Laser Thin Film Patterning of Embedded Strain Sensors on Non-Planar Surfaces

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Summary: Strain sensors build up directly on machine components by thin film techniques enable measurement of forces, strain and pressure even in harsh environments. Up to day, the application of thin film sensors is restricted to planar surfaces due to limitations in standard patterning techniques. We present an alternative patterning method based on laser thin film ablation. During laser processing of complex 3-D surfaces, the incidence angle of the laser beam changes with the topography of the component. In this work, the influence of varying incidence angle on the patterning process is discussed and the feasibility of the laser patterning process is demonstrated on tension specimen with integrated thin film sensors in v-shaped notches. The presented technology may enable new applications for miniaturized strain sensors on complex shaped components of machine tools for process monitoring purposes.

Keywords: Laser Micro Machining, Thin Film Strain Sensor

1. Introduction

Strain sensors based on thin film technology offer good long-term stability and high temperature capability [1,2]. If deposited directly on the surface of a machine component, these sensors show considerably improved properties compared to conventional strain sensors. Strain is measured directly on the surface without any transmission losses through sensor carrier or adhesive, which are eliminated.

Thin film strain sensors are generally built up using vacuum deposition processes followed by photolithographic techniques for sensor patterning. This is a very cost-effective method for mass production. However, in standard photolithography the transfer of sensor patterns from a mask to the workpiece restricts the application of thin film strain sensors to planar surfaces.

An alternative route to photolithographic techniques is laser thin film patterning [3] (Fig. 1). Thin films are directly ablated using a focussed laser beam without masking and etching steps. As shown in this work, this approach enables processing of NiCr based thin film strain sensors on components with 3-D surfaces.

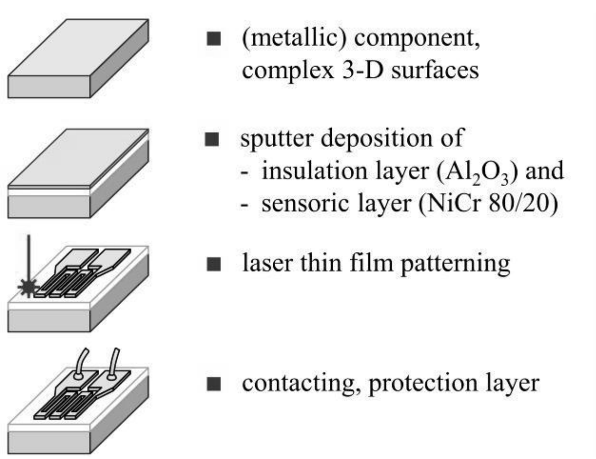

Figure 1. Basic processing steps for manufacturing laser patterned thin film sensors on component surfaces.

These sensors shall be used to equip components of a machine tool in order to enable real-time monitoring of production processes in harsh environments.

2. Laser Thin Film Ablation

A key aspect for successful sensor patterning is the usage of short laser pulses for thin film ablation. In principle, all solid materials can be ablated by short laser pulses. However, the ablation process is strongly governed by optical properties of the material since the ablation is directly related to the absorption of laser energy in the material. In NiCr films the laser energy is absorbed within a very top layer (a few tens of nm). By using laser pulses with durations of a few picoseconds or less, the ablation process is initiated even before significant energy is transported away from the exposed volume by thermal conduction. As a result, heat affection of subjacent layers is minimized. Thermal damage, e.g. generation of micro cracks or spallation, of insulation layers can be suppressed.

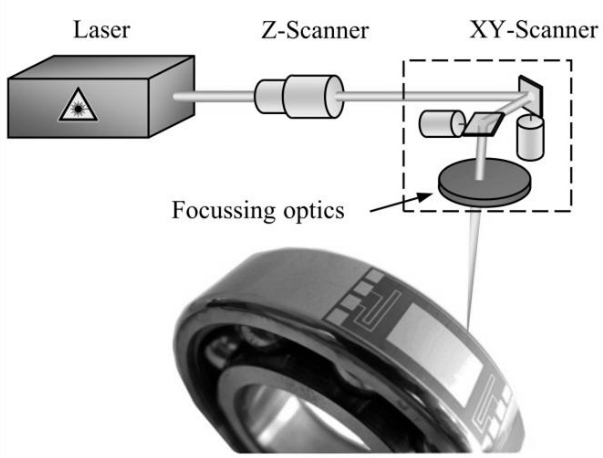

Figure 2. Scanning laser thin film ablation of thin films on component surfaces.

For a flexible and fast processing of sensors the laser beam is deflected in lateral direction by two mirrors driven by galvanometer motors (cf. Fig. 2). A variable focussing unit allows for fast scanning in vertical direction. Since the angle of incidence of the laser beam varies with the topography of the 3-D surface, the reflectance as well as the laser energy density on the surface is not constant during processing. Both parameters can affect the amount of laser energy which is transferred into material. In the following the influences of these two parameters are discussed.

2.1. Reflectivity Dependence on Angle of Incidence

The reflection of light depends on angle of incidence and the polarization state. The angle-dependent reflectivity of NiCr films for a wavelength of 515 nm is shown in Fig. 3. The reflection curves are taken for linear and circular polarization. The inset of Fig. 3 illustrates the principle measurement method. The incoming laser beam spans a plane of incidence with the surface normal. Using linear polarized light leads to a non-constant reflectivity depending on the angle of incidence as well as the orientation of the polarization plane with respect to the plane of incidence. Both parameters may vary with topography and results in inhomogeneous thin film ablation. However, with circular polarization the reflectivity is almost independent from the angle of incidence up to 60°. In addition, circular polarized light has no predominant polarization plane, and thus, does not need to be tracked to the surface orientation. Therefore, in the case of NiCr films the reflectivity can be kept constant for a wide range of incidence angles by processing with a circular polarized laser beam.

