3D reconstruction of hot metallic surfaces for industrial part characterization

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ABSTRACT

During industrial forging of big hot metallic shells, it is necessary to regularly measure the dimensions of the parts, especially the inner and outer diameters and the thickness of the walls, in order to decide when to stop the forging process. The inner and outer diameters of the shells range from 4 to 6 meters and to measure them a large ruler is placed horizontally at the end of the shell. Two blacksmiths standing on each side of the ruler at about ten meters from it visually reads the graduations on the ruler in order to determine the inner and outer diameters from which the thickness of the wall is determined. This operation is carried out several times during a forging process and it is very risky for the blacksmiths due to the high temperature of the shell when the measurement is done. Also, it is error prone and the result is rather inaccurate. In order to improve the working conditions, for the safety of the blacksmiths, and for a faster and more accurate measurement, a system based on two commercially available Time Of Flight (TOF) laser scanners for the measurement of cylindrical shell diameters during the forging process has been developed. The advantages of using laser scanners are that they can be placed very far from the hot shell, more than 15 meters, while at the same time giving an accurate point cloud from which 3D views of the shell can be reconstructed and diameter measurements done. Moreover, better dimensional measurement accuracy is achieved in less time with the laser system than with the conventional method using a large ruler. The system has been successfully used to measure the diameter of cold and hot cylindrical metallic shells.

Index Terms— 3D Laser based measurement systems, shell diameter measurement, dimensional measurement of hot surfaces.

1. INTRODUCTION

The ability of laser scanners to give accurate and dense 3D point clouds in a very short time has lead to the rapid development of laser scanner based systems for a wide range of applications such as the modeling of architecture, forest and engineering structures, and the measurement and monitoring of structural deformation [1, 2, 3, 4, 5]. Moreover, research work by Määttä et al. [6, 7] showed that Time Of Flight (TOF) laser scanners are particularly suitable for scanning hot surfaces and some examples of the scanning of hot industrial environment can be found in [8].

In this paper we present, a dimensional measurement system based on the use of two commercially available Time Of Flight (TOF) laser scanners for measuring the dimensions, particularly the diameters, of hot cylindrical shells during the forging process. The shells are forged starting from a red hot cylindrical ingot with a hole along the main symmetrical axis and gradually reducing the thickness in order to increase the circumference and the diameter. Figure 1 represents a shell under the press during the forging operation. The shell is supported by a mandrel that passes through the hole and rests on two supports, one on each end. Two rotating chains are used to rotate the mandrel which in turn rotates the shell. Thickness reduction in order to increase the diameter of the shell is achieved by repeatedly pressing the upper part of the shell in between the mandrel and the press hammer, and rotating it with a displacement equal to the width of the hammer after each pressing operation until the shell has reached the correct dimension.

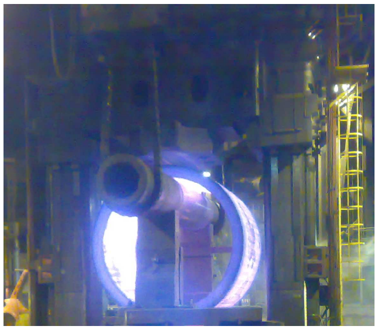

Figure 1: Shell forging

A forging sequence lasts two hours or more during which the diameter of the shell is regularly measured in order to stop the forging process when the correct value is reached. This is presently done in a visual manner using a large ruler positioned horizontally near to the shell. Two blacksmiths standing on each side of the ruler and at about ten meters from it visually reads the graduations on the ruler in order to determine the diameter of the shell. To measure several diameters the shell has to be rotated in order to position the diameters to measure horizontally. This method is time consuming and can result in inaccurate measures due to parallax error and due to the expansion of the ruler that depends on its temperature when the measurement is done. Moreover, measurement time should be short otherwise the shell might cool down below the critical temperature below which forging is impossible. In that case if the shell dimensions have not yet been reached then the shell has to be heated again resulting in longer production time and more energy consumption.

