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FAST AND COST EFFICIENT MEASURING OF GEOMETRY AND TEMPERATURE FOR OPEN-DIE FORGING

In open-die forging it is state of the art to use simulation tools for creating forging plans and setpoint values for the forging press and the automated part manipulator. These forging plans define required positions and forces. Therefore, the process can be fully automated. However, even small variations of not considered influence parameters lead to different forging results and thus to a discontinuous process. Influencing factors are, e.g. material parameter deviations, uncertainties in force measurements or variations in the part temperature due to varying environmental conditions. This paper presents an approach for a fully automatic open-die forging process with respect to actual conditions, based on a parallel measurement of the workpiece geometry and temperature and a "process-real-time" adaptation on the controller system. The focus of this work is the development of a measuring strategy and an according sensor setup for the combined temperature and geometry measurement of the workpiece. In addition, the structure, the characteristic features of the components and the beam path of the sensors scanning units are shown. Furthermore, first experimental results for the alignment of the beam path are presented. In the outline, the setup and calibration strategy of the measurement system are stated.

1. INTRODUCTION

Open-die forging process is normally used for middle and large sized workpieces in small quantities such as bars, blanks, rings, hollows or spindles [1]. Component diameters up to two meters and lengths up to ten meters with a total weight of several hundred tons can be realized [2].

Commonly used forging tools are flat dies (Fig. 1, left). However, round swaging dies, V-dies, mandrels, pins and loose tools are also used, depending on the desired part configuration and its size. This means, that even complex shapes can be produced with relatively simple tools, what makes the process suitable for customized metal components [3].

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Since no special tools have to be manufactured, the lead-time is shorter for small lot sizes compared to die forging or die-casting. At the same time, the simple tool geometries lower the achievable accuracy of the surface in comparison to drop forging. Higher effort for the subsequent mechanical processing of free-form parts with machine tools is the result [3]. To keep the irregular surface on a minimum, the requirements for the movement of the press and the part manipulation are higher compared to the mentioned manufacturing techniques. Hence, in open-die forging, it is state of the art to use simulation tools [4–9], for creating forging plans and setup values for the forging press and the automated part manipulator (Fig. 1, centre and right). These plans define the positions and the required forces for the forging press and the desired position of the manipulator by means of a known initial temperature and geometry of the workpiece.

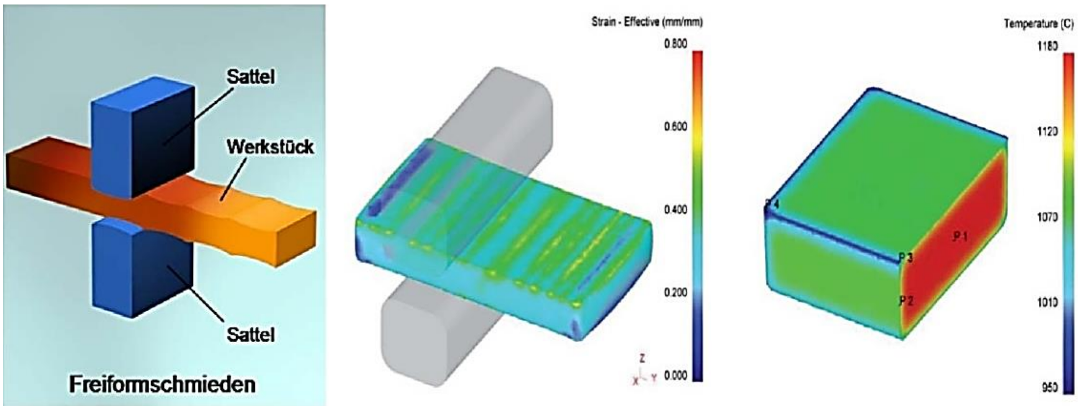

Fig. 1. Schematic representation of open-die forging (left, [1]), representation of the simulated component condition during the first forging phase (centre, [10]) and temperature distribution before the forging process (right, [10])

Under ideal conditions, the process can run fully automated. However, even small variations of the influence parameters lead to a deviation of the forging result. Influencing factors are, e.g. material parameter deviations, uncertainties in force measurements or variations in the part temperature due to varying environmental conditions [11–12]) These deviations add up and may lead to a process interruption after several forging steps.

