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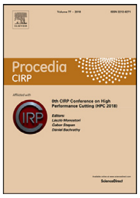

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Development of a form-flexible handling technology with active cooling for hybrid components in forging processes

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ABSTRACT

Tailored Forming is a novel manufacturing process for the production of forged hybrid components. In contrast to components made of mono-materials, hybrid components can be adapted to the respective loads by combining different materials with contradictory properties. Short processing times and high component quality, however, lead to the demand for automated handling and local active cooling within the forming process, since the appropriate processing temperature is particularly important. Due to the fact that the hybrid components are differently hot and change their shape during the forming process, a special gripper system must be provided, which can withstand high temperatures, and ensures both shape variability and local cooling. Nowadays, however, there is a gap between shape variable grippers and rigid grippers for temperature-sensitive processes without any integrated cooling functionalities. Therefore, this paper presents an approach for the development of shape variable high temperature grippers with the use-case of handling hot steel-aluminium hybrid components.

1. Introduction

In today's world, the economical use of resources is an important criterion. The effects of this perceived everywhere. In the automotive industry, for example, cars must meet increasingly restrictive standards by becoming more economical (Behrens et al., 2019). One way to achieve this is weight reduction through lightweight construction. However, lightweight materials that also have high mechanical strength are cost-intensive. In terms of cost optimisation, the production of hybrid components instead of components made of lightweight materials is the consequence. By combining different materials, hybrid components achieve better functionalities. They are therefore often superior to mono components (Behrens et al., 2018b), because they are tailored to their particular operational requirement profile. Also, there is a cost saving in comparison to lightweight construction materials because less expensive materials can be combined (Behrens et al., 2019). Up until now, such hybrid components have been produced by joining near-net-shape components. An alternative is to carry out the joining process right in the beginning of the manufacturing of the workpiece. This promises higher quality, because the early joining and subsequent machining results in a higher strength of the joining zone due to grain refinement (Behrens et al., 2018b). Another advantage of the early joining process is that shapes with a higher complexity are possible in comparison to joining near-net-shape. The described process, known as Tailored Forming, is investigated in the Collaborative Research Centre 1153 (CRC 1153) and will be elaborated in the following section.

1.1. Tailored forming process

The Tailored Forming process follows different process chains to manufacture different hybrid components (Behrens et al., 2016). In general, the process begins with the joining of the hybrid semi-finished products. Processes such as friction welding, extrusion and build-up welding are used to produce the semi-finished products. The components are then heated, before being formed. The transport and handling of the components before and after the actual forming process has a special role, which will be explained in the following.

In order to investigate the process of Tailored Forming, some demonstrators have been developed. The requirements for handling are based on manufacturing processes of the demonstrators. The demonstrators are shown in Fig. 1. For a better overview, the demonstrators are divided according to their funding period. In the first period, several shafts W1-3, a bearing bush H and a bevel gear K were investigated, which are mainly rotationally symmet-

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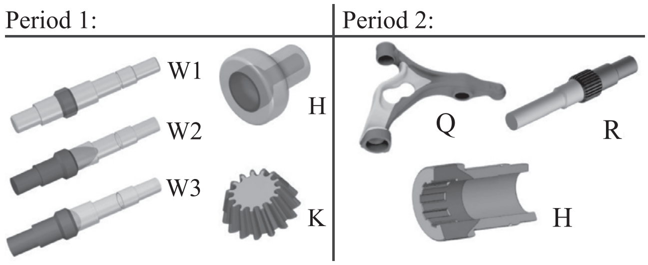

Fig. 1. Demonstrators grouped by first and second period of the Collaborative Research Centre 1153.

rical components with diameters between 25mm and 90mm and masses varying between 0.5kg and 1kg. These have already passed through the Tailored Forming process. Each of these components is subject to different heating strategies, manufacturing processes and material pairings. The demonstrators of the current period of the CRC 1153 are under development. However, it can be seen that the complexity in terms of shape and form is increasing. The most complex demonstrator is the wishbone Q shown in Fig. 1. A simple jaw gripper does not suffice to handle the different shapes. A flexible universal gripper is needed, as it is characterized by its ability to handle a wide range of different objects.

