed coating layers

The pre-stress is generated by a coating process which creates thermal and intrinsic stresses at the interface layer between substrate and coating. In our investigations, we used a thin silicon wafer coated with silicon nitride (Si_3N_4) by chemical vapor deposition. The material is deposited at 770°C which creates compressive stress in the silicon substrate at ambient temperature, in addition to the intrinsic stress caused by lattice distortions at the contact layer of both materials. In the adjustment process, this pre-stressed layer is being partially removed by laser ablation. This way, the stress propagation is locally interrupted and the coated actuator can relax, which results in a small displacement.

First experimental tests were carried out using rectangular samples (6 mm x 35 mm x 300 µm) of Si_3N_4-coated silicon. A single, perpendicular line was structured into the surface using an amplified femtosecond laser system and the achieved bending angle was evaluated by measuring the displacement of the samples tip. As the thermal and the non-thermal bending mechanism generate bending angles in different directions (see Fig. 1 and Fig. 2), it is easy to distinguish both effects. In this paper, positive bending angles are defined to be directed away from the laser beam, which corresponds to the non-thermal bending process. Fig. 3 shows the experimentally determined dependency of the bending angle on the scanning speed of the laser beam.

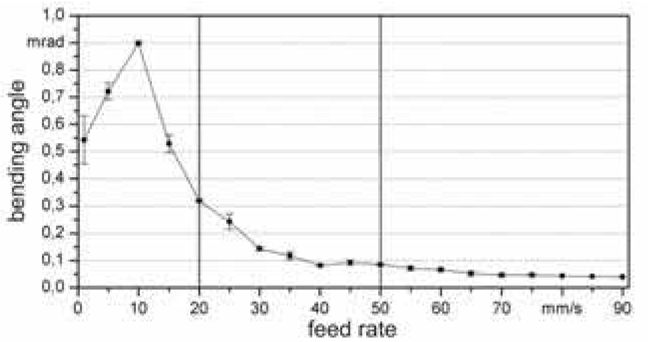


Fig. 3 Dependency of bending angle on laser feed rate
Sample: 300 µm silcon, 500 nm Si_3N_4 coated
Laser: Spectra-Physics Hurricane, 100 fs, 1 kHz, 1 mJ / pulse

Regarding the direction of the samples displacement, non-thermal bending process obviously can be observed. The decrease of the achievable bending angle at very low feed rates below 10 mm/s can be explained by thermal bending effects caused by accumulated heat which partly compensate the non-thermal bending. As the laser pulses do no longer overlap at scanning speeds above 50 mm/s leading to a only partial removal of the pre-stressed coating, the linear decrease in bending at high feed rates is also intelligible. However, there is no argumentation explaining why the bending angle strongly increases with decreasing scanning speeds between 50 mm/s and 10 mm/s, as the coating is always completely removed.

2.2 Numerical modeling

To achieve a better understanding of the stresses and tensions involved with non-thermal laser adjustment by ablation of coating layers, a Finite-Element-Method (FEM) simulation of the pre-stressed actuator samples was created using the numerical simulation program ABAQUS. Material and stress parameters are taken from literature sources [4] and derived from shape measurements of the employed wafers before and after the coating process. This way it is possible to determine the influence of gravity or different geometries of the ablation groove on the bending angle. The non-thermal ablation process was modeled in a simplified way as an abrupt removal of the concerned material areas without thermal impact on the substrate. Different ablation geometries were modeled, up to a depth of 50 µm, matching metallographic characterizations of ablation grooves at very low scanning speeds. Fig. 4 shows a stress simulation of this groove shape.

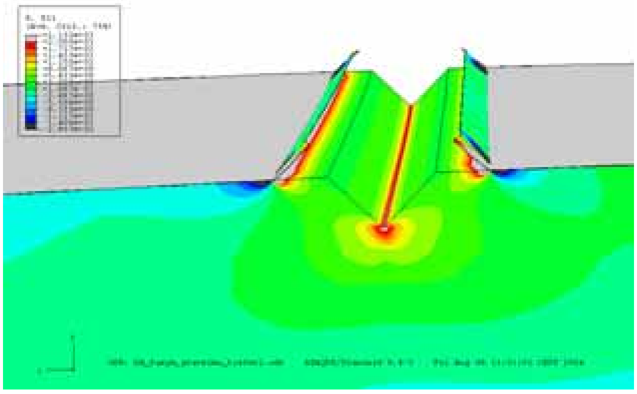


Fig. 4 FEM-Simulation of a V-shaped, 50 µm deep ablation trace and its effects on the stress distribution

Two effects can be observed which lead to an increase in bending: First, the high tensions in the interface layer between the substrate and the coating cause a delamination, covering approximately the same area as the ablation trace itself. This result is in very good accordance with experimental observations. Second, the V-shaped groove works like a notch causing a rise in stress at its bottom and a significant decrease in mechanical stability. Calculated values for the bending angles caused by the removal of a 100 µm wide trace of surface layer on different conditions are summarized in Table 1.

