Correlation between process parameters and quality characteristics in aluminum high pressure die casting

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ABSTRACT

Aluminum high pressure die casting is one of the most productive manufacturing processes. The complexity of the parts rises and the quality requirements are increasing. The challenge in high pressure die casting is to reach the high quality standards in spite of the huge number of quality influencing process parameters. The interaction of all quality influencing parameters leads to extremely high scrap rates of up to 10 - 25%. The parameters are not centrally monitored by one single unit but by the various systems of the process such as the die casting machine, the furnace, the thermal regulation system etc. The typical parameters being measured in the process to date are piston speed in the first and second phase, intensification pressure and others, but there are many parameters such as the humidity of the evacuated air which also control part quality.

The European research project MUSIC (MUlti-layers control and cognitive System to drive metal and plastic production line for Injected Components) has the aim to decrease the scrap rates in high pressure die casting by developing an intelligent cognitive system taking all quality controlling parameters into account. In the frame of the project a special casting geometry has been developed, that allows the production of parts with several defects such as shrinkage porosity, cold shuts and distortion. The die is instrumented with many new and innovative sensors to monitor new process parameters, such as the sound of the shot, which have not been applied to date. The sensor data, the process parameters of the machine and the peripheral devices are stored together with the quality index of the castings in one common database. The cognitive network will then be able to calculate the quality index for future parts based upon the measured sensor data.

INTRODUCTION

The number of high pressure die casting parts in the construction of the body of innovative cars is rising. The reason for the application of aluminum parts as structural elements is the reduction of the weight. At AUDI a weight reduction of 10, 9 kg was achieved using one casted shock tower instead of 10 joined steel plate parts. (Figure 1)

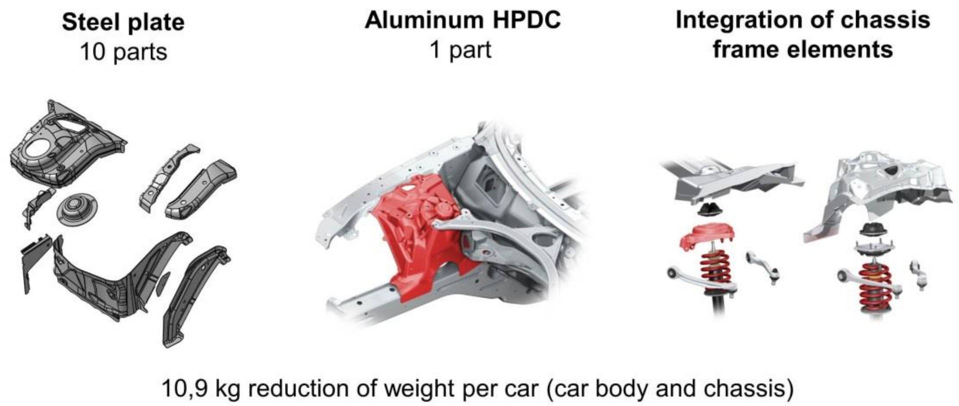

Figure 1: reduction of weight using structural aluminum high pressure die casting parts instead of joined steel parts [1]

The high pressure die casting process is a productive manufacturing method to produce complex cast parts near net shape in a very short cycle time. High pressure die casting parts are characterized by a good surface quality, a high dimensional accuracy and a high tensile strength despite the low weight. The requirements concerning quality and mechanical properties and also the geometrical complexity of the components are rising. In the HPDC process an enormous number of parameters are influencing the cast part quality. The known and controlled parameters are the piston speed in the first and second phase, the switching point and the intensification pressure, that build together the shot profile of the injection process. These parameters and other parameters like the temperature of the heating oil, the furnace temperature and the parameters of the spraying unit are controlled and measureable parameters. They are controlled and measured by the units shown in Figure 2. Additionally there are other quality influencing parameters, for example the remaining humidity in the die after spraying, the evacuated air quantity, the acceleration of the plunger and variations in the alloy composition that are not measured or stored to date. The interactions between all quality influencing parameters are leading to high scrap rates up to 10 – 25%. This value exceeds the scrap rates of other manufacturing processes by a factor of 10 or even 1000.