A closer look at the manufacturing process of the bevel gear K will show what conditions the handling must withstand. Two types of steel are joined to form a semi-finished product by the build-up welding process. Heating is carried out by induction and takes place from the outside. The gripper must therefore grip the surface, which is 1000°Chot. For such an application special high temperature grippers are necessary.

Furthermore, the distribution of heat in the component is a key factor for the quality, as identified by Behrens et al. (2018b). The temperature of the steel should be in the range from 900°Cto 1200°Cand the temperature of the aluminium in the range from room temperature to 300°C(Behrens et al., 2018a). In this case the flow behaviour of both materials is adapted to each other, which is necessary for the forming process. The necessary temperature gradient could not yet be achieved with inductive heating (Behrens et al., 2018b). The aim of the cooling system integration is to increase the temperature gradient. To achieve the aim, flexibility of both the cooling performance and the cooling system design is required in order to ensure adaptation to different workpiece sizes and shapes.

Moreover, investigations have shown that due to heat conduction in the material, the transport time has a significant influence on the temperature distribution. Thus, the aim is to minimize the transport time or adaptive cooling (Behrens et al., 2016).

1.2. Objectives

From the explanations on the process of Tailored Forming and the associated boundary conditions (section 1.1), the following requirements and objectives can be deduced: Development of a form-flexible handling system for Tailored Forming components with surface temperatures up to 1250Cwith an integrated active cooling of the components.

This paper will show how such a system can be designed. The sub-systems form-flexible gripper jaw, cooling system and the automated process of gripping are developed for this purpose. After a general introduction, the sub-systems are presented successively. They complement each other to form a system which fulfils the objectives.

2. State of the art

This chapter provides an overview of variable shape gripping, heat-resistant gripping and cooling techniques. The information presented serves as a base for the development of a new system.

2.1. Universal grippers

Universal grippers are characterized by the fact that they are suitable for several assembly and handling tasks due to their flexibility. The flexibility of universal grippers is realized through the using of grippers that are adaptable in shape. The adaptability allows the grippers to adjust automatically to different geometries. Various effects are used for this purpose. Since the entire thematic breadth of universal grippers would be far too broad to be discussed in detail in this paper, some grippers that are important for the paper are mentioned. A good overview of the entire field of universal grippers is given by Fantoni et al. (2014). On the one hand, there are grippers which consist of highly elastic materials and adapt to the shape of the object to be gripped, the so called soft robotic grippers. An overview of this type of gripper is given by Shintake et al. (2018). There are two types of soft grippers, those that combine elastic materials and compressed air (Ilievski et al., 2011) and those that use Granular Jamming (Brown et al., 2010). When compressed air is used, the elastic body of the gripper is deformed in such a way that the object is gripped or embraced, resulting in a form and force closure grip. In Granular Jamming, there is an elastic skin which is filled with a granulate. In the initial state, the granulate is permeated with air and deformable. The skin is applied to the object to be handled and thereby assumes the contour of the object. The skin is then evacuated. The air is extracted from the granulate and the granulate is stiffened. In this way, the skin retains its assumed contour and a form-locking grip is performed. The materials used, such as silicones or other polymers, are limited in their application temperature. For elastic variable shape grippers and their materials, a maximum operating temperature of 300°Chas been observed (Mosadegh et al., 2014). For this reason, it is not possible to use them in the high-temperature range of Tailored Forming.

A further type of variable shape grippers are those which reproduce the contour of the object to be gripped by moving elements and thereby enable a form closure. The advantage here is that metal materials are used instead of silicone.

