

FAST MEASUREMENT OF FREEFORM PARTS AT ELEVATED TEMPERATURE USING LASER-TRIANGULATION PRINCIPLE

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Abstract:

The increasing quality expectations and the global competition push manufacturing industry to adopt strategies of lean manufacturing and precision engineering. In order to reach these aims it is necessary that the measuring process be integrated in the production chain to provide timely feedback for process control. Nowadays, however, forged products are typically measured after the cool-down process, which can take several hours. The advantages obtainable if forgings would be measured online are clear: deviations in the production process would be recognized earlier and the production process would be promptly adjusted.

On-line measurement capabilities have the potential to reduce overall production costs and consequently are of interest to many forging industries, including those producing complex products such as turbine blades. Under these circumstances, the HOTGAUGE project was initiated: an international EUROSTARS project with the final goal to develop a measuring system, which is capable of measuring freeform shaped parts at elevated temperature (approx. 800 °C) directly after the forging step. The output of the measuring system is a 3D model of the hot part including temperature information.

The 3D measuring apparatus is composed by two main subsystems: a 2D laser-triangulation system capable to scan a complete section of the part, and a moving platform, which transfers the part through the measuring plane.

The architecture and the components of the measurement system as well as preliminary measurement results are presented in this paper.

Keywords: Complex Shape, Online Measurement, Hot Forged Product, Light-Sectioning, 3D-Measurement

1. INTRODUCTION

Measurements of forged freeform products are nowadays possible only at cold conditions, which may introduce hours of delay in the feedback to the forging process.. Measurements performed immediately after the forging process (at elevated temperature) would allow the production process being promptly adjusted. The desirable measurement of workpieces after forging at elevated temperature is very complex and subject of current research. There exist both commercial systems as well as scientific publications for the measurement of so-called endless products (e.g. T-bars or rods) and regular geometries at elevated temperature. Nowadays, three different optical measurement technologies are most commonly used for measurements at elevated temperature: Time-of-Flight, Stereo- and Triangulation Principle and Image Processing. A short overview is given in the following.

Fu et al. [1] use two laser scanners to measure outer diameters (standard size 5.75 m) of hot cylindrical shells and combine them with infrared temperature measurements (approx. 870 °C) to calculate inner diameters. They also show a 3D model made of the sparse point-cloud from the convex parts. A deviation of the outer diameter to the standard size of less than 15 mm is stated.

Bokhabrine et al. [2] use two commercial TOF sensors (Leica ScanStation2) to measure the outer diameter (nominally up to 6 m) of hot cylindrical shells (700 – 1000 °C). By carrying out three measurements they reconstruct the surface of the regular shell geometry.

He et al. [3] adopt a similar approach by using two time-of-flight sensors and rotary tables to measure the outer diameter of hot cylindrical shells (product temperature 850 – 1250 °C, diameter approx. 5.7 m). They simulate the

shrinkage of the workpiece after measurement; this yields an estimate of the diameter at ambient temperature. They report a maximum error of 0.235% of the estimated diameter compared to an accurate CMM measurement of the chilled workpiece.

Du et al. [4] measure hot heavy forgings using a commercial TOF sensor (Sick LMS100). Due to the use of a single sensor, the system is limited to depth measurements (2.5D measurements).

Tian et al. [5] use a TOF sensor to measure large workpieces (e.g. crankshafts over 20 m of length). Again, this system is limited to 2.5D measurements.

Määttä et al. [6] discuss the use of TOF systems for thickness measurements of hot (1100 – 1400 °C) endless products in steel production plants. They primarily focus on the TOF construction and electronics. A total accuracy of the system of +/-10 mm is stated. The measurement time for a single point distance measurement is 0.5 s.

The LaCam Forge product from Ferrotron/Minteq [7] is a Time-of-Flight based system that measures distances by deflecting the laser in two directions thus leading to a 2.5D measurement. The heat distribution is also measured by the system.

The 3D Portal from MERMEC S.p.A. [8] is designed to measure open-die forgings up to 1250° C by means of the time-of-flight principle. The software can evaluate diameter, thickness, length, straightness and eccentricity. The measurement Range (distance to object) is 1 m – 120 m.

Zhang et al. [9] show a triangulation-based system for the measurements of hot forgings. Measurement of a cylinder under controlled environment yields a maximum deviation of 3 mm from a reference value. The single triangulation sensor is moved on two orthogonal axes to combine measurements to a 3D model.

Liu et al. [10] present an active stereo-vision system composed of two cameras and of a DLP projector. Using an optical filter they reduce the effect of emitted radiation of hot steel workpieces (e.g. 200 mm length). They extract 1D distance measurements from the recorded data.

Stöbener et al. [11] investigate the usability of laser triangulation for workpieces at about 900°C. A point laser implies single point measurements.

