# Coining of Micro Structures with an Electromagnetically Driven Tool*

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## Abstract

*For coining micro structures into high-grade steel 1.4301 a highly dynamic tool system based on a pulsed magnetic field inside a cylindrical coil was developed. Two kinds of structures were coined at different tool velocities. The coining results were evaluated regarding geometrical accuracy, material flow behaviour and energy input. In addition the high velocity process was compared to a quasi-static process. By increasing the coining velocity to 30 m/s the accuracy of the quasi-static process can be reached. The energy that is needed for reaching a similar result is less for coining at high velocities. The tool velocity also influences the flow behaviour of the workpiece material.*

## Keywords

High speed forming, Impact, Coining

## 1 Introduction

Complexity and variety of micro components in electronics, precision engineering, micro system technology and medical engineering increase constantly. At the same time the number of applications of such components is rising. Production processes have to meet the requirements of these tendencies and must be suitable for mass production. Forming with its optimal utilization of material and high productivity offers potentials for excellent

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accuracy. For downscaling of conventional machining processes to the sub-millimetre domain miniaturization effects will occur. As a general challenge in machining of micro components not all machine components can be downscaled. Standard parts or drives, for instance, are only partly available. Furthermore a geometrical scaling of components can be impossible due to precision demands which require extra care regarding stiffness and low vibration.

Limitations to the availability of adequate tools as well as lack of available data about high velocity coining led to the present study. The magnetic pressure of a current discharge via coil is transferred to a coining tool, which is strongly accelerated. For the description of the relation between forming velocity and forming behaviour microstructures are coined into workpieces of high-grade steel. Aim of the project is thereby the improvement of processing high-grade steel for applications like micro reactors or heat exchangers. The effect of high energy input into the coining process through high tool velocities is investigated. This paper presents first investigations on the test stand and the topography of coined workpieces at different forming energies.

## 2 State of the Art

Downscaling conventional machining processes to the sub-millimetre domain causes miniaturization effects as mentioned in [1]. These effects are dependent on material, applied yield stress, uniform elongation, elongation at fracture and anisotropy. The miniaturization effects in turn influence forming forces, springback, flow of material and friction.

An overview of micro forming processes and of particular problems is given in [2]. When scaling macro forming processes down to micro forming and the microstructure of the workpiece as well as its surface topology remain unchanged the workpiece material cannot be regarded as a continuum, since large percentages of volume are occupied by an individual grain. Therefore the delimitations of the micro forming process are affected by the workpiece dimensions. This effect is called size effect. A decreased specimen size leads typically to a reduction of flow stress, a lower normal mean anisotropy and reduced ductility and forming limit. It is also noted that the increased share of workpiece grains in micro forming leads to a higher scatter of process results. Besides that a significant increase of friction when downgrading impact extrusion of a brass alloy was found by [3]. This multitude of influences on the results of micro forming makes an investigation of every single process inevitable as long as simulative prediction is not reliable.

The influence of the deformation rate on the limits of structural forming and the required power with high-speed forming of metallic miniature components with microstructures were examined by [4, 5]. With velocities of up to 8 m/s and equivalent energies of up to 10 J workpieces of Al99.5 and high grade steel 1.4404 were coined. Their investigations showed that less energy is needed for a complete form filling in aluminum than with quasi-static forming. For the steel probes an increase of strength was observed with higher deformation and higher forming velocity. A high forming velocity in turn results in lower friction between tool and workpiece. Structures with high aspect ratio benefit from lower friction on the effective surfaces. Hence the reduced strains cause a lower tool wear.

The influence of high forming velocities on formability of metals was also investigated by [6]. The investigated materials however were an aluminium alloy, a titanium alloy and a magnesium alloy. Effects of high forming velocities are beside lower friction on effective surfaces a lower elongation at fracture, a rising strain rate sensitivity as well as a higher instability of material. Strain rate sensitivity means a strong relation between yield strength and strain rate. The dependence of yield strength of different steel alloys on strain rates between 0.005 $s^{-1}$ and 200 $s^{-1}$ was investigated by [7]. The results for steel 1.4301 show an increase of yield strength of 310 MPa to 405 MPa as shown in Figure 1.

