Simulation of Light Deflection Due to an Inhomogeneous Refractive Index Field Induced by a Hot Measurement Object

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In this paper, we present 2d simulations of the light deflection of a laser spot on a hot, circular object's surface dependant on ambient pressure, angle of light discharge and the object's temperature. As conclusion, a reduction of pressure is suggested to minimize the amount of light deflection and therefore restrict the accuracy loss of an optical triangulation sensor when measuring hot objects.

1 Introduction

The aim of the Collaborative Research Centre 1153 *Process Chain for Manufacturing Hybrid High Performance Components by Tailored Forming* is to develop a process chain to produce hybrid components with locally adapted properties. A schematic representation of the process chain is given in Fig. 1, comprising a joining step to bond semi-finished workpieces of different materials, one or multiple forming steps and a finishing procedure. The joining zones' topography of these so-called *Tailored Forming* components need to be monitored – ideally inline, after each forming step and without waiting for the hot workpieces to cool down.

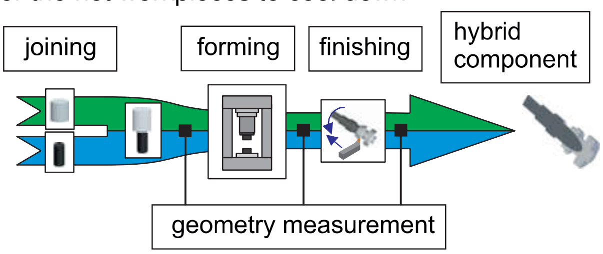

Fig. 1 *Process chain in Tailored Forming.*

The optical quality control of the joining zones is meant to be realized via triangulation techniques, for instance by fringe projection or the light section method. The triangulation principle is based on a rectilinear path of light (from illumination unit to measurement object to detection unit).

The heat transfer from the hot object's surface into the surrounding air induces a density decrease and thereby an inhomogeneous refractive index field. As a ray of light traversing such an inhomogeneous field is deflected towards the more dense air layers, the reachable measurement accuracy of the optical sensor is reduced.

Beermann et al. [1] visualized the inhomogeneous refractive index field above a hot ceramic cylinder using the 2d background oriented schlieren method. The effect of such a convective heat flow on the accuracy of a light section sensor has been examined in [2], using a bandpass filter design as proposed by Stöbener et al. [3] to separate measurement signals from the object's self-radiation. The aim of the implemented 2d simulation is to examine the effect of different boundary conditions (ambient pressure, hot object's temperature, angle of light discharge) on the amount of light deflection to identify potential advantages when optically measuring hot objects.

2 Implementation of Simulation

The simulation has been implemented using the software *Comsol Multiphysics*.

The geometric simulation set-up is given in Fig. 2 on the left-hand side. A cross section of a hot steel cylinder has been placed into a 2d plane of air. The 2d simulation plane is of 300 mm in height and 100 mm in width, the steel cylinder has a radius of 50 mm. Geometric symmetries have been exploited to reduce the simulation time.

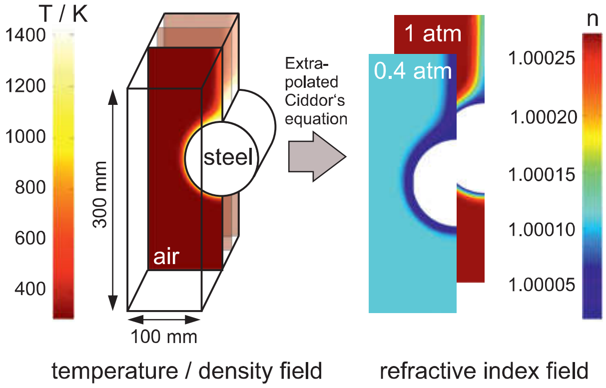

Fig. 2 *Left-hand side: Geometric simulation set-up with exemplary temperature field. Right-hand side: Derived 2d refractive index fields for different pressure scenarios.*

The simulation procedure is conducted as following: Initially the temperature and density fields are simulated in air with rising steel temperature to avoid high temperature gradients and numerical instabilities. The start temperature of the steel cylinder in the given example in Fig. 2 is 1473.15 K, the air tem-

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perature is 298.15 K. The simulation is performed in isobaric state, a laminar convective flow is hypothesized in dry air.
In a second step, the ambient pressure for air has been reduced from 1 atm to 0.4 atm. For each pressure scenario, the resulting density field has been coupled to a refractive index field (see Fig. 2, right-hand side) using extrapolated Ciddor's equation [4].

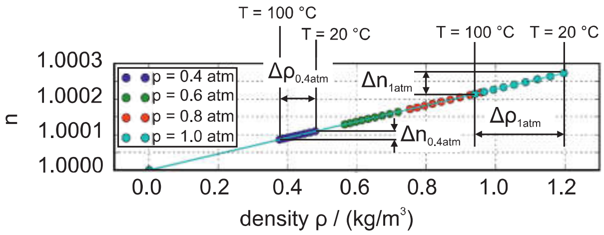

Fig. 3 *Refractive index of air as a function of density for different pressure scenarios based on Ciddor's equation.*

As Ciddor's equation is only valid for air temperatures below 100°C, it needs to be extrapolated to gain a density-refractive-index-relation for higher temperature values. This relation has been gained via the ideal gas law, linear extrapolation and the assumption, that a density value of zero leads to a refractive index value of one (see Fig. 3).
The refractive index fields for different pressure scenarios have been used to implement a ray tracing simulation (see Fig. 4, right-hand side). To keep the analysis of the light deflection results on the cylinder's surface as simple as possible, the curvature of the steel component has been straightened in the area of light incidence.

3 Results

The diagram on the left-hand side in Fig. 4 depicts the light deflection for a wavelength of 532 nm in dry air as a function of pressure, angle of light discharge and steel temperature. The geometric ray tracing details and parameters are given in the schematic on the right-hand side.
It is obvious, that the light deflection is reduced with decreasing ambient pressure. This conclusion is valid – independently of steel temperature and angle. For a steel temperature of 1200°C and an angle of 60° the amount of deflection is approximately divided in half by a reduction of pressure by 60 percent (from 6.998 to 3.434 µm). Greater amounts of deflection can be observed for higher steel temperatures, as the expansion of the inhomogeneous field is greater.

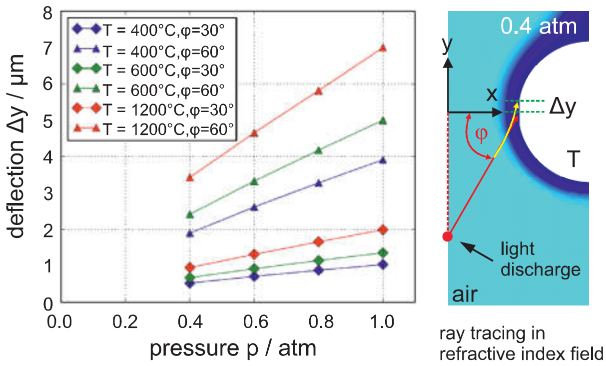

Fig. 4 *Right-hand side: Light deflection in dry air as a function of pressure, angle and steel temperature. Left-hand side: Definition of parameters.*

4 Conclusions

The simulation results expose the potential of a pressure reduction on the accuracy of optical triangulation measurements. As a reduction of pressure correlates with the amount of refractive index variation (compare to Fig. 3) and therefore with the amount of light deflection, the usage of a vacuum chamber is proposed to obtain highly precise geometry data of hot objects.

Acknowledgements

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