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Use of Monocrystalline Silicon as Tool Material for Highly Accurate Blanking of Thin Metal Foils

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Abstract. The trend towards miniaturisation of metallic mass production components combined with increased component functionality is still unbroken. Manufacturing these components by forming and blanking offers economical and ecological advantages combined with the needed accuracy. The complexity of producing tools with geometries below 50 μm by conventional manufacturing methods becomes disproportional higher. Expensive serial finishing operations are required to achieve an adequate surface roughness combined with accurate geometry details. A novel approach for producing such tools is the use of advanced etching technologies for monocrystalline silicon that are well-established in the microsystems technology. High-precision vertical geometries with a width down to 5 μm are possible. The present study shows a novel concept using this potential for the blanking of thin copper foils with monocrystalline silicon as a tool material. A self-contained machine-tool with compact outer dimensions was designed to avoid tensile stresses in the brittle silicon punch by an accurate, careful alignment of the punch, die and metal foil. A microscopic analysis of the monocrystalline silicon punch shows appropriate properties regarding flank angle, edge geometry and surface quality for the blanking process. Using a monocrystalline silicon punch with a width of 70 μm blanking experiments on as-rolled copper foils with a thickness of 20 μm demonstrate the general applicability of this material for micro production processes.

Keywords: Microforming, blanking, monocrystalline silicon, machine design, accuracy.

PACS: 81.16.-c, 81.20.Hy, 83.50.Uv

INTRODUCTION

Particularly in industrial sectors producing high-precision parts in great quantities an ongoing trend of miniaturisation is recognisable. This distinct tendency is additionally supported by the integration of mechanical and electronic functions in compact mechatronic elements. An economic and ecologic way of producing such metallic micro parts with an adequate precision provides metal forming [1]. But conventional process knowledge cannot directly be transferred to microforming technology. Occurring size effects change the process behaviour and the process layout has to consider these special challenges [2]. Increasing ultimate shear strength with decreasing foil thickness was investigated by Kals in blanking experiments with metal foils down to a thickness of 500 μm [3]. Typical workpieces produced by blanking are leadframes for integrated circuits shown in Fig. 1a. In addition to the blanking of the leads also the dam-bar cutting process has to be done by blanking [4]. After moulding of the chip the stabilising frame, the so called dam-bars between the leads, has to be pierced out (Fig. 1b, c) for the electric isolation of two leads. This requires a high-precision blanking process and must also take the anisotropy of the metal foil into account as the blanking lines have different angles to the rolling direction [5]. In comparison to etching of leadframes, which is another possible method producing such structures [6], blanking is characterized by its high accuracy. Another aspect is the disposal of waste from the etching process as environmental implications become also in the field of micro technology more important [7].

The manufacturing of tools for blanking processes with geometries below 50 μm needs cost intensive serial production methods like micro electro discharge machining, laser milling, electro chemical milling, or micro grinding [8-10]. Well established tool materials in industrial applications are tool steels and cemented carbides,

FIGURE 1. Leadframe with a thickness of 150 μm for integrated circuits packaging (Shinko) (a) and illustration of a dam-bar cutting process (b,c) [4]

whereas cemented carbides have a higher surface hardness resulting in better wear characteristics, which are important for mass production. On the other hand the production and finishing of cemented carbide tools are more complex compared to tool steels because of its high hardness and shrinking after the sintering process. Increasing demands on the workpiece details resulting in decreasing tools dimensions along with high requirements on the tool surface intensify the effort in tool production. Beside the miniaturisation of conventional tool manufacturing processes new approaches are necessary in microforming offering key benefits but also containing new challenges.