Table 1 Overview of FEM calculation results

Model description	Calculated bending angle [µrad]
Removal of coating	25.0
Removal and delamination	54.5
50 µm deep ablation groove with delamination	82.5

Obviously, the consideration of gravity, delamination and notch effects lead to a significant increase in bending compared to an exclusive removal of the coating layer. Still, the calculated value even assuming a critical groove geometry with a depth of 50 µm is below 0.1 mrad, whereas angles of up to 1 mrad could be measured in experimental studies (see Fig. 3). These deformations, which are obviously linked to the laser scanning speed respectively the number of pulses or the pulse overlap on the material surface cannot be explained by stresses through the coating layer, gravity effects or increasing ablation depths.

The only logical conclusion is to consider an additional bending effect which is caused directly by the interaction of the ultrashort laser pulses with the sample's surface. As for specific process parameter constellations the experimentally determined bending angle exceeds by far the calculated influence of the coating removal, the newly discovered effect is in fact the dominating bending mechanism.

2.3 Micro-bending by ultrafast laser induced shockwaves

To identify the principle of the discovered ultrafast laser bending process, a number of possible interaction effects have to be taken into consideration:

- Changes in the materials microstructure could cause changes in density and volume and create stresses
- Chemical reactions of the irradiated surface, e.g. oxidation could take place and lead to stressed surface layers
- Thermal interactions, either caused by the laser's energy directly or by the laser generated plasma in the air could create stress conditions leading to the observable deformation
- Mechanical effects, especially shockwaves caused by the instant vaporization and the fast plasma expansion of the ablated material could initiate a micro-forming process

Due to the ultrashort interaction times of femtosecond laser pulses with matter, a direct observation of the process with optical or electronic sensors is impossible. Still, the experimentally investigated dependencies of the resulting bending angles on several process and material parameters as well as metallographic grinding patterns and microscopic photographs presented and discussed in section 3 clearly show that mechanical micro-deformations caused by ultrashort pulse induced shockwaves constitute the sought bending mechanism. The process model for micro-bending by ultrafast laser induced shockwaves is schematically depicted in Fig. 5.

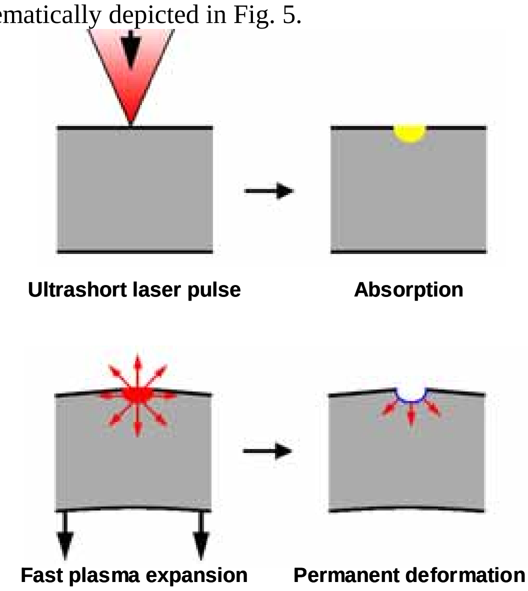


Fig. 5 Micro-bending by ultrafast laser induced shockwaves – process model

First, the ultrashort laser pulse hits the sample's surface and its energy is absorbed by the electrons within the absorption layer. Due to the extreme energy density and the short interaction time, a complete energy balance between the exited electrons and the lattice cannot be established. Bonds are broken and the material is abruptly transformed into a plasma state without significant heat transfer into the surrounding volume.

At this point in time the plasma is in an unstable state of high density and pressure and expands very fast causing a short but intense shockwave. As towards the surface, the expanding plasma meets minimal resistance, the main mechanical impulse hits the sides of the ablation trace, causing a surface near micro-deformation. The mechanical inertia of the actuator regarding the time-scale concerned and the slightly elevated temperature of the material encourage a partly plastic deformation. Therefore, in the last phase of the process, a permanent bending angle – directed away from the laser beam – is reached.

3. Experimental results

This theory is verified by comparing two identical silicon samples one with and the other without a pre-stressed Si_3N_4 coating. The resulting graphs (Fig. 6) clearly show, that the uncoated sample is deformed in exactly the same way as the coated sample, apart from a constant shift of about 0.1 mrad. This difference corresponds very well to the calculated influence of the pre-stressed coating layer (54.5 – 82.5 µrad, cf. Table 1).