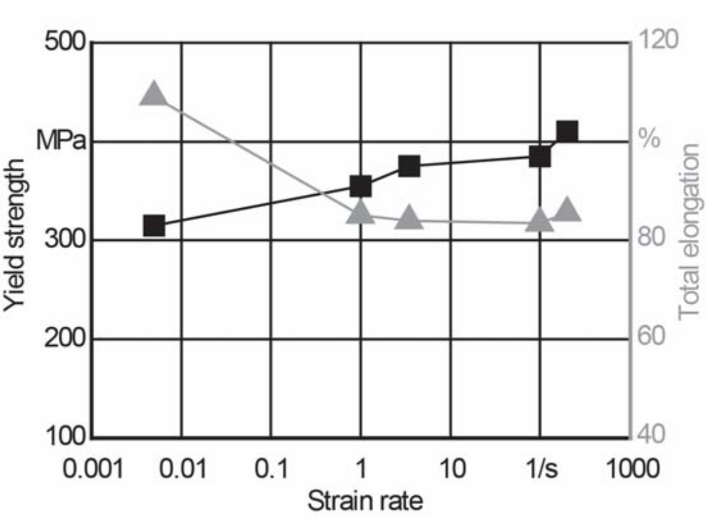


***Figure 1:*** *Strain-rate sensitivity for high-grade steel 1.4301 based on [7]*

All investigated alloys showed a similar behaviour. The ductility in turn decreased as strain rates rose from 0.005 $s^{-1}$ to 1 $s^{-1}$. This characteristic was observed for austenitic stainless steels. Other alloys either showed no significant change or a dramatic in- or decrease of elongation at a strain rate rise from 100 $s^{-1}$ to 200 $s^{-1}$.

Despite different materials were examined in the mentioned works they agree that the heat generated by the deformation cannot dissipate within the process due to high forming velocity. This leads to thermally activated processes inside the material. The acceleration of tools, e.g. for coining, cutting or riveting, offers potentials for improved processing of high-grade steels [8].

## 3 Experimental Setup

To improve micro coining of high strength steels the effect of high energy input into the process through high tool velocities is investigated. The forming behaviour depends strongly on the forming velocity. Thermally activated processes take place since the heat, generated during forming, cannot dissipate into to whole workpiece. Ductility and yield strength show a clear dependency on the strain rate as shown in Figure 1 and also the characteristics of friction between tool and workpiece change at high tool velocities. Since micro structures have a high amount of active surfaces this becomes especially relevant.

The coining tool is applied to a projectile which is located inside a cylindrical tool coil. The discharge of a pulsed current via the coil is used to accelerate the tool to high velocities. The necessary energy is stored in capacitors and is unloaded as an alternating current. The implicated magnetic field around the tool coil induces eddy currents in the projectile opposite to the discharge current. These shield the magnetic field of the tool coil in a way that the orthogonal Lorentz force can be used to accelerate the projectile as shown in Figure 2. The force vectors inside the projectile are orthogonal to the magnetic field lines. Since the Lorentz force appears inside the projectile due to the induced current Figure 2 shows only a facilitated model. The projectile is accelerated by the axial component of the force vectors. The radial components would compress the projectile; therefore it has to be designed as solid body to be able to resist deformation. The discharge current is alternating which leads to several impulses that accelerate the projectile as long as it is still located inside the tool coil.