With modern etching technologies on monocrystalline silicon vertical structures with a width down to 5 μm and high aspect ratios above 50 are industrial standard in cost efficient bulk production methods. These geometries used for electrical components like silicon switches are achieved using the etching behaviour of monocrystalline silicon by deep reactive ion etching (DRIE) or etching with aqueous potassium hydroxide (KOH) without the need of finishing by machining operations [11]. The process is based on the significant difference in etch rate between the $\{100\}$ and $\{110\}$ faces versus the $\{111\}$ face of monocrystalline silicon. The difference in etching rate between different crystallographic orientations of silicon is also known as the anisotropy ratio or anisotropic etching [12]. Using this potential for the manufacturing of tools for blanking processes additionally offers advantages on the surface quality and form modifications like controlling the edge radius of a vertical geometry. Mechanical properties of monocrystalline silicon shown in Table 1 as the Young's Modulus or hardness are acceptable for blanking processes and only slightly below the corresponding properties of tool steels. As monocrystalline silicon has pure linear elastic deformation behaviour until fracture occurs, no geometrical work piece deviations due to plastic tool deformation have to be expected. The main challenge using monocrystalline silicon as a tool material is its brittle behaviour ending in tool fracture by reaching critical tensile stress peaks. This behaviour is indicated by the low fracture toughness and bending strength, the latter of which is strongly dependent on the surface quality and microcracks.

TABLE 1. Mechanical properties of monocrystalline silicon [11].

Hardness HK	850 kg/mm ²
Young's modulus E	130 - 188 GPa (anisotropic)
Bending strength σ_b	300 MPa
Fracture toughness K_{IC}	1.75 – 2.19 MPa m ^{1/2}

In this study the fundamental behaviour of monocrystalline silicon punches produced by advanced etching technologies at the Furtwangen University of Applied Sciences is investigated in micro blanking of thin copper foils with a thickness of $t = 20 \mu\text{m}$. To obviate bending and minimize forces and local stress peaks in the punch a high-precision, self-contained machine-tool with compact outer dimensions was developed for a careful and accurate alignment of punch, die and copper foil, which is described in detail in [13].

FIGURE 2. SEM image of the tool system with glued monocrystalline silicon punch onto a steel adapter (a) and basic geometries of the silicon punch (b)

MONOCRYSTALLINE SILICON PUNCH SYSTEM

For a better handling the etched monocrystalline silicon punch is glued with an epoxy adhesive to a steel adapter, which can be connected by a screw to an actuator generating the punching force. Previous experiments have shown that avoiding pores in the adherence layer is important to prevent fracture of the punch while blanking. Considering this result the glueing process is performed between two aligned plates and surplus adhesive can flow into the voids shown in the scanning electron microscope (SEM) picture in Fig. 2a. The silicon punch itself has a fixed base area of 5 mm x 5 mm. Different punch widths b are achieved by anisotropic etching of the area around the punch shown in Fig. 2b. The punch height is fixed to 250 μm which is half of the thickness of a silicon wafer. With this design it is possible to produce 250 punches in one step out of a commercially available 4" monocrystalline silicon wafer.

Taking the brittle material behaviour and low fracture toughness of monocrystalline silicon into account a smooth surface free of microcracks is essential. Especially in highly stressed areas near the cutting edge microcracks or notches lead to an immediate punch fracture. As this fact is more critical compared to for example tool steels a

FIGURE 3. Top view of a monocrystalline silicon punch with a punch width $b = 70 \mu\text{m}$ (a) and profile geometry measured by a confocal white light microscope at three different areas of the punch (b-d)

characterization of the tool surface is necessary before blanking experiments. Figure 3a shows exemplarily an optical microscope image of an area of an etched silicon punch with a width $b = 70 \mu\text{m}$. No microcracks can be detected and the punch width is constant in the range of $0.2 \mu\text{m}$ over the full length. Deviations in the punch width are critical because coming to punch die clearances in the range of $1 - 2 \mu\text{m}$ this would lead to a contact. Using a confocal white light microscope for analyzing the profile geometry (Fig. 3b-d) proves the good consistency of the punch shape with only little variation in the flank angle. The flank angle is $90^\circ \pm 2^\circ$, which is important for avoiding punch die contact that would occur with an enlarging punch. Only at the bottom of the punch surface irregularities are recognizable but irrelevant for the blanking operation. These results are verified by tactile profilometer measurements on the tool surface showing same results for the punch geometry.

