INTERNATIONAL DESIGN CONFERENCE - DESIGN 2004
Dubrovnik, May 18 - 21, 2004.

DESIGN 2004

MICRO INTERLOCKING MANUFACTURED BY LASER ABLATION

H. Liess and U. Reiländer

Keywords: laser ablation, micro-teeth, micro-ridges, piezo-actuators

1. Introduction

Piezoelectrically driven linear actuator devices, such as inchworm motors are widely spread in technique and research since their introduction in 1975. The inherent disadvantage of those actuator devices is the insufficient carrying capability substantially. To obtain carrying capabilities greater than 100N, the devices have to be designed very stiff, which eventually leads to big and heavy housings. To overcome those problems the traditional friction clamping mechanism can be substituted with diverse interlocking mechanism (static friction, electrostatic clamping, micro ridges).
The general approach to make surfaces with micro ridges is to pattern a silicon dioxide layer by photolithography. The exposed silicon underneath is anisotropically etched i.e. in a potassium hydroxide (KOH) solution to obtain the desired grooves into the silicon. So far, micro ridges structures based on silicon structures support maximum loads up to 500N [Chen99, Jungnickel02].
This paper presents the advantages of micro-tooth interlocking mechanism in steel to significantly increase the carrying capability up to kN ranges of piezoelectric actuators. Furthermore it offers a technique to process these structures by using laser ablation. Additionally ways of a cost-efficient mass production were discussed.

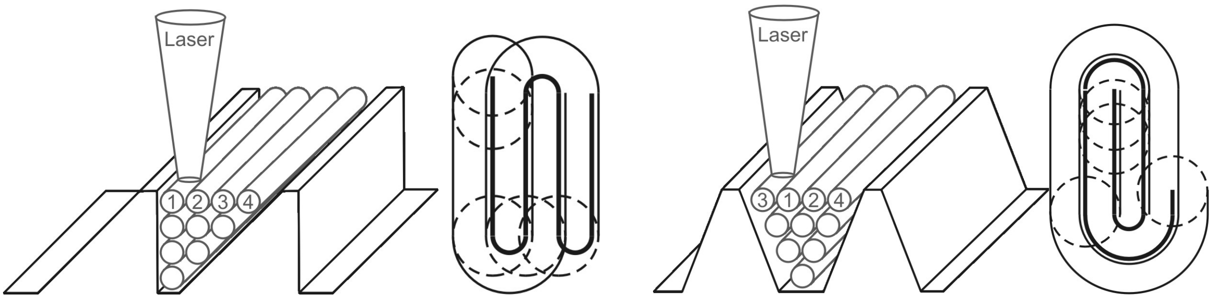
2. Objective of investigations

Through positive locking structures such as micro-ridges, it is possible to make use of the whole force capability and position accuracy of piezo-ceramics. This could be achieved by avoiding the undesired slipping between the actuator, the clamping element and the guide rail.
Due to different requirements of the piezo actuator devices it should be possible to adapt the geometry of micro teeth and make usage of several materials. Therefore laser ablation constitutes an ideal tool to structure several materials such as hardened steel or copper.
It allows a fast manufacturing process, combined with the possibility to influence the shape of the teeth. The decision to use hardened steel was made due to the very good material properties such as small abrasion and high tensile strength. Copper on the other hand was chosen to analyze the possibilities of die-sinking electrical-discharge machining (EDM) techniques. This leads to an optimization of the manufacturing process and offers further technologies to cost-efficient mass production.

3. Micro-teeth processing techniques

In this paper the process of micro teeth is accomplished by using two different laser systems. A Nd-YAG IR laser with a wavelength of 1064nm (pulse length < 100ns) and a third harmonic Nd-YAG, UV laser with a wavelength of 355nm (pulse length <12ns). Both systems are working with a x, y scan module and a f-theta lens with a focal length of 100mm. Thus results in focal diameter of 30µm (IR)

and 10µm (UV). Short pulse length between 12 – 100ns and adjustable output power of 0-3W minimizes the thermal power input into the material and the resulting thermal damaging of the fringe.
The excavation of one tooth is attained in two steps in which the material is removed layer by layer with patterns of overlapping lines. In the first step the scan head dissects the first flank of a tooth. Subsequently the work piece is traversed for a tooth pitch. The remaining flank is now processed to uncover the tooth profile.
The process order and a schematic sketch of the used pattern for saw teeth (s. Figure 1a) and trapezoidal teeth (s. Figure 1b) are displayed in the following figure.