One example of such grippers is the Omnigripper by Scott (1985). In the Omnigripper, pins are arranged in two separate matrices. The pins can be moved axially independently of each other. At first the pins are extended by compressed air. Then, without compressed air, the gripper is applied to the object and the fingers that come into contact are retracted again. This creates a gripper that is specially adapted to the contour. To perform the grip, the two matrices are moved together and there is a force-locking and form-locking connection. Another gripper that uses pins in a matrix arrangement to grip with variable shapes is the matrix gripper by Matrix GmbH (Meinstrup, 2013). Here, two of the jaws face each other. The pins are pushed out by a spring. Upon contact with the object to be gripped they retract again. As soon as the negative is ready, the pins are locked and thus the image is locked. Another approach that is being researched is the reproduction of the human hand as a universal gripping tool. Such technical hands have 3 to 5 joint fingers, with one of the fingers being designed as an independently movable thumb to achieve a high degree of flexibility. Examples of highly developed technical hands are the DLR-Hand II (Butterfass et al., 2001) and the Robonaut-Hand 2 (Bridgwater et al., 2012). These are very complex in their kinematics and meet requirements that are not set by the process.

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The grippers shown so far are variable in their shape. In contrast, the most important design-elements of a high temperature resistance gripper are characterized by Cutkosky and Kurokawa (1983). Their work shows that the fingers or jaws are the thermally most stressed elements. The choice of material is particularly important. Depending on the material, there are different mechanical and thermal properties, such as thermal resistance or thermal conduction. The gripper developed by Cutkosky et al. is adaptable to uneven surfaces. For this purpose, fingers are used which are independently beared. However, the shape variability is limited compared to the elastic grippers.

Summarizing, the highest form variability is achieved by elastic materials, because they can reversibly perform high deformations (Mosadegh et al., 2014). These materials belong to the group of polymers that have a maximum working temperature of 300°C. In Tailored Forming, temperatures of up to 1250°Care reached, making the use of polymer based materials impossible. Grippers for this high-temperature range are made from metals, in order to withstand temperatures above 1000°C. These materials, in turn, have no form flexibility and therefore metal grippers must make us of rigid jaws or fingers. Overall, the metal grippers with sliding pins are more suitable for the temperature range in tailored forming due to their simple kinematics and the material used.

2.2. Cooling techniques

As outlined before, the cooling is necessary to adjust the temperature gradient in the object. The temperature distribution is essential for the quality of the formed parts. Therefore, the different cooling techniques are explained to provide a basis for the choice of method.

Basic cooling techniques are immersion cooling, spray cooling, cooling with gas and cooling by conduction in solids of different temperatures. In immersion cooling, the workpieces are cooled in a bath of a liquid. Spray cooling is the spraying of a workpiece with a cooling medium, using single or dual fluid nozzles for spraying. If several solids of different temperatures come into contact with each other, conduction occurs and the temperatures equalize, the workpiece with the higher temperature is cooled.

The immersion cooling achieves the highest cooling effect. The disadvantage is that the fluid must be in a reservoir. This prevents permanent cooling because it is difficult to move. Therefore an integration into the gripper is not possible. The outstanding advantage of spray cooling is the flexible and simple change of the heat transfer in a wide spectrum by varying the media pressures (Golovko et al., 2014; Herbst et al., 2015) as well as the easy installation and low weight of the nozzles. This allows for an adaptation to different applications. Selected areas can be sprayed with the generated spray cone, which increases the geometric adaptability. A disadvantage is the need for a liquid coolant flow and the necessity to remove the coolant after the cooling process. Cooling with gas has the advantage that harmless gases such as air do not have to be removed from the environment. However the achievable heat transfer coefficients are relatively low (Stark et al., 2011). In conduction with contact of solids, the workpiece can be cooled at defined areas on the workpiece, but solid structures are disadvantageous due to the limited geometric flexibility. Still, spray cooling is particularly suitable as a cooling technology for the forming process due to the adaptability of the cooling effect over a wide range and the geometric flexibility.