LIMAB [12] proposes systems for 2D measurements based on multiple single-point triangulation measurements.

The Danieli HiPROFILE [13] is a triangulation-based system which is made for measuring profiles at elevated temperature (1000 °C steel bars). The system can evaluate measurements on several profile classes in a 2D manner.

Zumbach Electronic AG is well known for complex hot 2D measurements of convex section profiles. Zumbach's Steelmaster systems [14] are able to provide the highest measurement repeatability (10 µm) up to temperatures of 1200 °C. Such systems have been deployed all over the world. In particular, the rotating SMR Steelmaster model offers the leading technology for 2D measurement systems.

The literature review shows that there are no state-of-the-art measurement systems capable to acquire complete 3D geometry of hot freeform shaped parts. Moreover, for most

of the systems mentioned above, no statements about uncertainty or Maximum Permissible Error (MPE) are available. In this paper we present preliminary results from a new measurement system, which is capable of 3D geometry measurements of freeform shapes at elevated temperature using Light-Sectioning technique. Additionally, temperature measurements are acquired synchronously using up to three pyrometers.

The Light-Sectioning technique, which is well-known to the project partner Zumbach Electronic AG because of the year-long experience with profile measurement systems for 2D section measurements in extrusion lines, was preferred to other methods because of the accuracy in the measurement range [15] of typical freeform workpieces of interest in this study, e.g. forged turbine blades, and the ability to generate fast 2.5D measurements. The MPE of the system was specified as 0.2 mm.

The details of the system are presented in section 2. Preliminary measurements are shown in section 3. Conclusions and an outlook are given in section 4.

2. DESCRIPTION OF THE MEASURING SYSTEM

The 3D measuring system (Fig. 1, Fig. 2) is composed of two main subsystems: a 2D scanner and a linear axis. The first one acquires 2D cross-sections of the workpiece. The second one moves the piece through the 2D scanner device, giving information about the third axis position. The geometry of the cross-sections and the positions are then combined using customized meshing algorithms based on the work of Chae and Lee [16].

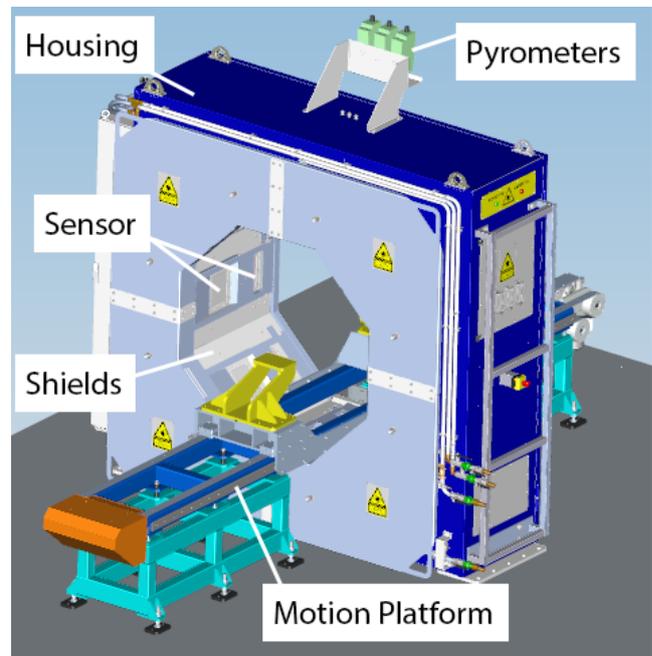


Fig. 1: CAD Model of the measuring system.

The 2D measuring system is based on the line-laser triangulation principle and uses up to eight Light-Sectioning

sensors; every sensor is composed of a laser emitter and of an industrial CMOS camera. The sensors are arranged on an octagonal metrology frame (Fig. 2) to obtain complete information of the freeform section. The measurement area of the 2D system is a circle of 800 mm diameter (Fig. 3).

The point laser emitter optics contains a cylindrical lens to generate a line. The CMOS cameras extract the laser line position internally with a proprietary line detection algorithm, which delivers a sub-pixel resolution.

An optical band-pass filter is installed in front of each camera in order to minimize the interference of ambient light and of the infrared radiation originating from the hot workpiece.



Fig. 2: Photo of the measuring system installed at the forging plant of Pietro Rosa TBM srl.

Moreover, an internal procedure introduced by Zumbach [17] is used to adjust the position of the lasers to make the beam of all lasers coplanar. Then, a proprietary calibration procedure [18] calibrates the measurements from the camera images by providing an accurate mapping between the camera image coordinates and the world coordinates. This mapping includes the model of the geometric projection from the 2D plane to the camera chip as well as the model of the lens distortion.