The main objectives of the system that we have developed are to overcome all of the above mentioned disadvantages of the current measurement system and to improve the working condition and safety of the blacksmiths. These objectives have been reached since our system achieves better accuracy in less time and is capable of giving the value of any diameter without requiring that the diameter to measure be positioned horizontally. It is also safer for the blacksmiths since it uses two TOF laser scanners placed at more than 15 meters from the hot shell and connected to a personal computer. The blacksmiths thus do not need to go close to the hot parts in order to visually read the graduations on the ruler. In the next section we will describe fully the system that we have developed as well as the measurement method. Some results on both cold and hot shells will be given in section 3 before we conclude on this work in section 4.

2. DIMENSIONAL MESUREMENT SYSTEM

2.1. System setup

The dimensional measurement system is composed of two commercially available TOF laser scanners and a personal computer on which runs the software that we have developed. The laser scanners are placed at about 15 to 20 meters from the press and in such a position that the views of the inner and the outer surface area of the shell are maximal. The optimal positions of the two scanners that maximize the views are determined by simulation using a software that we have developed and in which the press and forge environment are modeled and constraints can be defined. Among the constraints are the number of scanners (two in our case) and the maximum height of the scanners that should not be over 1.5 meters so that it can be easily reached by any human being for mounting and dismounting. Indeed, the solution that is adopted is to mount the scanners during the forging process and to dismount it after. Moreover, for more flexibility, the scanners are mounted on industrial tripods that can be displaced so that the positions of the scanners are not fixed and can be changed if necessary according to the type of shell or to any modification of the forge environment.

Figure 2 gives an overview of the system setup in the press area. This setup allows us to obtain views of both ends of the shell in order to be able to measure the diameters at both ends. Due to the use of two scanners that are mounted and dismounted after each process the location of the scanners, one with respect to the other, need to be determined each time the system is setup for measurement in order to be able to register the point clouds returned by both scanners. This is achieved using three spherical targets placed in the press area and that are automatically detected by both laser scanners when the system is initialized after it is setup.

Figure 2: System setup

2.2. Measurement method

To be able to measure the diameter of the cylindrical shell a complete three-dimensional (3D) representation of it is required. This is achieved by collecting data for different angular positions of the shell since with only one acquisition it is impossible to obtain a complete point cloud of the whole shell. Three acquisitions with an angular shift of about 120° between each acquisition are necessary. Each acquisition produces two point clouds (one per scanner) that are automatically registered in order to produce only one registered point cloud. Figure 3 is an example of the point cloud returned by the two scanners and that are automatically registered.

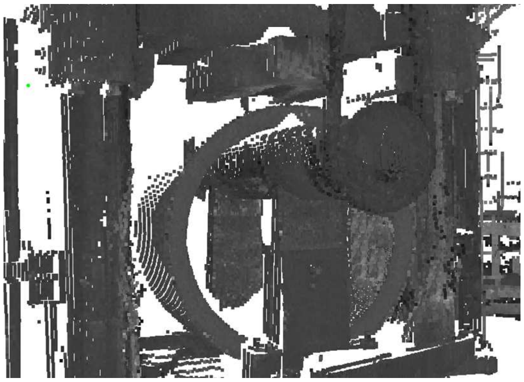

Figure 3: Automatically registered point clouds returned by the two scanners

The automatically registered point cloud obtained during an acquisition contains points that belong to both the shell under measurement and the press. Since we would like to measure the dimension of the shell only, it is better to have a complete point cloud of the shell only. Consequently, for each of the three automatically registered point clouds returned by the three acquisitions, the points pertaining to the shell only are extracted. This is done by computing the difference between two bounding cylinders: one containing the shell and the other one the mandrel found inside the shell. The computation of the bounding cylinders requires the knowledge of the axis of the cylindrical shell as well as its radius. To obtain these two data the user needs to select three points on the thickness of the shell by pointing and clicking with the mouse. The reason for using three points is because three is the number of points required in a three-dimensional space to uniquely define a plane and a circle. The three points must be as far as possible from each other however it is not necessary that their location be exact. An example of the three points is shown in Figure 4.