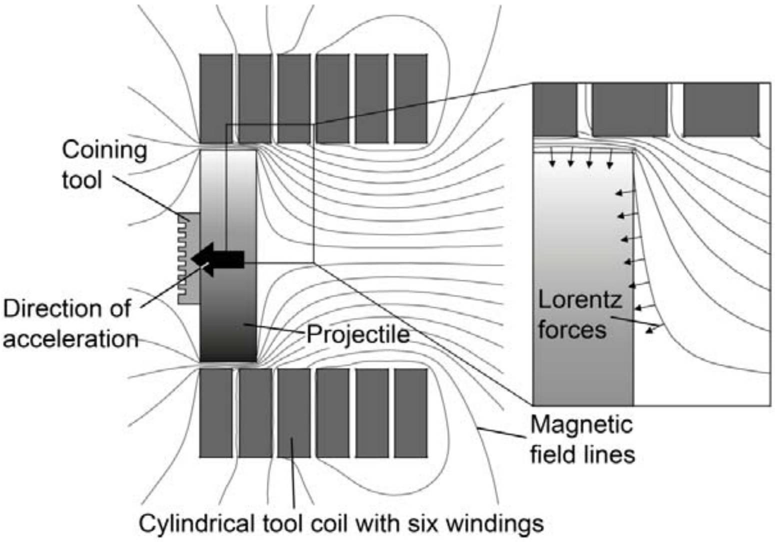


***Figure 2:** Coil accelerator with electrically conductive projectile*

The duration of the accelerating impulses depends on the frequency $f_D$ of the discharge current according to equation (1), including the overall inductivity L and the capacity C.

$$f_D = {}^{1}/_{2\cdot\pi} \cdot \sqrt{{}^{1}/_{L\cdot C}} \tag{1}$$

The tools are placed underneath the workpiece as shown in Figure 3. The workpiece is pushed into the tool through the impulse of the projectile that is transmitted by the push rod. The impulse depends on the accelerated mass and its velocity. A part of it is transformed into deformation work and results in a coined surface of the workpiece. Another part is stored inside the system in form of vibration. But the highest amount is stored as elastic deformation of the system and released to push back the projectile. The velocity of the projectile is measured with a position sensitive device (PSD) which detects the position of the projectile at any time by laser shading. The velocity between workpiece and tool, coining velocity $v_c$, is calculated following the conservation of momentum as in (2) with the mass of the projectile $m_p$ and the mass of the push rod $m_{pr}$.

$$v_c = {}^{m_P \cdot v_P}/_{m_{pr}} \tag{2}$$

The impact is registered by a force measurement system which shows the duration of the impulse flow into the workpiece what leads to its deformation. With this setup velocities of up to 35 m/s were reached. They are limited only due to limitations of the stiffness of the test stand. The impulse duration was in each case about $t_I$ = 60 µs.

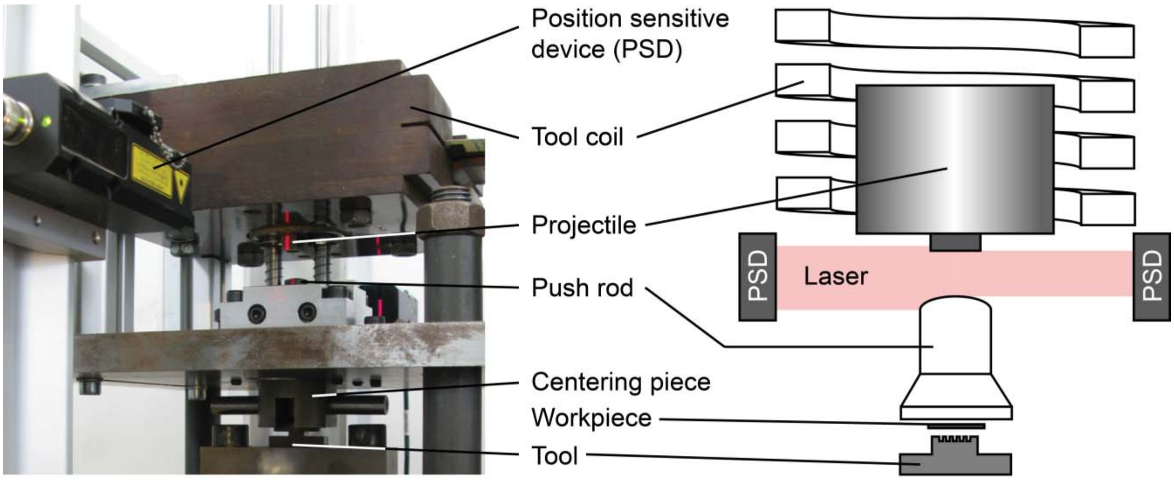
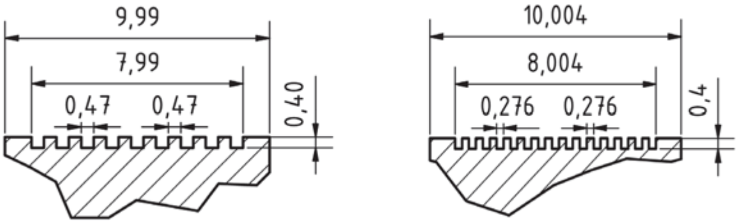