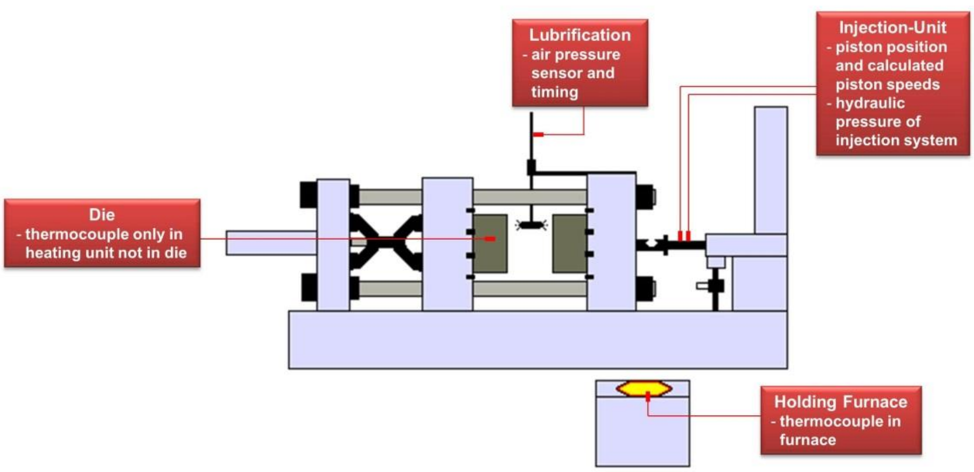

Figure 2: conventional data acquisition during HPDC process

RESEARCH OBJECTIVE

The European research project MUSIC (MUlti-layers control and cognitive System to drive metal and plastic production line for Injected Components) has the aim to decrease the scrap rates in high pressure die casting by developing an intelligent cognitive system taking all quality controlling parameters into account.

As shown in Figure 3 the high pressure die casting machine and the peripheral devices are equipped with sensors. All devices are attached to a network that is connected to one common data base. In this data base all sensor data and the controlled process parameters of the machine and the peripheral devices are stored. In the training phase the quality data of the casted parts is also entered in the data base. The correlation of the sensor data, the process parameters and the quality of the investigated cast parts allows training the cognitive system which is able to predict the quality of future cast parts during production.

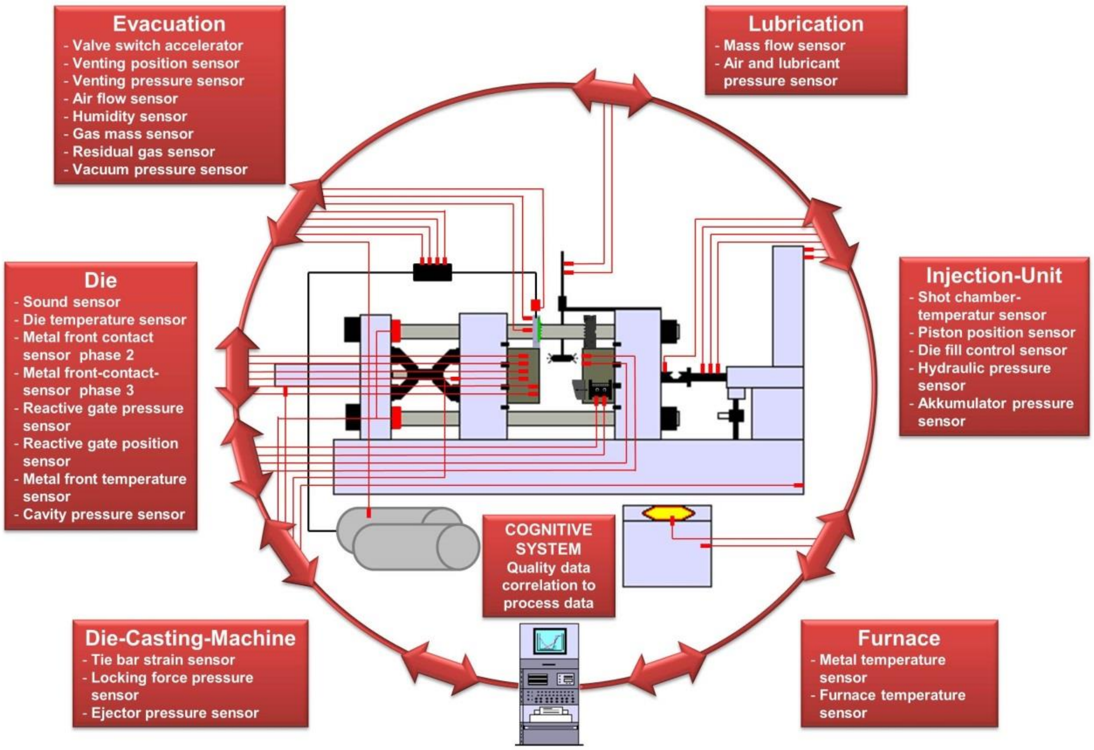

Figure 3: Innovative sensor network and cognitive system

EXPERIMENTAL CASTING GEOMETRY

To produce casting defects intentional a special casting geometry was designed in the foundry laboratory of Aalen University of Applied Sciences (Figure 4). The casting has two areas with a thickness of 2 mm, which can be used to analyze the mechanical properties of the parts with the help of bending tests. At the top left of the casting geometry there is a stepped wedge that has a final thickness of 1 mm. The thin walled area offers the possibility to analyze cold shuts. The whole casting was designed in the shape of a horseshoe to measure the distortion of the part between the two arms like marked with the black arrow in Figure 4. To provoke turbulences and to entrap air six round cores with different diameters were placed in the arms of the horseshoe. The cast part also shows shrinkage porosity in the three thick-walled dome areas. One is placed close to and one far away from the gating system to see a difference in the feeding efficiency as a function of the distance to the gate. The dome area on the right arm of the horseshoe is equipped with a squeezer that allows to compress the melt and to minimize the shrinkage porosity. A special feature of the die is the movable gating system. An actuator in the gating section can be moved with a hydraulic cylinder to increase or decrease the cross-section of the gate. A bigger cross-section of the gate allows a better feeding condition. With a smaller gate thickness the speed of the melt during filling in the gate area is higher and a better surface of the cast part will be expected.