The current state of the art real-time measurement of the forging process includes temperature and geometry control. Of course, temperature can be measured through both a contact [13] and noncontact way [14]. Only noncontact measurement methods concerning e.g. wavelength, temperature range and accuracy appear properly for hot open-die forging. There are also two different principals for distance determination such as ToF (time of flight) and stereo vision. Pros and Cons of the principals have to be considered according to the specific application and parameters to develop the ideal measuring set up.

At the COMTES facility (Fig. 2) a pilot line for an automated open die-forging process was realised. It comprises the simulation software, a furnace, a press and a manipulator, automated by a programmable logic controller. The furnace temperature and the forging force can be measured. The position of the manipulator with the forging tongs can be estimated. In addition, the measurement of the actual temperature condition and the geometry of the workpiece are required as an input for a real-time forging simulation.

Fig. 2. Furnace, forging-press and manipulator in the project partner COMTES´ facility [15]

The goal of the German-Czech collaborative project “iPress” is an approach for a fully automated open-die forging process with respect to actual conditions based on the measuring of the workpiece geometry and temperature and a process adaptation in real time on the system controller (Fig. 3). The process model obtains the actual state of the workpiece from the sensor and calculates a forging plan for the next step until the final geometry is reached. The main controller manages all components and exchanges information with the simulation software.

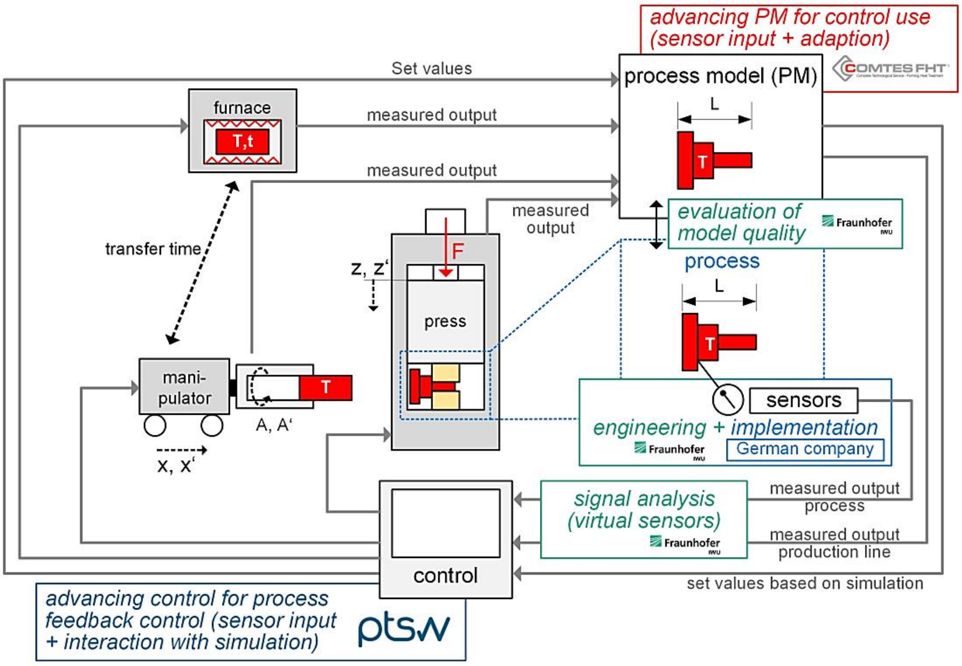

Fig. 3. Signal flow between the components

The focus of this article is the development of the measuring strategy and sensor setup for the combined temperature and geometry measurement of the work piece. Requirements for this sensor are: low cost, rugged sensors, fast measuring times, geometric accuracy of less than 5 mm and temperature accuracy of less than 5–10°C. The workpiece dimensions vary between 500 mm and 2000 mm in length with a cross section between 60 mm and 400 mm. The forging process requires temperatures for semi-hot forming of 650 to 950°C and for hot forming 1000°C to 1250°C [3]. Usually hot forming is used.