3. Development of a form-flexible gripper with active cooling

This section introduces the solution concepts for the gripper mechanism and the cooling system. A brief look at the system in Fig. 2 shows that the system consists of the gripping unit, which in turn consists of the two formflexible gripper jaws and a parallel jaw gripper. Furthermore, the cooling system, which includes the nozzles and their holder, is shown. The design of the gripper mechanics and the active cooling system are presented in the following.

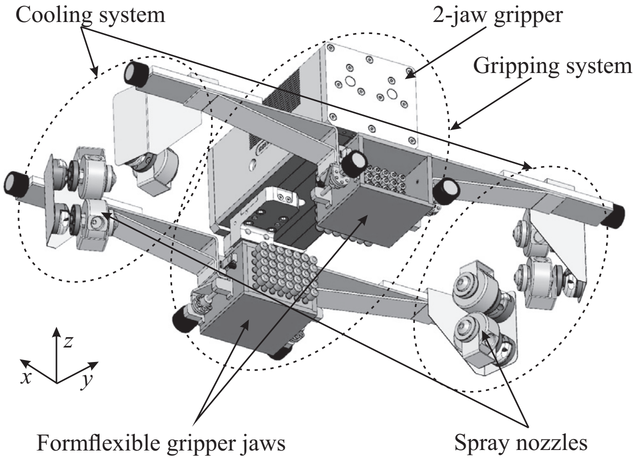


Fig. 2. Overall system consisting of: 2-jaw gripper with formflexible gripper jaws and spray nozzles for the active cooling.

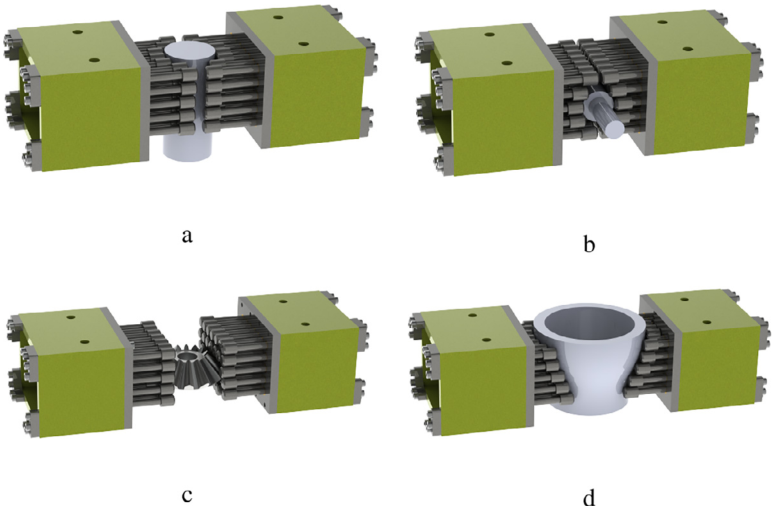
3.1. Gripper mechanics

In order to meet the demands of the Tailored Forming process, a novel gripper was designed. As shown in Fig. 3, the gripping principle of the Omnigripper, pins actuated by air pressure and the Matrixgripper, opposing gripper jaws, is combined. The jaws have a matrix with 7x5 pins each with a stroke of 24mm, which are well suited for the demonstrators in Tailored Forming (Fig. 3). The dimension of one jaw are 86x66x60 mm and can be extended as required. The independently movable pins allow differently shaped objects to be handled. Fig. 3a shows the workpiece of the bevel gear clamped in the gripper. The other pictures of the figure show the gripped demonstrators of the first period of CRC 1153. The shape variability is given by the gripping principle. The pins are extended by compressed air. The jaws are then closed by the parallel gripper without compressed air being applied to the pins. The pins, which will face resistance, are retracted during further movement of the jaws. When the jaws have reached their position defined by the user, compressed air is applied again. The pins act on the object with a force regulated by the compressed air and secure the grip. To release the grip, a vacuum is applied instead of compressed air. The pins retract and the object is released.

With this, the functionality to grip differently shaped objects with one flexible gripper can be provided.