**Figure 3:** *Prototypical coining apparatus (left) and schematic presentation (right)*

The investigated structures are struts with a height of $h_s$ = 0.4 mm and two different aspect ratios. Figure 4 shows the two investigated structures. Both structures cover an area of 10 x 10 mm². Structure 1 has eight struts and nine grooves; structure 2 has 14 struts and 15 grooves.



Structure 1, aspect ratio 0.85 Structure 2, aspect ratio 1.45

**Figure 4:** *Strut structures used for coining*

Plates of steel 1.4301 were coined at velocities of $v_c$ = 18 m/s, $v_c$ = 22 m/s and $v_c$ = 30 m/s. For a qualification of the high velocity coining results coinings at a tool velocity of $v_c = 1.67 \cdot 10^{-5}$ m/s were performed on a material testing machine. The results are given as “quasi-static” in the following. All coinings were done with both structures. The coined workpieces were scanned with an optical surface measurement system. The scanned geometries were evaluated by geometrical criteria and related to the coining tool they were made with. Also the deformation of the workpiece and its flow of material were investigated through the data of the surface scans.

## 4 Experimental Results

To investigate the accuracy of the coining results at different energies the geometries were measured and compared to each tool. Criteria were the angle between surface and flank of the struts α, the strut height $h_s$, the strut width $w_s$ and the groove width $w_g$ as shown in Figure 5.

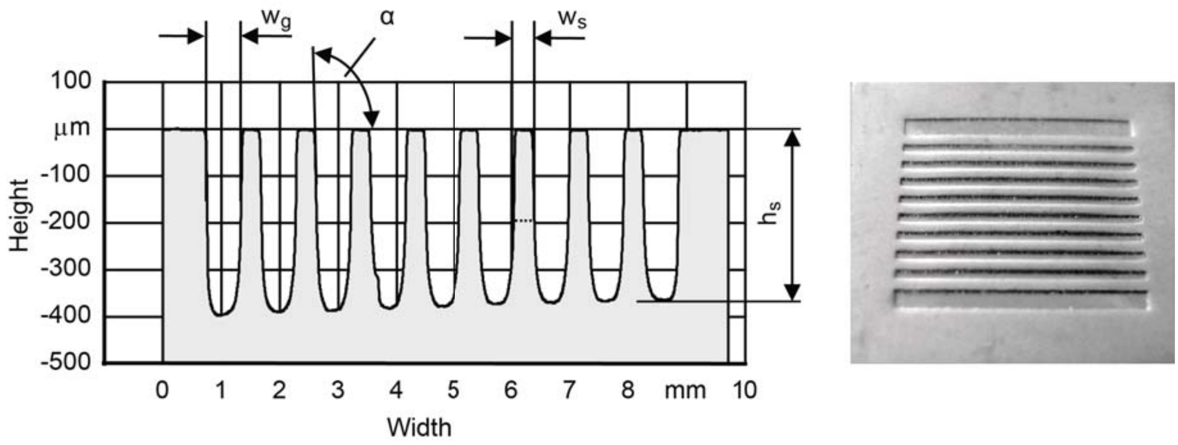


*Figure 5: Profile of a coining tool of structure 1 with criteria for accuracy evaluation (left) and coined workpiece (right)*