HIGH-PRECISION BLANKING OF THIN COPPER FOILS

The blanking experiments are performed in a self-contained machine-tool with compact outer dimensions, shown in Fig. 4a. Its design is optimized towards flexibility and accuracy considering the brittle material behaviour of monocrystalline silicon. A piezo actuator generates in its initial position a punching force up to $F = 4.5 \text{ kN}$ and has a maximum stroke of $180 \mu\text{m}$, which is sufficient for blanking thin metal foils up to a thickness of $50 \mu\text{m}$. The actuator in combination with the low outer dimensions of the machine tool avoids vibrations coming from punch force generation and reduces thermal expansion due to large outer dimensions. The alignment of punch, die and metal foil, using several mechanical adjustment devices, is controlled by micrometer screws and a CCD camera. Using this method, as shown in Fig. 4b, allows adjustment resolutions down to $1 \mu\text{m}$. As the present study deals with as-rolled copper foils with a thickness $t = 20 \mu\text{m}$, the punch die clearance is set to $2 \mu\text{m}$ which corresponds to a conventional ratio for macro blanking operations. Bulging of the copper foil, shown in the CCD picture, is reduced by the transport system tightening it to the die. For this reason the metal foil is coiled on reels.

As optical devices have an insufficient resolution for investigations on even smaller clearances and geometries and an in-situ observation of the process, the self-contained machine-tool is optimized towards an operation in an SEM to improve process understanding in forthcoming project steps in the future. A special SEM at the university of Erlangen-Nuremberg makes it possible to inspect specimens with dimensions up to $700 \text{ mm} \times 600 \text{ mm} \times 1400 \text{ mm}$ so that the whole machine-tool can be inserted and operated in the vacuum chamber. For this reason all materials are vacuum capable, components have venting holes and no lubricants are used.

FIGURE 4. Setup of the machine-tool for high-precision blanking processes (a) and CCD picture of the blanking process (b)

FIGURE 5. Grain structure of an as-rolled pure copper foil with a thickness $t = 20\ \mu\text{m}$

As a result of the rolling process an anisotropic material behaviour of thin metal foils has to be expected. Figure 5 shows a strong grain deformation in rolling direction on an as-rolled pure copper foil with a thickness $t = 20\ \mu\text{m}$. While the grains have an average size of $0.5\ \mu\text{m}$ perpendicular to the rolling direction they are elongated by the rolling process to an average length of $20\ \mu\text{m}$. This has to be considered by the workpiece design to have comparable results without interference of anisotropy effects.

For transportation and accurate positioning of the copper foil after each blanking process only parts of the metal foil are punched. Figure 6a illustrates the workpiece design which is based on the dam-bar cutting process of leadframes. The cutting lines are perpendicular to the rolling direction and have a length of 3 mm. Relief holes are inserted prior to the blanking experiments so that only the central part of the monocrystalline silicon punch is used. Blanking experiments are performed with the previously analyzed punch with a width $b = 70\ \mu\text{m}$ free of microcracks and outbreaks careful aligned parallel to the metal foil surface and centred to the die.

The cutting lines of the blanked copper foil run parallel without scattering. The sheared edge shown in the metallographic cross section in Fig. 6b is the same on both sides of the copper foil workpiece. The sheared edge is characterized by the typical elements rollover, a shear zone and a burr height. The deformed zone has a width of $10\ \mu\text{m}$ where a direction change of the elongated grains is recognizable. A large shear zone can be detected with no fracture of the copper foil. For the evaluation of tool wear the monocrystalline silicon punch is analyzed by an optical microscope after 1, 3, 10, 30 and 50 blanking experiments. No obvious tool damage is detectable after 30 blanking experiments, but a small outbreak after 50 blanking tests (Fig. 6c). This crack with a width of $10\ \mu\text{m}$ and a length of $20\ \mu\text{m}$ does not result in an immediate punch fracture, but has an influence on the blanking process. Therefore further experiments aiming at an improved process understanding (e.g. in the SEM) have to show how to avoid these outbreaks.

FIGURE 6. Workpiece design for the blanking experiments (a), sheared edge of a copper foil with thickness $t = 20\ \mu\text{m}$ (b) and outbreak in the silicon punch after 50 blanking operations (c)

CONCLUSIONS

This study presents a novel concept for blanking of thin metal foils using monocrystalline silicon as a tool material. Silicon punches producible in large quantities by anisotropic etching are characterized by their high accuracy and plane functional surfaces. They are generally applicable for high-precision blanking of thin copper foils. A compact machine-tool concept with a piezo actuator generating the punching force is suitable for micro blanking operations with monocrystalline silicon by considering the brittle material behaviour by an accurate punch, die and foil alignment. Further experiments and an in-situ process observation in a special SEM have to be performed for a better process understanding aiming at an increased tool life.

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