a) **b)**

Figure 1. a), b) Schematic of the laser processing of different micro-teeth

For the grooving of a trapezoidal tooth a symmetrical pattern is required (s. Figure 1b). Accordingly the processing starts in the middle and is moving helically outwards. The dashed circles symbolize the overlap of the laser pulses.
To minimize the surface roughness the processing took place with low power and a pulse and line overlap of 60% and more. Using this technique it could be verified that interlocking up to the length of the linear stage (300mm) could be manufactured.
The mentioned process together with an UV-Laser could also be used to groove copper. This opens the possibility of cost-efficient manufacturing processes with e.g. electric-discharge machining (EDM) techniques [Michel01].

4. Laser Ablation results

By means of laser radiation for the processing of micro tooth interlocking a wide range of materials can be used. Starting with several metals such as steel, copper, aluminum to nonmetals like ceramic as well as plastics.
Steel turned out to be one of the most suitable materials due to its hardenability and its good mechanical and non-abrasive characteristics. The material was chosen by means of the simultaneous development of a piezo-inchworm actuator device for heavy loads.

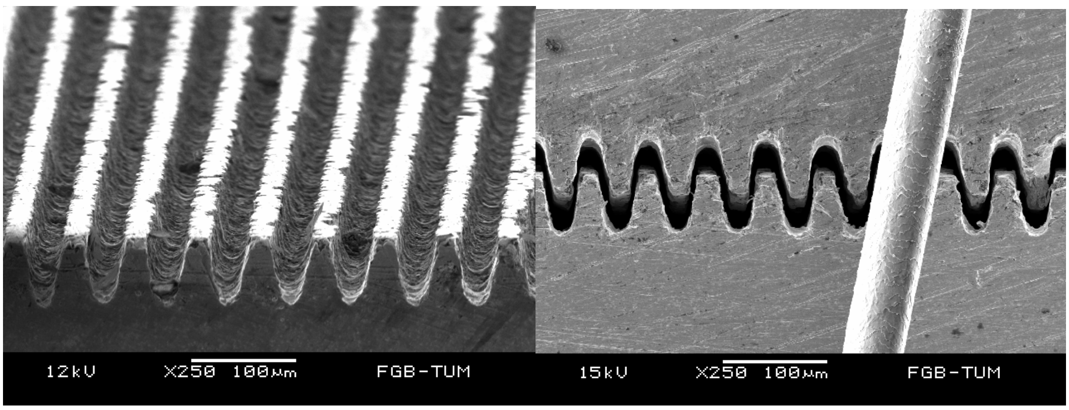


Figure 3. Bidirectional micro teeth in hardened steel

Furthermore the grooving of copper and wolfram-copper was investigated because of the very good electrical conductivity and the necessity of a suitable electrode material for micro-electric-discharge machining.The following SEM figures, 250-times magnified, shows trapezoidal micro teeth in high-speed steel with a hardness of HRC65 and a tooth pitch of 60µm. In the right figure a human hair is displayed as a standard of comparison.
These micro interlocking were processed up to lengths of 300mm only restricted by the travel range of the linear stages. The geometrical parameters and mechanical properties of the interlocking are listed in the following table.