The paper is organized as follows: First, the state of the art for optical temperature and geometry measurement is explained. Examples for sensors are shown and an estimation of the sensor characteristics in comparison to the requirements is given. Subsequently, a concept for a scanning device is presented, which meets the requirements for the measurement of the forging workpiece in the described use case. The verification of this scanning concept by a test setup of sensors and a calibration wall is presented. Finally, a short summary and an outlook for the further proceeding of the project is given.

2. STATE OF THE ART – PRINCIPLE OF TEMPERATURE MEASUREMENT

For a high accuracy noncontact temperature measurement the correct measuring wavelength and the emission ratio is important. The wavelength of the maximum radiation depends on the object's temperature (Fig. 4). For the temperature range used in forging, a wavelength between 1.5 and 2.9 μm is optimal. For an extended measuring range, the wavelength should be adjusted. For another forming process, e.g. the press hardening process, the ideal wavelength for the purchased parts is between 2.5 and 2.9 μm, but cooled parts (200°C) require a specific wavelength of 14 μm to be measured adequately [16] Hence, for the selection of the wavelength, the process specific layout has to be carried out or a compromise must be made to keep the sensor flexible for different applications. Another characteristic to consider is the geometric resolution of the sensor. Table 1 gives additional information about the available sensor types.

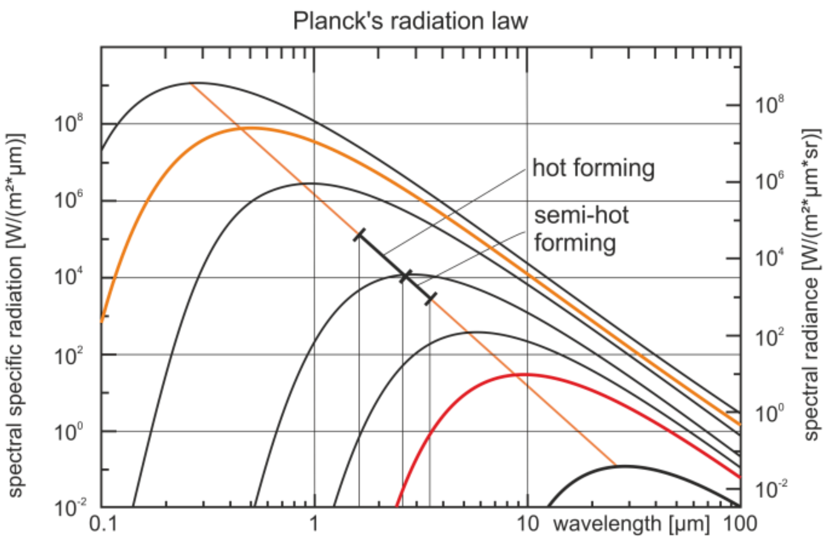

Fig. 4. Planck's radiation spectra [17]

Two measurement principles are available for capturing the temperature: the pyrometer for single point measurement [18] and thermal imaging cameras for surface measurement [16]. Both types of sensors are available with the optimum wavelength between 1.5 and 2.9 µm (Table 1). An important requirement for the intended application is the measurement spot size on the object. The sensor calculates the temperature for this spot. Thus, the resolution on the component surface is limited by the pixel size. Unfortunately, the most important details of the workpiece are the edges (Fig. 1 right). Therefore a high resolution is required. According to the criteria the best choice is the thermal camera PI 1M with a resolution of 0.38 mm at the workpiece surface. Another suitable possibility is the substantially cheaper pyrometer CTLaser 2MH, whereas the low resolution at the component surface can be compensated by repeated measurement and averaging (Table 1).