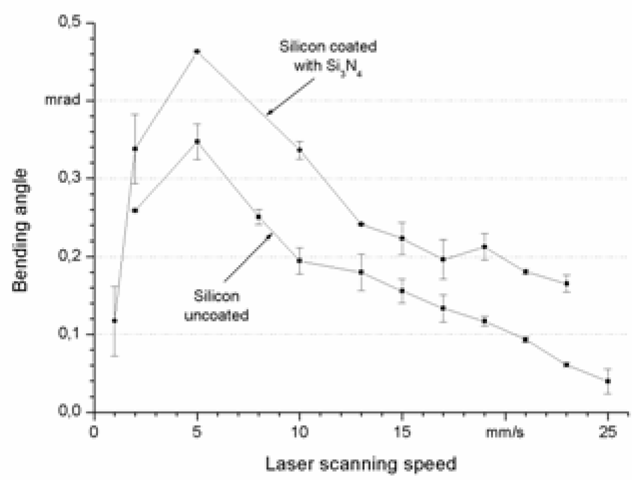


Fig. 6 Dependency of bending angle to feed rate for coated and uncoated silicon, laser Coherent LIBRA, 800 nm, 100 fs, 1 kHz, 750 µJ / pulse

This result prooves that micro-bending using ultrafast lasers does not require a pre-stressed, coated actuator and allows the use of a much wider range of materials to be employed. Fig. 7 shows the bending angles achieved for copper, steel and silicon samples in comparison. 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 2).

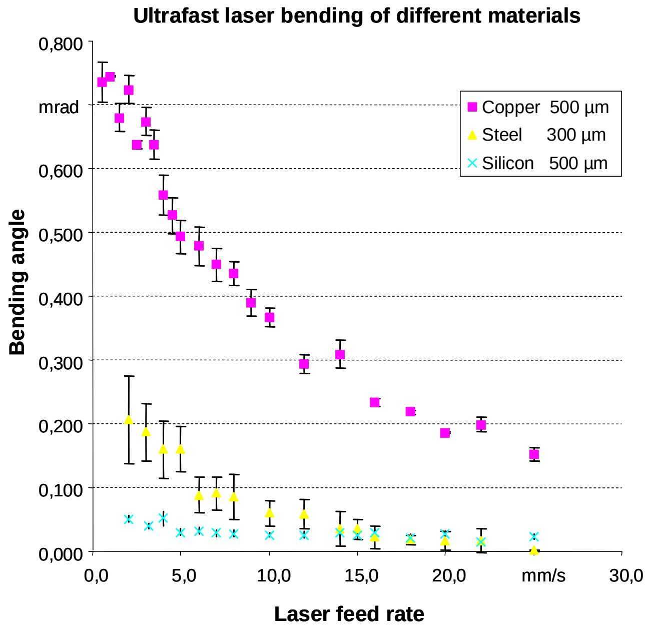


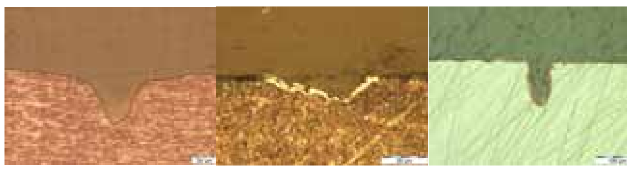
Fig. 7 Dependency of bending angle to laser feed rate for copper, steel and silicon, pulse energy 750 µJ

Table 2 Material characteristics

Material	Young's Modulus [N/mm²]	Yield point [N/mm²]	Thermal conductivity [W/m·K]
Copper (C17410HT)	129000	110	398
Steel (X5CrNi1018)	190000	186	16
Silicon	170000	-	157

As copper features the lowest coefficient of elasticity as well as the lowest yield point, its resistance to plastic deformation is comparatively low and using this material 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 gradients. 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.

In order to test whether changes in microstructure should be considered to be the cause for the observed bending mechanism, grinding patterns of all materials were prepared and analysed (Fig. 8).



Copper Steel Silicon

Fig. 8 Etched grinding patterns of different materials feed rate 0.5 mm/s, pulse energy 910 µJ

Only deep ablation grooves produced with very low laser feed rates are suitable for this examination method to ensure distinct results. However, even at a feed rate of just 0.5 mm/s – leading to a very high energy input per unit length and to ablation grooves up to 50 µm in depth – only steel shows marginal microstructural changes, whereas copper and silicon remain nearly unaffected. Therefore, the theory that structural modifications are the driving force of ultrashort pulse laser bending can be rejected.