Table 1. Parameters of the trapezoidal micro-tooth profile

Symbol	Value	Unit	Parameter	Symbol	Value	Unit	Parameter
p	60	μm	Tooth pitch	$\sigma_{n,\max}$	900	N/mm^2	Max. tensile stress
h	56	μm	Tooth height	α_0	1	-	Shear coefficient
α	10	°	Flank angle	E	210000	N/mm^2	Young's modulus
ρ_F	12	μm	Foot radius	υ	0.3	-	Poisson's ratio
b	12	mm	Teeth depth	μ_S	0.1	-	Sliding friction coefficient
s_{Fn}	38	μm	Teeth width	h_{Fan}	33	μm	Distance load incidence

In connection with the use of these micro teeth systems for positive load transmission in piezo-actuator devices some inherent characteristics of the trapezoidal tooth profile have to be considered.
The first issue relates to the problematic of engaging the teeth. In opposite to a saw tooth profile the two rows of teeth have to be aligned in respect of each other to ensure a proper fitting. Any misalignment, which e.g. can arise from alternating load, leads to an additional stress of the teeth or even in a missed step of the actuator device.
A second issue arises from the circumstances of the tooth profile. Due to the non-perpendicular flank angle a reaction force under load is inevitable. On the one hand a smaller flank angle results in a reduced normal stress in the bottom of the tooth profile, but at the same time in an increased contact stress and an intractable reaction force.
The calculations based on a desired carrying load of F_t = 1000N an available normal force of F_N =100N and an experimental determined sliding friction coefficient for steel of μ_S =0,1. Thus the flank angle can be calculated to be α = 11,5°, compared to a processed flank angle of 10°.
In opposition unidirectional tooth systems such as saw tooth interlocking with only one load transmission direction easily engage into each other. In addition they don't have a reaction force due to the perpendicular flank angle and a higher transmitting force (s. Figure 4.).

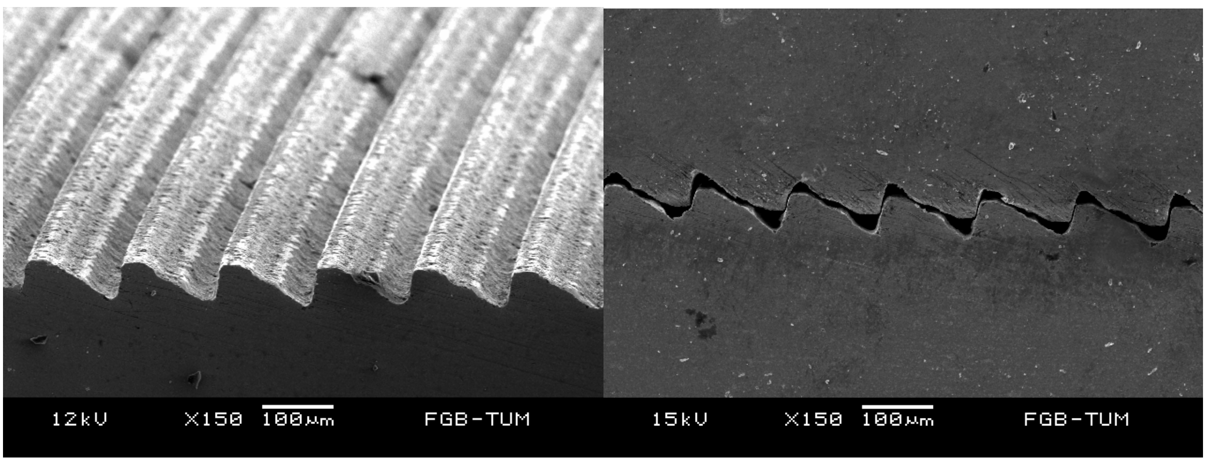


Figure 4. Unidirectional micro saw teeth in hardened steel

In the face of a later usage in a piezo-actuator device analytical calculations of the transmittable force were accomplished in the run-up. The results showed that a trapezoidal tooth (s. Figure 3) with an assumed maximal tensile strength of $\sigma_{n,max} = 900\,N/mm^2$ is able to carry a load of $65.72\,N$. Thus an interlocking area of 10 x $12\,mm^2$ with a tooth pitch of 60µm and an interlocking number of teeth = 167 should be able to transmit a load of about $F_{t,analytic} = 10.97\,kN$.

To verify the analytical calculations and include notch strength effects in the interlocking, the trapezoidal tooth profile was subject to a FEM analysis with ANSYS. Furthermore the objective of the simulation was to determine an optimal flank angle in terms of the occurring contact and teeth stress (s. Figure 5). The simulations results yielded an optimal flank angle of $\alpha = 21°$ (s. Figure 6.). The maximal carrying load was determined to be $F_{t,ANSYS} = 9.82\,kN$, which is only 11% off the analytical result.