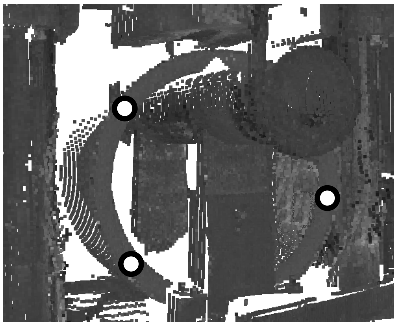

Figure 4: Example of the location of the three points

The idea is to use these three points to define a plane from which the normal to the plane can be determined giving thus the symmetrical axis of the shell. Also, knowing the location of the plane all the point clouds that are before the plane (point clouds pertaining to part of the mandrel and the support on which it rests) can be automatically removed. Next, the center of the circular cross-section of the shell is computed. This is done by computing the center of the circle that passes through three other points located in the middle of the thickness and derived from the initially selected points for more accuracy.

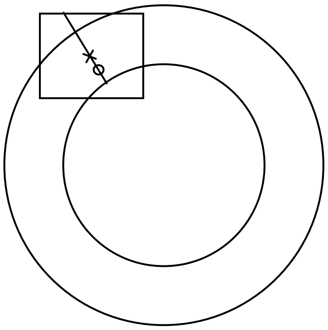

Figure 5: Computing the points for circle fitting

Figure 5 illustrates an example of how the more accurate points are derived from the less accurate ones for fitting the circle. A bounding box is drawn around the initial point represented by a dot in the figure. This bounding box allows us to obtain the inner surface of the shell from which the normal to the surface that passes through the initial point is computed. The intersection of this normal with the inner and outer surfaces of the shell gives two points from which the thickness of the shell can be computed and thus the location of the more accurate point denoted by a cross in Figure 5.

Knowing the symmetrical axis, the center and the thickness of the cylinder, the two bounding cylinders used to extract the shell can be determined. Figure 6 represents an example of the extracted partial point cloud of a shell.

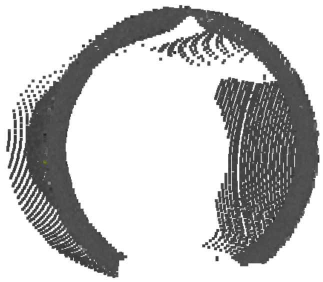

Figure 6: Extracted partial point cloud of the shell

For each of the three acquisitions with an angular shift of about 120° the partial point cloud is extracted and registered two by two in order to obtain a complete point cloud of the shell. Registration is done using the Iterative Closest Point (ICP) algorithm [9, 10] with some a priori knowledge of the shape of the object (a cylinder) and the relative position of the two point clouds (about 120° angular shift). Figure 7 is an example of the complete point cloud of a shell after the registration of three partial point clouds.

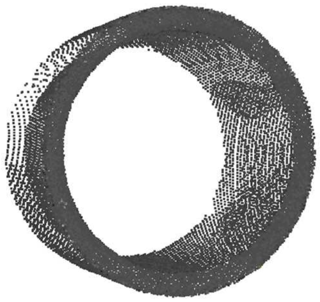

Figure 7: Complete point cloud of the shell

On the complete point cloud several diameters, by default 17 but this parameter can be changed in the software, with an equal angular shift are measured at both ends of the shell. The values of the diameters are next used to display two two-dimensional cross-sectional sketches of the shell (one sketch for each end). To draw the cross-sectional sketch B-splines are used to interpolate between two measured diameters. Moreover, knowing the values of the target inner and outer diameters the over-thickness with respect to the desired thickness can be deduced.

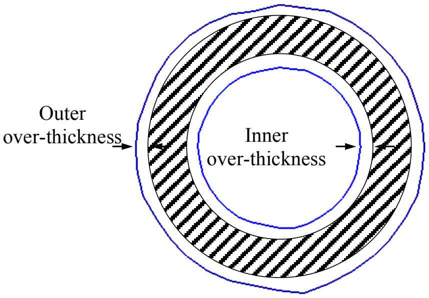

Figure 8: Cross-sectional sketch of one end of the shell

Figure 8 represents an example of the cross-sectional sketch. The shaded part in between two perfectly circular rings represents the theoretical minimum cross-section. All forged shell must have an outer and an inner over-thickness so that the true cross-section is greater than the minimum cross-section. If this is not the case then the forging process has failed and the part is rejected.