Special attention was given to the insulation of the metrology frame from the heat radiation caused by the hot workpiece, which is necessary to protect the cameras and to guarantee the dimensional stability of the metrology frame. In particular, the metal plates protecting the system from radiation are water-cooled by cooling coils. Moreover, the temperature inside the housing of the metrology frame is stabilized. The inside air temperature of the housing is kept constant at 20 ± 1 °C. This is achieved with the help of two

conditioning systems: an air chiller and a water flow inside the metrology frame. The second one is enabled when the chiller is not sufficient to maintain the temperature within the specified range.

Since the typical shop floor environment is dusty, the optical components may get contaminated. For this reason, a blowing system is installed to keep away dust from the windows placed between the sensors and the workpiece.

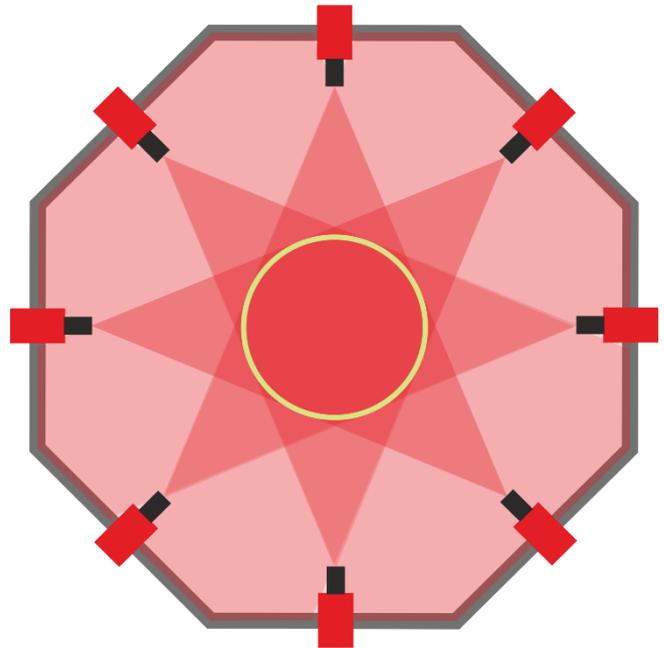


Fig. 3: Sketch of the metrology frame, with laser planes shown in red, and measurement area inside the yellow circle.

Additionally, shield plates are mounted on the front side of the measurement system in order to protect the system from accidental impacts occurring during the handling of the workpieces.

Up to three pyrometers can be positioned on the top of the housing to record surface temperature data. Each pyrometer can be adjusted to point to a specific location of interest on the workpiece.

The linear axis is providing position information using a magnetic encoder system with a resolution of $2 \mu\text{m}$. The advantage in using a magnetic encoder system instead of an optical encoder system is that it is less affected by harsh environment conditions (dust, dirt). The magnetic scale is also protected from heat radiation in order to avoid elongation due to temperature gradients. The motion platform is built using two rails (Fig. 1) positioned outside the measurement field.

All data of 2D sections, position and pyrometer temperature are collected in a synchronous way by an electronic controller thanks to a hardware trigger signal.

The section points from all cameras are merged into complete 2D sections. Measurement points in 3D space are obtained by augmenting the 2D point information of the sections with information from the encoder system. By combining measurement points from each section, a 3D

point-cloud is constructed. A customized meshing algorithm then generates a TIN (Triangulated Irregular Network) model (i.e. a STL File) of the point-cloud (see examples in Fig. 5, Fig. 6).

Depending on the exposure time of the CMOS cameras and their AOI (Area of Interest), the system can deliver full-section profiles at acquisition frequencies of up to 200 Hz (for 2D measurements the frequency can be up to 500Hz). For a typical blade (e.g. Fig. 4) the number of points per cross-contour is about 3000, resulting in 600'000 points/s.

The motion platform can move at about 0.16 m/s. For a 700 mm long turbine blade, a full 3D measurement takes about 4.2 s, generates 840 cross-contours and approx. 2.5 million points.



Fig. 4: Blade from Pietro Rosa TBM being measured at approx. 800 °C.

In the current prototype of the motion platform, the workpieces are loaded and unloaded from the same side of the measurement system but in the final realization application the unloading will be done on the other side.

The loading and unloading of a turbine blade on/from the prototype motion platform currently takes about 10 seconds each. Forward and backward movement of the linear axis takes about 12 seconds each, which results in a total measurement cycle time of about 42 seconds.

In this prototype flexibility was preferred over speed. In a final realization in forging processes, the transportation system can be optimized to minimize cycle times. For endless products the loading and unloading processes is not necessary at all.

3. PRELIMINARY RESULTS

In this paper preliminary results are presented with focus on the functionality and performance of the whole system.