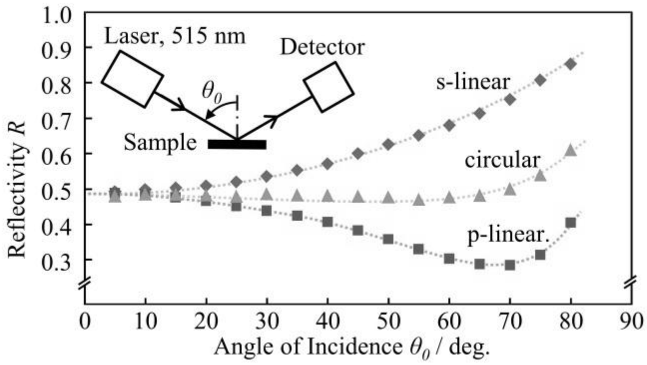

Figure 3. Reflectivity of NiCr at 515 nm wavelength.

2.2. Laser energy density on tilted surfaces

During laser processing of tilted surfaces the intensity profile of the laser beam is projected onto the surface. Thus, with increasing angle of incidence the irradiated area increases and the projected energy density decreases. The irradiated area on the surface follows a cosine law. For example, at an angle of 60° the irradiated area would be twice the area of normal incidence and the projected energy density would be halved to the value of the incoming beam. There are two ways of compensation in order to keep the laser energy density constant on tilted surfaces: (i) The pulse energy of the laser pulses is adjusted accordingly to the incidence angle or (ii) the number of pulses per area is increased. The first approach would require a fast pulse energy controller which is synchronized to the scanner movement. The second approach does not need any additional device. The number of pulses per area can be controlled by varying the scanning parameters, e.g. scan speed, pulse triggering (pulse frequency), pitch of scan paths, or number of scan repetitions. Thus, the last approach would be preferred in order to keep the machining setup as simple as possible.

3. Patterning of Strain Sensors on 3-D Surfaces

The laser patterning process is demonstrated on a tension specimen with v-notches, as shown in Fig. 4. A v-notch acts as a local stress raiser. In the notch root radius the stress is concentrated, and thus, the strain is increased. In rigid components or machine elements, notch-like geometries with strain sensors can be used to increase the sensitivity of the sensor while maintaining the overall stiffness of the component almost constant. In order to benefit from this ‘geometrical amplification’ of the sensor signal, strain sensors are placed into the root radius of the notch.

The specimen are sputter deposited with an insulating Al_2O_3 layer (about 3 µm thickness) and a NiCr (80-20 wt.-%) layer (200nm). Strain resistors are patterned by selectively ablating the NiCr film. A 100 µm wide isolating boundary is scribed around the contour of the sensor geometry (dark area in the photograph), leaving meandering sensor paths with a line width of 30 µm in the root of the notch. The sensors are connected to contact pads on the slope of the notch (angle of incidence: 30°). Without any extensive time optimization we reached processing times of less than 15 s per resistor.

The resistors are interconnected to a Wheatstone bridge. By applying a force to the specimen the electrical resistance in the strain sensor changes. The measured sensor response is plotted in Fig. 4. It reveals a highly linear dependence to a mechanical load.

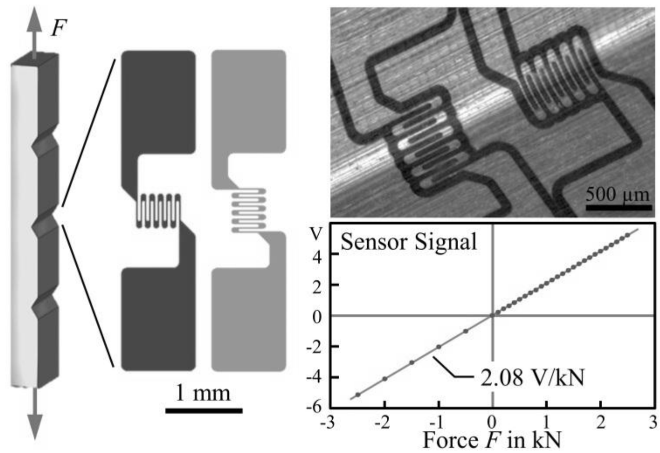

Figure 4. Tension specimen for sensor testing. Sensors are patterned into the radius of V-notches and interconnected to a Wheatstone bridge. Gain factor of electronic amplifier is 500.

4. Conclusion

In this work we present a route for patterning thin film strain sensors on complex 3-D surfaces. The process is demonstrated by generating functional strain sensors in v-shaped notches of tension specimens using a scanning laser beam. Though demonstrated only at fairly small angles of incidence, it is hypothesized to process surfaces which are tilted up to 60° with respect to the laser beam. The presented results implies that laser thin film processing can become an important integration technique for patterning thin film sensors on complex components, and thus, may open novel applications for sensing systems in automotive, medicine, and production engineering.

Acknowledgement

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References

[1] Choi, H., Datta, A., Cheng, X., Li, X., 2006, Microfabrication and characterization of metal-embedded thin-film thermomechanical microsensors for applications in hostile manufacturing environments, J Microelectromech S, 15:322-329.
[2] Lei, J.-F., Will, H.A., 1998, Thin-film thermocouples and strain-gauges technologies for engine applications, Sensor Actuat A-Phys, 65:187-193.
[3] Suttmann, O., Duesing, J.F., Klug, U., Kling, R., 2010, Patterning of NiCr(80/20) on Al_2O_3 using picosecond laser pulses, J. Laser Micro/Nano Eng., 6/1:31-36.