The next requirement to the system is the temperature resistance. To withstand the high temperatures acting on the pins, a material research was carried out. A special stainless steel has been identified which is designed for high temperature use. This stainless steel, called 1.4148, is used for the pins and has long term operating temperatures of up to 1150°Cand a low thermal conductivity coefficient (Brnic et al., 2015). Higher temperatures are possible at short term.

The poor thermal conductivity of the material has the effect that the heat input into the rest of the system is low. For this purpose, simulations have been carried out with Ansys Mechanical which take into account the process times of the handling and compare the associated heating of the system with the resulting thermal expansion. To simplify the simulation, only heat conduction was taken into account. Due to the fact that there were no



a

b

c

d

Fig. 3. Demonstration of shape variability by the example of some demonstrators: (a) workpiece bevel gear, (b) shaft, (c) bevel gear, (d) bearing bush.

significant aspects besides the expected expansion, the results are not presented in detail in this work. Following from these results, the fits of the pin bearings are adapted to the thermal expansion at operating temperature.

3.2. Active cooling

After the gripper is introduced, the cooling system follows, which is mainly based on spray cooling. The choice fell on a two-stage nozzle, as this allows for cooling with either a gas or a liquid or both simultaneously. The heat transfer can be adjusted by varying the pressure of the media or the ratio of gas to liquid. By using several nozzles and a flexible arrangement of these, different workpiece areas can be cooled. The combination of air and water is used as a coolant for the two-substance nozzle. The advantage is the good availability of the media as well as the low costs.

3.2.1. Investigation of nozzle arrangement

To determine the arrangement of the nozzles, an analysis is carried out. This will show whether the setting parameters are sufficient to adjust the nozzles individually. The projection of the spray cones onto the surface of the workpieces before and after forming is simulated using the software Blender. The objective of investigation is to identify and maximize the area reached with the cooling fluid while simultaneously achieving a maximum homogeneous cooling surface. Fig. 4 shows an example of possible nozzle configurations for the bearing bushing. Surfaces covered by the spray cone are shown in light grey, areas with higher spray densities in lighter grey scales. The heat transfer also decreases radially from the spray center (Puschmann, 0000). For a more homogeneous heat transfer, an overlapping of the spray cones in the edge area is advantageous. Several configurations are considered, in which the number, position and orientation of the nozzles were varied. The position and rotation of the nozzles can be adjusted to adapt to different workpiece sizes and shapes.. In addition, different arrangement configurations can be compared and the cooling can be optimized. The translatory adjustment l of the nozzles is done manually via screw drives or slotted holes. The angles ϕcan be adjusted via swivel joints. Both parameters are marked in Fig. 4.

In addition to the already mentioned parameters, the number of nozzles is also varied. Arrangements with four nozzles and eight nozzles are considered. By using four nozzles (Fig. 4a), the distance to the workpiece is greatest compared to the other arrangements, which results in a lower spray density. In addition, there is a greater overlap of the spray cones.As a result, this arrangement is not useful. In Fig. 4b eight nozzles are rotated around the z-axis to reach areas behind the pins that are left untouched in other arrangements. The disadvantage of this solution is that areas inside the semi-finished product are sprayed directly or there are unsprayed areas in the edge area. On the semi-finished product in Fig. 4c the spray cones overlap in the edge area and on the formed component there are unsprayed areas between the spray cones. The variant in Fig. 4c can be modified in such a way that there are no unsprayed surfaces between the spray cones in the formed component, which leads to a larger overlap on the semi-finished product. This would resemble Fig. 4b, but without rotation around the z-direction. The objective is therefore to find a good compromise between homogeneous spraying of the semi-finished product and the formed workpiece.

It should be noted that the spray cone is approximated by a light cone. The interaction with the environment cannot be anticipated in this simplified simulation. Therefore, experimental determination of the ideal nozzle arrangement is needed. Due to turbulences, surfaces not located in the ideal spray cone can be affected by the cooling medium.