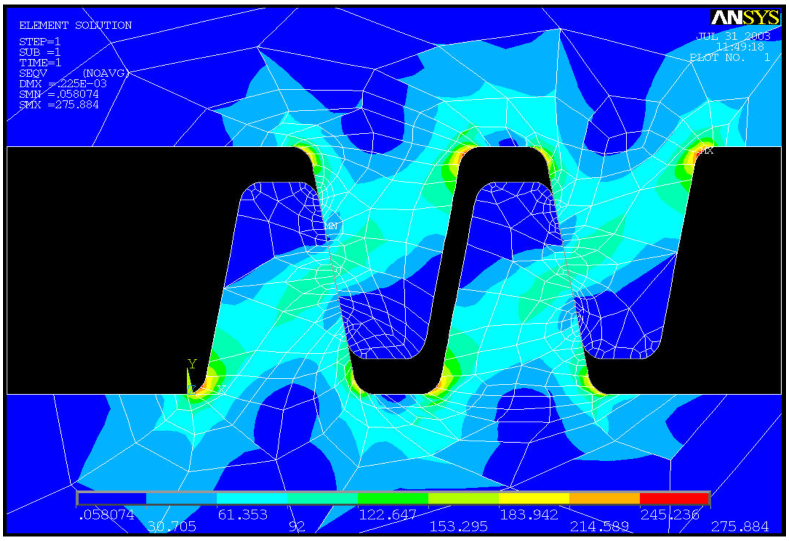


Figure 5. FEM-Simulation of trapezoidal teeth

The results don't consider dynamic effects e.g. alternating load and high-cycle fatigue effects, but gives a first impression of the high potential of micro interlocking in steel. Due to the surface roughness of the teeth the analytic calculation as well as the FEM simulation considered the fact that the teeth aren't able to fully engage into each other. The height of engagement was measured to be 68% or 38 µm compared to the teeth height of 56µm.

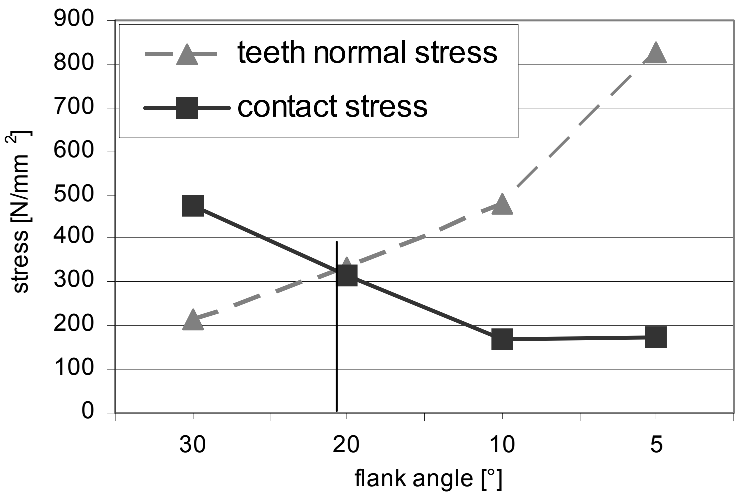


Figure 6. Contact stress and teeth normal stress in terms of the flank angle (FEM)

In the following figure the gradient of the normal stress and the contact stress in the teeth is displayed in terms of the flank angle. The tooth pitch was kept constant during the variation.

To verify the simulation results experimental tests with a trapezoidal interlocking were accomplished. During the tests the teeth were charged with normal forces in the range of 60-300 N and the load-displacement diagram was recorded. The measured maximal values are compiled in Figure 7 in terms of the relating normal force.