$w_g$ and $w_s$ were taken at 50 % of the strut height $h_s$. The struts of the tools correlate to the grooves of the coinings. The correlations of the geometrical criteria of the coined structures from the tool structures are given in Figure 6. The coining results at a coining velocity $v_c$ = 18 m/s of structure 1 were not evaluable due to a very low forming depth. 100 % on the ordinate corresponds to the tool geometry. The higher the column the better is the correlation of the criterion of the coined structure with the one of the tool structure.

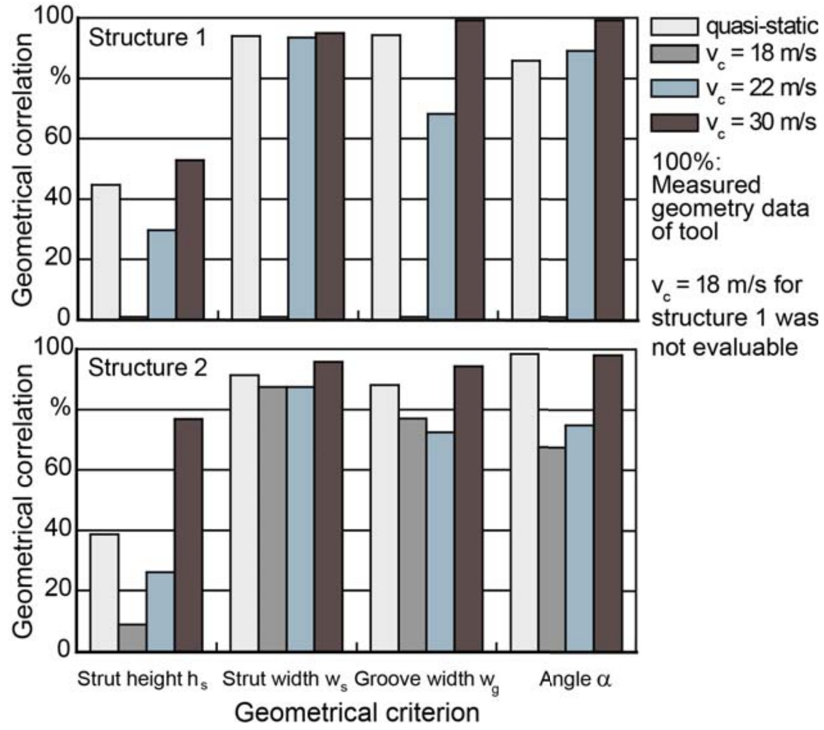


*Figure 6: Correlations of the geometrical criteria of the coinings with the tool structure*

During deformation the workpiece material is pressed into the grooves of the tool. Because of the friction at the tool flanks the coined struts show pointed surfaces. The grooves of the coining are always more narrow than the struts of the tools, while the struts of the coining are always wider than the grooves of the tools. A spring back of the work piece material can be assumed. Due to friction at the tool flanks the angles α are always bigger than 90°. The dependency of these geometrical results of the tool energy can be seen already. Figure 7, left and Figure 7, right compare characteristics of the coined workpieces at different coining velocities $v_c$ and show the energy that went into the forming process. The energy in the quasi-static process is the integral of the force-displacement-curve. The forming energy in the high-velocity-process was estimated by calculating the difference between the velocity of the projectile $v_p$ before and after the impact. An exact determination was not possible since the kinetic energy of the projectile was transformed into different manifestations. Only a part of elastic deformation can be measured as velocity after impact. The deformation ratio d given in Figure 7 is the logarithmic relation of remaining workpiece thickness under the grooves after coining $s_1$ and original workpiece thickness $s_0$, as given in (3).