The next goal of our experiments was to evaluate the effect of ambient vacuum on the bending process. By comparing bending angles achieved under the influence of air and vacuum two more possible interaction effects can be evaluated.

First, chemical reactions of the surface with the ambient atmosphere are blocked in vacuum. This way e.g. the formation of a stress inducing oxidation layer can be prevented.

Second, the influence of thermal effects on the process can be studied, as in air more heat is transferred into the material than in vacuum. There are two ways how at least small amounts of thermal energy can be conducted into the sample during ultrashort pulse laser irradiation. As the laser beam features a Gaussian intensity profile, at a certain distance from the center its power density is no longer sufficient for ionisation and ablation of the material. The outer rest of the laser beam is directly converted into heat. This effect is supported by low power densities, which can be generated e. g. by de-focused irradiation. The other way for transfer heat is interaction of the material with the plasma spark generated by the laser through ionization of ambient air, which provably has an elevated temperature. Under the influence of vacuum, both mechanisms are affected: As the plasma spark is absorbing a part of the energy of the laser pulses and damaging the beam profile (cf. Fig. 9), its elimination in vacuum does not only prevent plasma-matter interaction but also leads to higher power densities on the material surface. Therefore, substancially less heat dissipation is created through ultrafast laser processing in vacuum. Fig. 9 illustrates the effect of air and vacuum on the beam profile by comparing measured beam diameters at different focal positions.

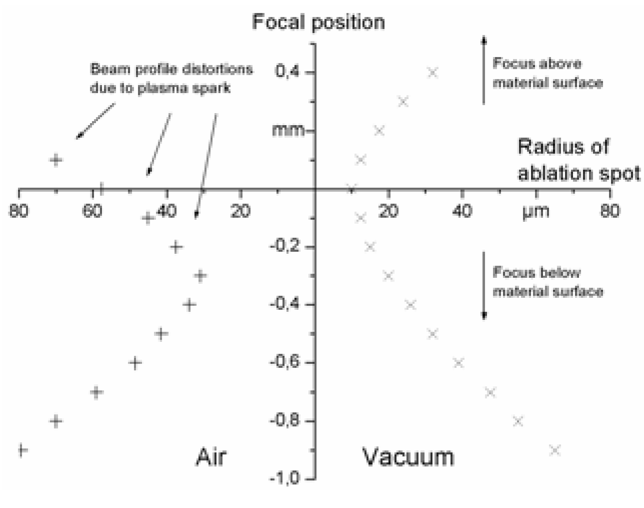


Fig. 9 Beam profile of LIBRA CPA-System derived from measured ablation traces in air and vacuum

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. 10 shows the resulting bending angles as well as the corresponding power densities. 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. Therefore it can be considered extremely unlikely that chemical surface reactions as well as thermal interactions are responsible for the bending process.

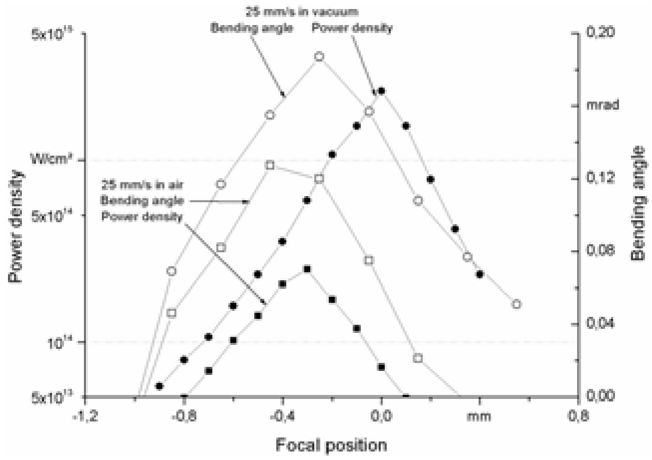


Fig. 10 Bending angle and power density in air and vacuum
Sample: copper 500 µm, pulse energy 910 µJ

Following the process model of micro-bending by ultrafast laser induced shockwaves however, the graphs can logically be explained: better focusing conditions respectively higher power concentration in vacuum 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. 3, Fig. 6).

The correlation of the bending angle to the amount of deposited laser energy per length unit becomes apparent in Fig. 11. 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, 160 µJ in Fig. 11), no bending at all can be observed, regardless of the scanning speed and the energy input. Metallographic examinations of the samples show, that with these parameters the ablation threshold of the material is barely reached and nearly no ablation groove is formed.