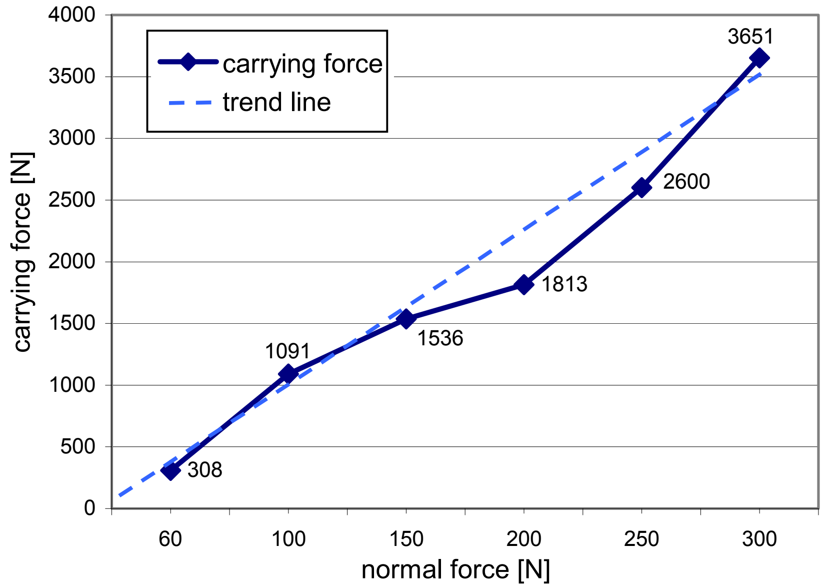


Figure 7. Carrying capability of trapezoidal teeth in hardened steel under different normal forces

As the experimental results show, a carrying capability of 1091 N at a normal force of 100 N is possible. The number of interlocking teeth was 167, with a tooth pitch of 60µm and a corresponding area of 10 x 12 mm^2.

5. Conclusion and future work

The aim of the research presented in this paper is to offer alternatives to significantly improve the carrying capability of piezoactuator devices with micro-ridges grooved in hardened steel and to show ways of cost-efficient manufacturing. So far, solutions to increase piezoelectrically driven linear actuator devices based on etched silicon structures with micro ridges have offered limited output forces and moderate travel ranges.

By means of laser technology it could be shown that it is conceivable to process micro-teeth with a desired shape in materials such as steel and copper on length up to 300 mm. Parameters like the tooth pitch and the tooth profile in general (flank angle, depth etc.) could easily be adapted by using different ablation patterns. To determine the carrying capability of the micro-teeth an analytic calculation as well as a FEM analysis with ANSYS were accomplished. Although the results don't consider dynamic effects e.g. alternating loads, but allow a view of the high potential of micro interlocking in steel. The analytic considerations excluded fatigue stress in the tooth, but yielded a maximal load of $F_{t,analytic} = 10.97\,kN$. Compared to the calculation, the simulation yielded a maximal load capability of $F_{t,ANSYS} = 9.82\,kN$. Both considerations were done with a trapezoidal interlocking with a tooth pitch of 60 μm and an engaging area of 10 mm x12 mm.

Furthermore the simulations allowed retrieving the optimal shape of the tooth profile. In respect to normal and contact stress a flank angle of 21° was found to be optimal.

Finally a maximal load test with trapezoidal teeth was able to confirm the calculations. The experimental results with a normal force of $300\,N$ yielded a carrying capability of $3.65\,kN$.
Further investigations with different tooth profiles and flank angles combined with increased normal forces should carry even higher loads. For prospective cost-efficient manufacturing of the interlocking, grooved copper electrodes could be used and applied on e.g. steel with micro electric-discharge machining techniques (µ-EDM) [Michel01].

Acknowledgement

We thank the Bayerischen Forschungsstiftung (BFS) for funding this project as part of the collaborative research centre "ForµProd - Forschungsverbund Mikroproduktionstechnik". The Bayerischen Forschungsstiftung (BFS) is a public funding organization for academic research in Germany.

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Helmar Liess, Dipl.-Ing.
Technische Universität München, Lehrstuhl für Feingerätebau
Boltzmannstr. 15, 85747 Garching, Germany
Telephone:+49 89 289 15179, Telefax: +49 89 289 15192
E-mail: liess@fgb.mw.tum.de