First, the system was tested with a simple cold workpiece, namely a steel cylinder of diameter approx. 100 mm. It was verified that the measurement system and data processing work properly (Fig. 5, Fig. 6).

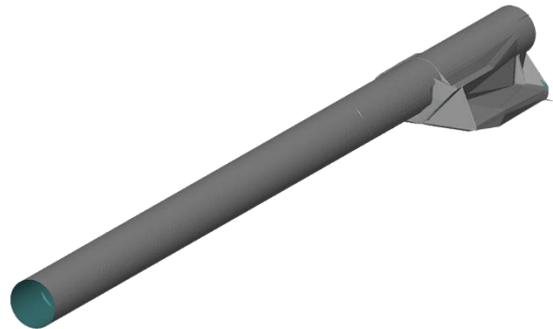


Fig. 5: STL Model reconstructed after measurement of a stainless steel cylinder.

In a second test a turbine blade (approx. 800x200x300 mm) (Fig. 6) was measured. The geometry acquisition delivered data as expected and a high density point cloud was obtained. The system is also able to acquire correctly data from high slope parts.



Fig. 6: STL Model reconstructed after measurement of a turbine blade from Pietro Rosa TBM srl (measured at approx. 800 °C).

Finally, two hot geometries were acquired: a blade at about 800 °C (Fig. 6) and two times a billet at about 1000 °C (Fig. 7). It was validated that the system is well insulated. In fact, the average air temperature inside the housing remained between 19 and 21 °C when moving the hot product with the motion platform for about 30 minutes. Thanks to the optical bandpass filters [10], the geometry acquisition wasn't disturbed by the infrared light emitted by the glowing steel.



Fig. 7: Photo of hot billet inside the measurement system.

Preliminary temperature measurements of the billet were also recorded (Fig. 8) for an assumed emissivity value of 0.85 for the hot billet. This value was chosen based on previous tests performed with the same material, where the temperature collected by the used pyrometers had been compared to the data delivered by thermocouples.

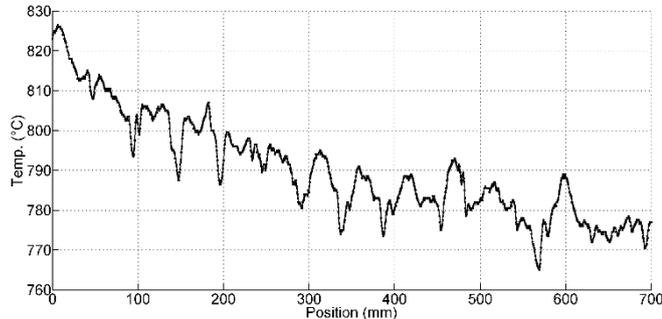


Fig. 8: Temperature measurement of hot billet.

During these acquisitions the temperatures of the whole system were monitored (Fig. 9). The temperature of the protection shields increases over time because of the workpiece radiation. After about 1800 s (30 min) of repeated measurements the shields reached a maximum temperature of about 31 °C.

Due to the conditioning provided by the air chillers, the temperature of the metrology frame remained at 20 ± 0.3 °C (Fig. 9). The housing temperature did not leave the range of 20 ± 1.1 °C (Fig. 9). During the whole test phase the water cooling system designed to condition the temperature of the frame has never been activated. Thus, it can be concluded that the measurement system is able to handle even hotter workpieces.

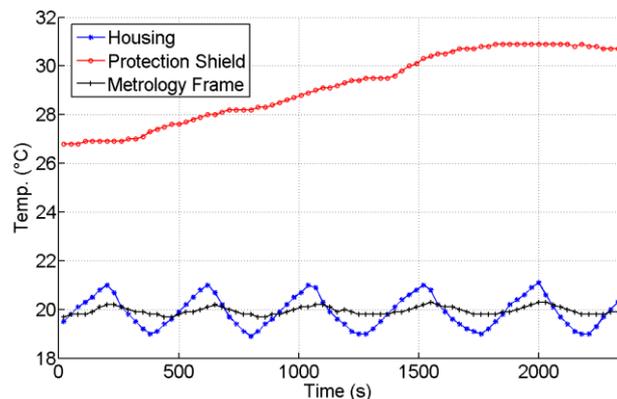


Fig. 9: Temperatures of the measurement system.

4. CONCLUSIONS AND OUTLOOK

After a number of preliminary tests it was demonstrated that the measuring system is working properly in terms of performance under harsh conditions and with hot workpieces. The temperature of the metrology frame was kept at 20 ± 0.3 °C.

The system is capable of measuring hot turbine blades. It can be concluded that the system can be used to measure freeform shaped workpieces at elevated temperatures.

Next step is the metrological characterization of the system with specific tests with the aim to quantify the Maximum Permissible Errors of the system.

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