Table 1. Characteristic of available temperature sensors [14], [19–21]

Characteristic	Pyrometer		Thermal Imaging Cameras	
	CTLaser 2MH	Metris H311	PI 450 (f = 41 mm)	PI 1M (f = 75 mm)
Measuring Rate	1 KHz	10 KHz	80/27 Hz	1000/80/27 Hz
Wavelength	1.6 µm	0.75…1.1 µm	8.0…14.0 µm	0.85…1.1 µm
Temperature Range	385–1600°C	650–1300°C	–20–900°C	450–1800°C
Temp. Accuracy	±0.3%, ±1°C	±0.5%,	±1.0%	±1.0%
Geom. Resolution	1 Pixel	1 Pixel	382×288 Pixel	764×480 Pixel
Aperture ∅	12 mm	16 mm	14 mm	12 mm
Spot Size @2m	12 mm	5 mm	1.22 mm	0.38 mm
Costs	~790 €	~4900 €	~4000 €	~3200 €

3. STATE OF THE ART – PRINCIPLES OF GEOMETRIC MEASUREMENT

For the desired application in open-die forging, another important aspect is the geometric measurement of the part. Similar to the discussed temperature measurement there are two different measuring principles for distance determination as well: time of flight (ToF), and stereovision (triangulation). These have different assemblies and ranges. The ToF are available as point [22–26] and as area measurement device, the stereovision system is working as area scanning system only (Table 2).

Table 2. Typical characteristics of scanning sensors

Characteristic	ToF Sensor	ToF Camera	Stereo-Vision
	Single Point	Area Scan	Area Scan
Wavelength	650 nm	850 nm	400 … 650
Geom. Resolution	1 point	640x480 pixel	2× 2540×2048 pixel
Range	0–100 m	0–26 m	4 m
Accuracy	±5 mm	±5 mm	±0.5 mm
Costs	~1000 €	~5000 €	~25000 €

Stereovision is a passive triangulation with two or more cameras and works texture based with the reflected or emitted visible light by the object. An active triangulation with a luminous light source is not possible in the given case, because of the unsuitable and rapidly changing surface of the workpiece [27–36]. Furthermore, the wavelength of the workpiece temperature radiation is similar to visible light. This complicates geometric measurement under changing light conditions as they occur in production. The environmental conditions in the press shop, such as dust and dirt, also have a negative influence on the measurement result of a stereo camera.

4. INNOVATIVE, COMBINED SENSOR CONCEPT

4.1. CHOICE OF A SUITABLE MEASUREMENT PRINCIPLE SETUP

To overcome these drawbacks, a measuring system consisting of a stereo camera and a laser scanner was developed in a previous project OMEGROS. A first requirement for this setup is to ensure, that the wavelength of the laser and the temperature radiation of the component differ significantly. Secondly, it is important to keep a certain distance between the stereo camera and the workpiece, due to the forging process and the present thermal conditions. At the same time, the necessary base distance between the two stereo cameras increases with the distance to the object to be measured. In the given case, the base distance of both cameras is set to be quite large (~2 m), which means, that unavoidable thermal and mechanical stress have a great influence on the measuring accuracy. ToF sensors, on the other hand, work with lasers of different wavelengths. It is important, that the measuring object reflects the measuring beam with sufficient intensity in the adequate wavelength range [37]. For this, a wavelength must be selected, that differs in an adequate way from the thermal radiation of the part. Therewith the measurement with the ToF sensor is not falsified. Furthermore, a sufficient laser power is required, taking into account, that the laser power has to be distributed over the target area. These requirements of ToF area sensors cause problems, because they increase the laser power demand even more and it is not possible to arbitrarily increase the laser output above class 2 for reasons of occupational safety. Due to these constraints, the solution is using a point-like ToF sensor with an appropriately selected wavelength. For the measurement of the component's geometry, active beam guidance must be realised in order to create a scanning unit.