$$d = \ln\left({}^{s_1}/_{s_0}\right) \tag{3}$$

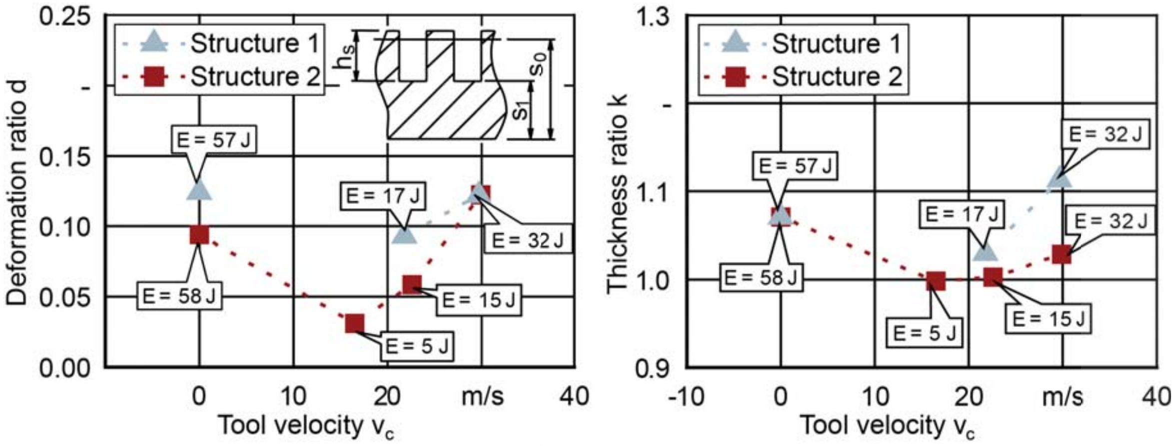


***Figure 7:*** *Deformation ratio (left) and thickness ratio (right) of the coined structures vs. tool velocity*

The thickness ratio k is the workpiece thickness after coining divided by the original workpiece thickness $s_0$ as in (4).

$$k = {}^{h_s+s_1}/_{s_0} \tag{4}$$

That means for $k > 1$ an increase of thickness and therefore a flow of material into the cavities of the tool structures.

## 5 Conclusion

The calculation of the correlation of the coined structures with the tool structures show the accuracy at the investigated coining velocities $v_c$. The results are compared to the results of a quasi-static process. With the high velocity coining process by increasing the energy input through an increase of the coining velocity the accuracy of the regarded criteria can reach the accuracy of the quasi-static process. As can be seen in Figure 7 the energy that is needed for reaching a similar result is less for coining at high velocities. The friction characteristics are influenced by the tool velocity since the pointed strut surfaces, depicted by the angle α, show different expressions. Higher elevated coining velocities $v_c$ lead to lower angles α, lower friction at the tool flanks can be assumed.

The deformation shown in Figure 7, left is higher for structure 1 than for structure 2 but as the coining velocity $v_c$ rises the difference disappears. The lower active surface of tool structure 2 that causes higher compressive stress on the workpiece is a possible explanation. More experiments with higher coining velocities and a simulative approach will bring more information.

The thickness ratio k given in Figure 7 shows that the workpiece material flows mainly into the cavities of the tool structures as k is greater or equal to 1. At a coining velocity of $v_c = 18$ m/s the material flow into the struts is lower than for quasi-static deformation but at higher tool velocities k rises significantly. Structure 1 shows a higher thickness ratio due to lower friction at the flanks of the tool. Because of its wider grooves the workpiece material experiences less resistance while flowing into the cavities.

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