The main concern of the blacksmith is to obtain a perfectly cylindrical shell with a certain over-thickness that allows the industrial part to be machined out from the forged shell. However, the cross sectional shape may sometimes be elliptical rather that circular with a larger and a smaller diameter with respect to the diameter of the perfectly circular cross section. In that case the angular positions of these two diameters are displayed on the cross sectional sketch of the shell. Moreover, a pointing function available in the software allows the blacksmiths to use the laser to point to the locations of the larger and smaller diameters on the shell. In this way, the larger and smaller diameters can be tracked during the adjustment of the circularity of the shell.

To measure a particular diameter only a partial point cloud pertaining to either the inner or the outer surface depending on which diameter is measured is considered. Figure 9 shows an example of the partial point clouds considered for the measurement of a diameter. Moreover, only points that are at a distance of at maximum 50 cm from the extremity of the shell are considered and not over the whole length of the shell. The reason is because we would like to compute the true diameter at the end of the shell and not an average diameter over the length of the shell.

The diameter value is computed by searching for the cylinder that best fits the partial point clouds and by computing the diameter of the cylinder as illustrated in Figure 9.

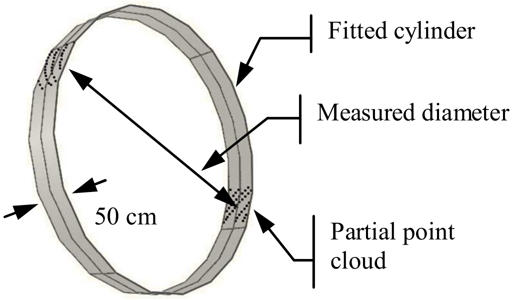

Figure 9: Diameter measurement

3. SOME MEASUREMENT RESULTS

The measurement system has been first validated on cold machined shells for which the inner and outer diameters are known with good precision. Then, it has been tested on hot shells and compared with the measurements obtained using a large ruler.

3.1. Diameter measurement on cold shells

Experiments on cold shells have been carried out under the same environ and in the same way as for hot shells, that is the cold shells are placed on the mandrel under the press and then rotated in order to acquire three 3D point clouds with an angular shift of about 120° between two successive acquisitions. Then, the diameter is measured on both ends known as the head and the tail. Table 1 gives the exact values of the diameters for both the head and the tail. The diameters are not the same for the head and the tail because the shell used for this experiment is a special one but it is perfectly circular that is the diameter is the same wherever it is measured on the head or tail.

	Outer diameter	Inner diameter
Head	4473 mm	4272 mm
Tail	4418 mm	4269 mm

Table 1: Exact diameters of the cold shell

Since the tolerance of our system is one millimeter any difference in diameter of more than one millimeter is considered as a different diameter value. For this reason, depending on the angle at which the diameter is measured the result may not be the same even for a perfectly circular shell because of errors due to acquisition noise. 17 diameters at regular distances over the whole circumference are computed and in the advent that all the values are not the same, a large and a small diameter are determined. This is the case with our example although as we have said before the shell is perfectly circular. This explains why in the results given in Table 2 we have a large and a small diameter.

	Outer diameter		Inner diameter	
	large	small	large	small
Head	4479 mm	4477 mm	4275 mm	4272 mm
Tail	4426 mm	4415 mm	4271 mm	4269 mm

Table 2: Example results for a cold shell

Table 3 summarizes the difference between the large (respectively small) diameter and the exact diameter of the shell. One can notice that the maximum difference between the exact and the measured diameters is 8 mm.

	Outer diameter		Inner diameter	
	large	small	large	small
Head	6 mm	4 mm	3 mm	0 mm
Tail	8 mm	3 mm	2 mm	2 mm

Table 3: Difference between the exact and the measured diameters

Now, if we compare the average measured inner and outer diameters with the exact diameters for both the head and the tail, we can see from Table 4 that the maximum difference is 4 mm.