4.2. OVERVIEW OF OPERATING PRINCIPLE OF SCANNING UNITS

For the necessary active beam guidance, galvanometric scanners, rotation line scanners or gimballed mirrors can be used (Fig. 5). In addition to the criteria speed and cost, the most important selection parameters for the chosen application are the adaptability of the field of vision and the mirror size. These must enable the measurement of the entire component geometry and still achieve a high measuring point density. For the selection of a suitable scanner system, the properties of the variants are listed in Table 3.

Table 3. Characteristics of scanners with active beam guidance [38–40]

Characteristic	Galvanometer	Scanner BLK360*	Gimballed mirror
Scan Area	±30°	360° ± 160°	360° ± 160°
Scan Speed	900°/s	3 min (full scan)	180°/s
Encoder Resolution	0.036 µrad		39 µrad
Accuracy @2m	5 µrad / 8 hrs	6 mm (10 m)	58 µrad
Costs	5.000 €	30.000 €*	30.000 €

Gimballed mirrors have a large field of view and the laser beam can be selectively positioned. However, for a high local measuring accuracy of the workpiece geometry, very accurate position encoders are necessary, which will significantly increase the price of the scanning unit.

Fig. 5. Devices for active beam guidance: galvanometric scanner (left, [39]), middle rotation line scanner (middle, [40]) and gimballed mirror (right, [38])

Rotation line scanners have a comparably large field of view, but no possibility to selectively position the laser beam. The deflecting mirrors rotate at a constant speed, which results in a constant distribution of points on the workpiece. A workpiece-specific adjustment of the field of view is not possible.

Galvanometric scanners have a limited field of view, but a very high local resolution. Furthermore, the scan speed and accuracy is higher, compared to gimballed mirrors and rotation line scanners (Table 3). If the field of view can be adapted to the geometric boundary conditions of the application scenario, galvanometers are the most suitable measurement principle.

4.3. SELECTION OF SCANNING DEVICE SETUP FOR THE OPEN-DIE FORGING PROCESS

A fast scan of the part, which is differently positioned in the working area after each stroke, is necessary. The measuring setup must be adaptable to the conditions of the press and the geometric properties of the workpieces (Fig. 6). The scanner setup represents a compromise between minimum scanning time, achievable accuracy and total costs. To achieve uniform detection of the workpiece surface, an arrangement of four sensors (S_1–S_4) around the workpiece is suitable. If only two sensors are used, the workpiece must be rotated by at least 180° to be measured again, which requires additional time in which the workpiece cools down and the achievable process accuracy is reduced. It is also important, that the angle of impact of the measuring beam on the component surface is as close to 90° as possible in order to avoid inaccuracies due to distortions of the measuring spot. However, this is not suitable for all workpiece geometries and sensor arrangements. This is remedied by overlapping areas, in which the workpiece is scanned from several viewing directions (Fig. 6 top right). Under the given boundary conditions, an opening angle of 30° is sufficient for the sensors. Moreover, for each scanner a position-specific measuring path is derived from the arrangement of the scanners that refers to the workpiece's contour (Fig. 6 bottom right). As shown in Fig. 6, a tailored measuring path is suitable for reducing the measuring time.