3.2.2. Simulation ofcooling process

After investigating the arrangement of the nozzles, the influence of the spray cooling must be analyzed. For this purpose a simulation in Matlab was set up. For the simulation of the heat transfer, material properties such as the thermal conductivity λ,the specific heat capacity c, the material density $\rho$and the heat transfer coefficient αmust be considered. The following heat transfer model is to be considered as the energy balance for heat conduction through an infinitesimal non-moving volume. To describe the thermal effects of the system, the model (Eq. (1)) is solved. For simplification, temperature independent material properties are used for the simulation. The used average heat transfer coefficient of $7\mathrm{kWm}^{-2}\mathrm{K}^{-1}$is achieved according to Golovko et al. (2014) at an air pressure of 0.2MPa and water pressure of 0.1MPa and can be increased by increasing the pressure, which in turn increases the cooling effect. The temperature distribution is important, especially for the bearing bushing blank, because it is inductively heated from inside. The problem is that the aluminium on the outside is heated strongly by the thermal conduction, as can be seen in Fig. 5a. The aluminium comes close to its melting temperature of 650°C. By heating with activated cooling, however, the temperature of the aluminium remains within a normal range of tempera-

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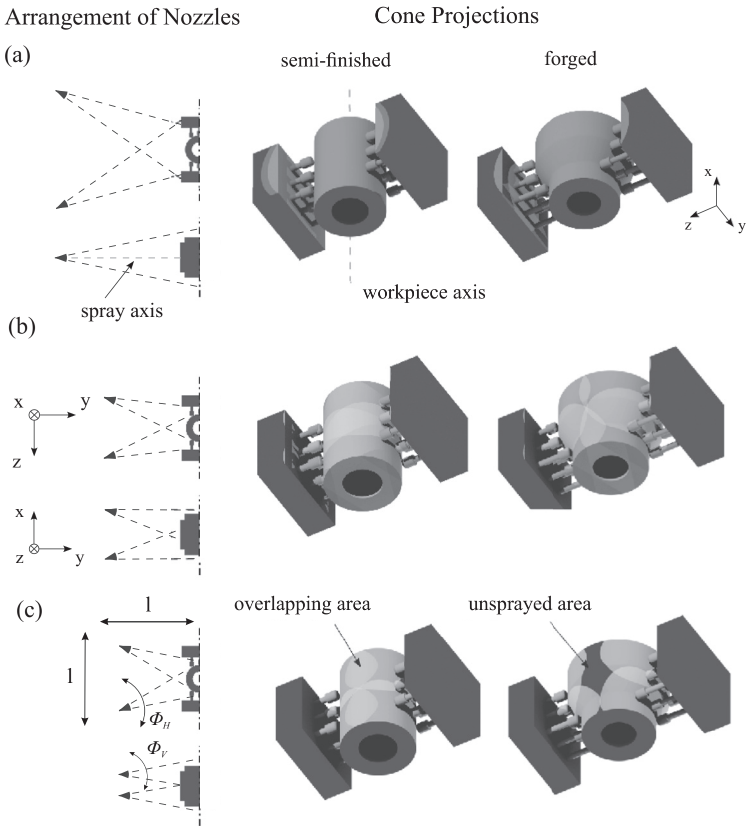

Fig. 4. Arrangement of nozzles and resulting cone projections (a) four nozzles with spray axis perpendicular to workpiece axis, (b) eight nozzles with spray axis inclined to workpiece axis (c) eight nozzles with spray axis perpendicular to workpiece axis.