	Outer diameter	Inner diameter
Head	2 mm	2 mm
Tail	4 mm	1 mm

Table 4: Comparing average measured diameters with exact diameters

3.2. Diameter measurement on hot shells

On hot shells measurements are done in real working conditions on the production line and it is difficult to compare our results as with cold shells since we have no means to measure the diameter of the shell with a very good precision. However, we are confident in our system since the laboratory experiments that we have conducted on hot metallic surfaces and the work of Määttä et al. [6, 7] show that temperature has negligible influence on the quality of the measurement as long as we are below 1400°C. In our experiment, a metallic cylinder has been heated in an oven as shown in Figure 10 and then scanned at different temperatures ranging from 400 °C to 1050 °C. From the point cloud the diameter of the cylinder is measured and the radius deduced.

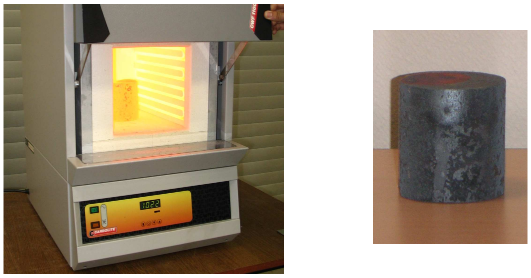

Figure 10: Experiment on hot metallic surfaces

The curve of Figure 11 is a comparison between the measured radius of the cylinder and the theoretical one derived from Eq. 1,

Eq. 1
$$L = L_0 \left(1 + \lambda\, T\right),$$

where L0 is the length or radius at 20°C, T the temperature in °C and λ the thermal expansion coefficient of the material which is assumed to be constant. One can note that the maximum difference in the values is less than 1 mm.

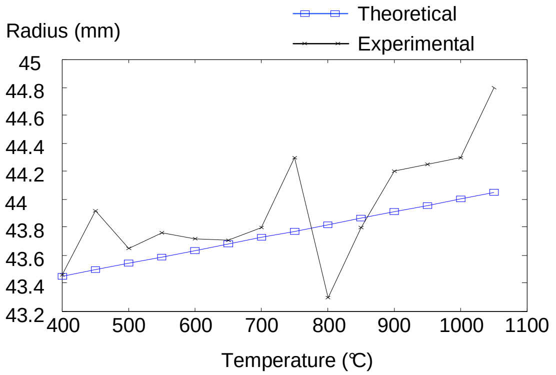

Figure 11: Results on hot surfaces

Table 5 gives an example of the result obtained for a hot metallic shell. One can notice that the value given by the laser system is in the range of values defined by the value measured by the ruler with its uncertainty. The latter is equal to 25 mm since the distance between two graduations on the ruler is 25 mm. The value obtained with our system is thus of the same order of magnitude and consistent with the value obtained with the ruler.

	Outer diameter	Inner diameter
Laser system	5234 mm	4628 mm
Ruler	5226 mm	4620 mm

Table 5: Comparing laser system measurement with ruler measurement

4. CONCLUSIONS

We have developed a Time Of Flight (TOF) laser based measurement system for diameter measurements of large hot metallic shells during the forging process. Our system uses two commercially available TOF lasers and requires the acquisition of three 3D point clouds with an angular shift of about 120° between each acquisition. From the three 3D point clouds only the points belonging to the shell are extracted and used to reconstruct the latter. Finally, dimensional measurements are done on the reconstructed shell and in particular the diameters of the shell at both ends are computed.

Tests conducted on cold shells in real working conditions on the production line show that our system is very accurate and relatively fast compared to the traditional method using a large ruler. Also, our system is capable of giving the value of any diameter with only three acquisitions. With the traditional method each time a diameter measurement is required, the diameter to measure must be placed horizontally and the ruler set up. This is time consuming.

Our system is also safer for the blacksmiths since it uses two TOF laser scanners placed at more than 15 meters from the hot shell and connected to a personal computer. Compared to the current method using a ruler, there is no need for the blacksmiths to go close to the red hot shell in order to visually read the graduations on the ruler. All measurements can be done at more than 15 meters from the hot part and the press. The system is flexible and can be easily extended to more than two laser scanners. By increasing the number of scanners measurement time can be further reduced since less acquisition or data collection is required to obtain the complete point cloud of the shell. The choice of two scanners in the current system is due to the fact that it is the best trade-off between financial cost and measurement time. If the cost of a scanner decreases then the measurement time can be further decrease by using three scanners instead of two.

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