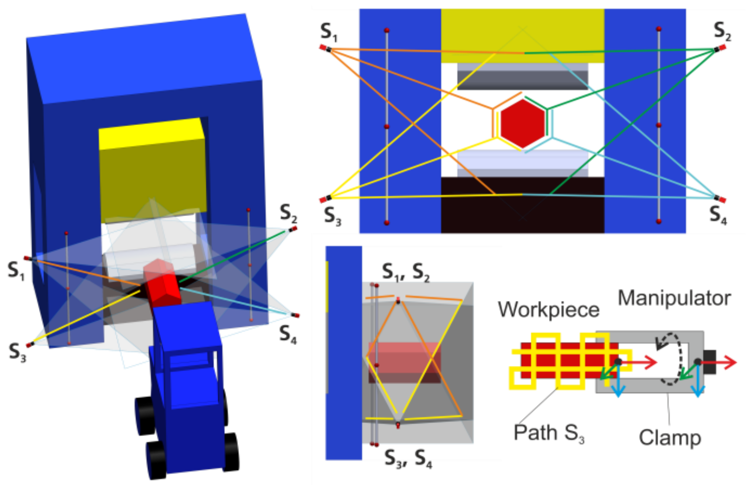

Fig. 6. Geometric restrictions at COMTES facility and scan path at the work piece

Galvanometric scanners in combination with distance meters and pyrometers are appropriate (Fig. 7). This allows a measurement setup that meets the requirements of the intended application.

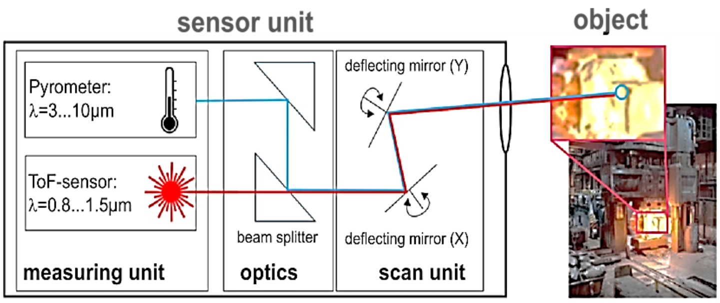

Fig. 7. Scanning device

5. VERIFICATION OF THE SCANNING CONCEPT

To verify the geometric accuracy of the sensor unit, a calibration wall consisting of a modular basic structure and 1100 optically detectable markers (paper and retroreflective) was set up (Fig. 8). The markers were measured with an optical measuring system (Aicon DPA) with a high accuracy result (root-mean-square error RMSE < 35 µm) and serve as geometric reference for the evaluation of the sensor unit. Based on the known positions of the retroreflective markers, an orientation of the sensor unit is possible. This allows the development of a calibration concept for the entire system, consisting of two or more sensor units, whose fields of view do not or only partially overlap.