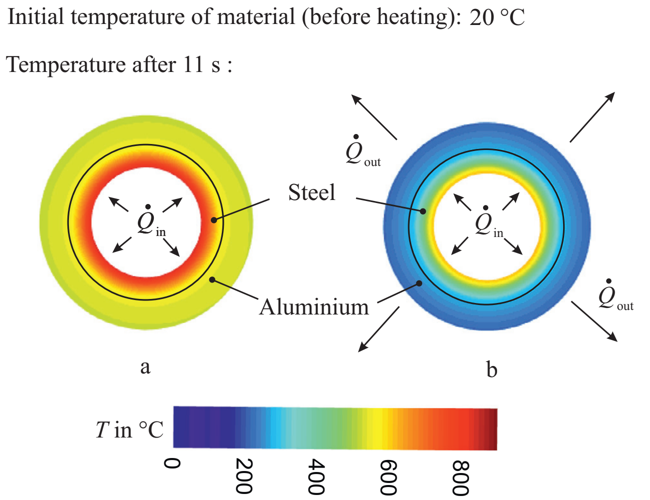

Fig. 5. Simplified simulation of the temperature distribution in the semi-finished bearing bushing during inductive heating (a) without and (b) with active cooling.

ture (Fig. 5b). The disadvantage of this, is that the heat conduction between steel an aluminium leads to cooling of the steel side. This results in an optimization problem for the right settings to cool the aluminum while keeping the steel at the required temperature. This problem must be investigated further.

$$\rho c_v \frac{\partial T}{\partial t} - \nabla(\lambda \nabla T) = \sum_{i=0}^{N} \dot{q}_i \tag{1}$$

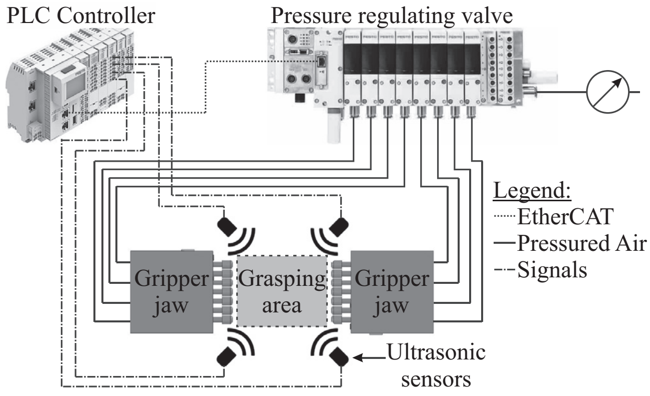

Fig. 6. Regulation and control system.

4. Automated process design

The system presented so far is not able to grip independently. In order to automate the process of handling, a control system is needed. The control system is also needed because of the danger of the object in the gripper moving. The risk is based on the consideration that due to different pressures on the jaws, the pins of one jaw apply a greater force than those of the other. So the object would drift to one of the jaw. As a result, the position of the object in the gripper is unknown and precise handling is not possible. Thus, the following concept was designed.

The control system necessitated by the above circumstances is shown in Fig. 6. Sensors are needed for the detection of the position of the gripped object. In this case, ultrasonic sensors are at-

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tached to the jaws, which continuously detect the position of the object. The data from the sensors is sent to the controller, which calculates whether the position has deviated. If the case occurs, a pressure control is carried out, whereby the object is returned back into the initial position. The controller forwards the new pressure values to the pressure controller (Festo Motion Terminal), seen as pressure regulating valve in Fig. 6. This ensures that the object is in a known position throughout the entire handling process, enabling precise placement.

A further consideration is that the pins should be controlled in groups. This allows the pressure of the pins to be controlled column by column or line by line, depending on the configuration. Thus, the object is positioned more precisely in the gripper. In addition to rows and columns, further interconnections like diagonal or group configurations are possible.

5. Conclusion and outlook

The paper describes the process of Tailored Forming within the CRC 1153 and the positive effect of a gripping system with integrated cooling function for the objects to be handled. In this context, a concept for a gripping system with variable shape and temperature resistance was presented. The concept for cooling was also discussed and various aspects, such as the nozzle position, were examined. Also a concept for a control system with the corresponding components is demonstrated.

The next step is to validate the concept by testing with first prototypes of the individual subsystems. A first prototype produced with the 3D printer can be used for the evaluation of the control system and for functional testing. Furthermore, the cooling system can be built and validated at the same time as the gripper. If these systems work as required, the gripper will be built in stainless steel and real experiments will be carried out at operating temperature. On the basis of the results, improvements will follow.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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