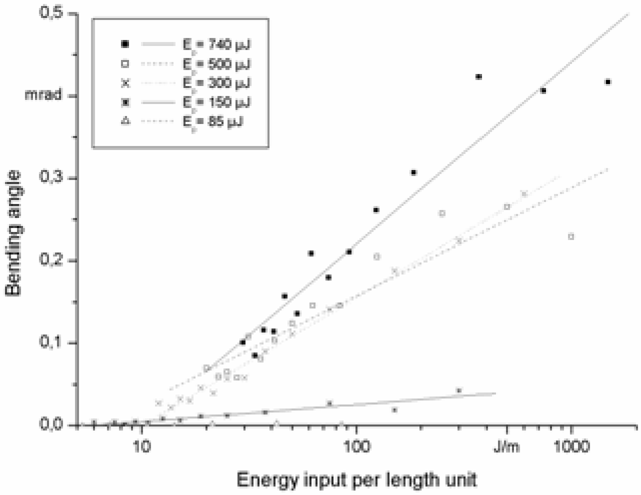


Fig. 11 Bending angles achieved with different pulse energies Samples: copper 500 µm

The result that a high number of pulses with low energy leads to the same bending angle as few high-energy pulses strongly suggests that in general the process itself is repeatable. This theory was verified by scanning ablation lines over samples of copper, steel and silicon multiple times at the same spot. Fig. 12 shows the additional bending angle reached with one scanning process after repeated precedent irradiations. The bending process is indeed repeatable, even though lower additional angles are reached with increasing count of irradiations. This happens because deeper ablation grooves are formed which entail increased light scattering and diffusion.

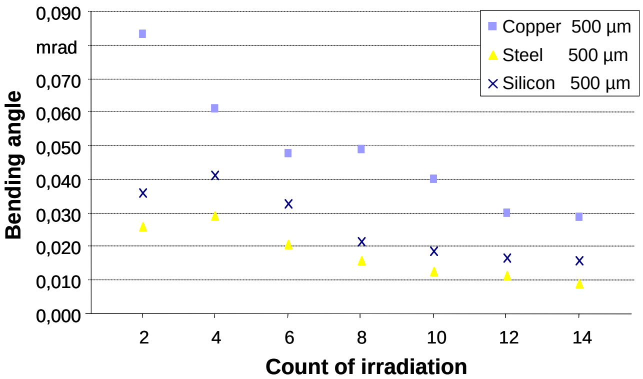


Fig. 12 Bending angles reached with multiple irradiations Laser scanning speed 25 mm/s, Pulse energy 910 µJ

Whereas copper and steel samples show no observable damage even after repeated irradiation it is most interesting to examine etched grinding patterns of silicon.

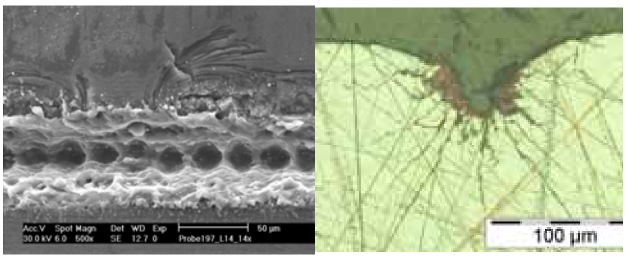


Fig. 13 SEM-picture and etched grinding pattern of silicon after 14 processing steps, feed rate 25 mm/s, pulse energy 910 mW

As this extremely susceptible and brittle material cannot sustain 14 scans with full pulse energy without damage, the effects of the micro-shockwave mechanism can directly be visualized in terms of dislocations and micro cracks. The effects and directions of the visible impacts correspond very well with the process model sketched in Fig. 5.

4. Conclusion

The theoretical and experimental investigations presented in this paper led to the discovery of micro-bending by ultrafast laser induced shockwaves, a fundamentally new concept in laser forming. This process offers significant advantages compared to thermal laser forming methods, such as the elimination of thermal downtimes and thermally induced damages. Ultrashort pulse laser bending allows micro-adjustment of a wide range of materials without special pretreatment, practically with any accuracy desired, as laser pulses without or spatial overlap have been proved to still cause a deformation (cf. Fig. 10). Micro-adjustment can therefore even be realized by applying single laser pulses, though the achieved bending angles are beyond the level of detectability of the measuring equipment employed in this work. Drawbacks of the new technique are the relatively high costs for the laser system and the low maximum bending range compared to thermal forming.

The main application area for ultrashort pulse laser bending is expected to become the field of mechanical and optical microsystems, 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-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. It is assumed that already in the near future many complex hybrid microsystems – e. g. micro-optical benches or medical devices such as drug delivery implants – will highly benefit from this concept.

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