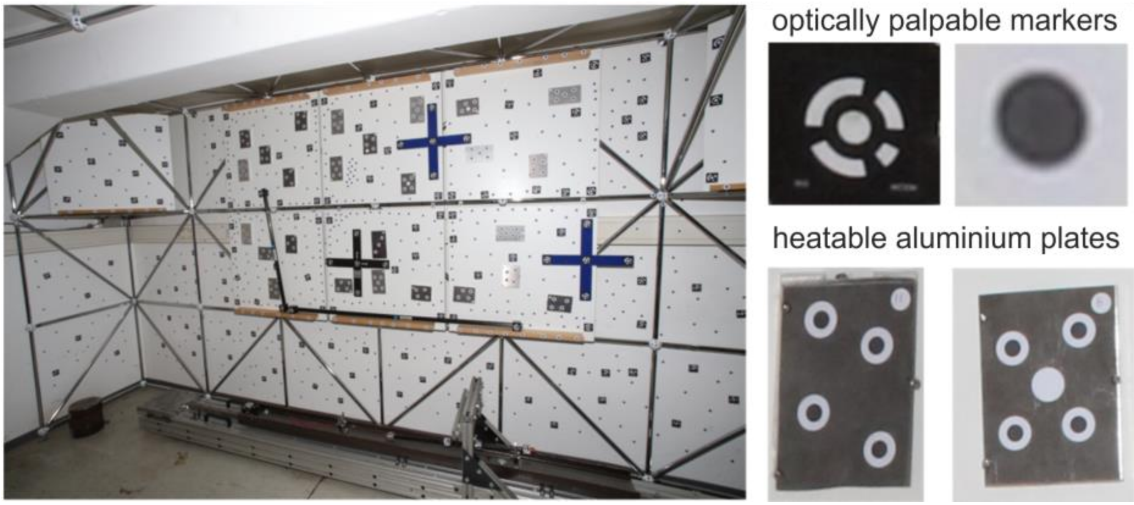

Fig. 8. Calibration wall with markers and heatable segments

Furthermore, the calibration field is equipped with marker labelled, heatable aluminium plates. They allow temperature gradients to be realised for the orientation of spectrally different systems. For a temperature measurement with the pyrometer, the emission grades of the markers have been determined. This calibration field offers the possibility to check the alignment of the beams of the distance and temperature-measuring device and calibration if necessary.

Fig. 9 shows a manual scan with a test facility, consisting of a Leica distance meter and an Optris pyrometer. For distance measurement, the plate height of 14 mm and the measurement noise of approx. 0.25 mm are clearly visible in both scan paths. In this setup, temperature measurement does not depend on the absolute temperature but on the temperature jumps. Both, the geometric position of the markers on the plate and the edges of the plate are clearly visible as temperature jumps. With this method, the beam alignment of distance and temperature measurement can be verified well. Currently, the heatable marker fields on aluminium are replaced by feedback controlled ceramic heating elements. Then a temperature range of up to 600°C can be reached and therewith the temperature accuracy of the pyrometers can be calibrated.

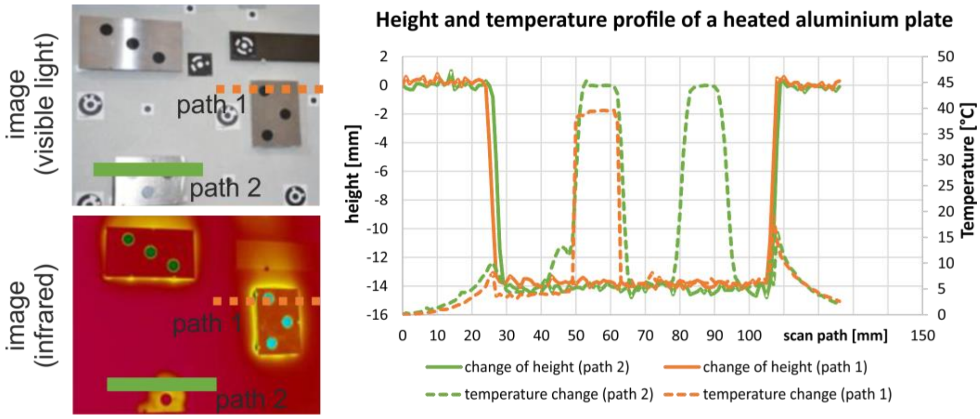

Fig. 9. Distance and temperature by two scans of two paths

6. CONCLUSION AND OUTLOOK

The purpose of the project is the development of a fully automated open-die forging process. The project faces two main challenges, before this goal can be achieved. Firstly, a central control system needs to obtain all relevant information. Therefore, it will be connected to the forging simulation and collects information of the forging tools, especially the press, the manipulator and the furnace. Secondly, a simultaneous measurement of the workpiece's temperature and geometry is required, as these parameters change during the individual forming steps. This measurement monitors the current temperature and geometry and updates the simulation with real conditions.

The focus of this article was the conception of a scanning unit to realise this. Based on a review of the state of the art temperature and geometry measurement, variants for scanners are discussed.

From these possibilities a sensor unit is selected under consideration of the applications boundary conditions. The basic design of the chosen variant is presented. The ongoing calibration and verification of the geometric and the temperature measurements accuracy as well as first functional tests are demonstrated. Currently, the sensor unit is under construction and the calibration wall is adapted to the pyrometer to be used. The next steps are the verification of the accuracy of the sensor unit at the forging workpiece in combination with the test of the forming simulation to realise the automation of the open-die forging process.

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