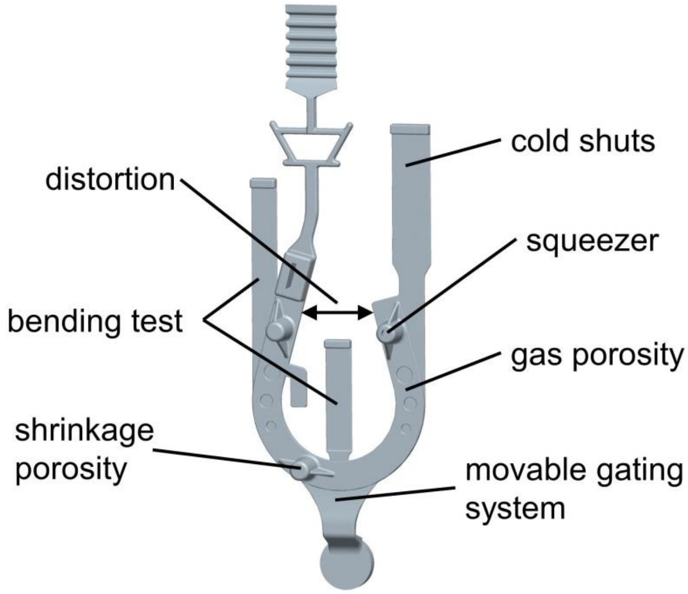

Figure 4: special casting geometry to produce defects

To validate the final design of the cast part a filling and a solidification simulation was done with MAGMA[5]. Figure 5 shows the comparison between a real cast part and the simulation results. The simulation result shows the temperature distribution at the end of the filling phase. The blue areas mark very cold regions where cold shuts are expected. The real casting confirms the simulation with cold shuts and incomplete filling.

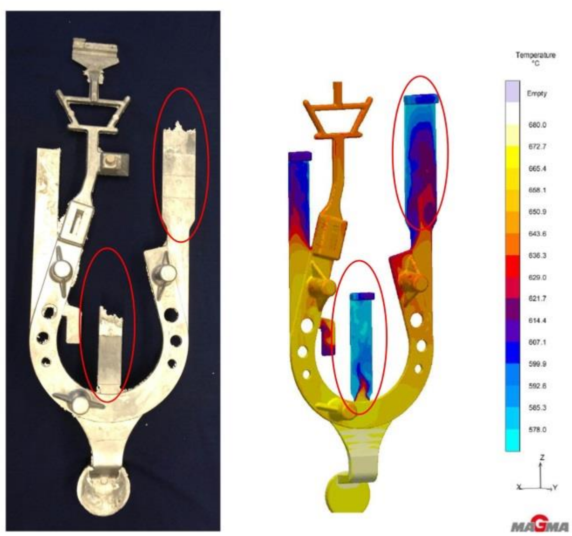

Figure 5: Comparison of real cast part and simulation results regarding cold shuts [2]

PROCESS MONITORING WITH SENSOR NETWORK

The training of the cognitive model is the initial step for the prediction of the casting defects. Basis for this is the availability of process and quality data. The data are acquired during a design of experiments (DoE) varying the most important process parameters like the piston speed in the first and second phase, the switching point, the intensification pressure, the spraying time, the melt and die temperature etc. In contrast to the serial production the process parameters are not only controlled, but also stored for each cast part. Every casting has its identification number to relate the parts quality to the process data. The traceability can also be ensured with a RFID transponder that is inserted in the die and surrounded by aluminum after the shot. In addition to the process parameters many sensors that are monitoring the injection process are placed at the casting

unit, in the die and the vacuum unit. The positions of the sensors in the die are shown in Figure 6. The sensors in the die are measuring the conditions directly at the surface of the die, which means that they are in contact to the aluminum alloy. The metal front contact sensors provide a signal when the melt touches the sensors. With a metal front contact sensor in the gate and in the area of the last filling the position of the switching point and the rising moment of the intensification pressure can be supervised. The metal front temperature sensors measure the temperature on the surface of the die during the injection process. This indicates the temperature distribution in the die and also the temperature development during the injection. Additionally to the sensors in the die two thermographic cameras are installed on the machine plates to trace the die temperature before and after spraying. The cavity pressure sensors are measuring the pressure that is applied on the melt during the filling of the cavity and during the intensification phase. One pressure sensor was especially placed in the squeezed region of the part. A new sensor that records the sound in the cavity during the filling phase was placed in the movable die. To measure the vibrations of the piston during the first and second phase an acceleration sensor was placed at the piston rod. This signal can be used to detect an irregular piston motion during the first phase and it provides an acceleration profile during the filling phase. The full potential of this sensor is not discovered and exploited until now. The so-called Multi-airpipe-sensor-system is integrated in the vacuum channel. The system consists of four different sensors that analyze the evacuated air concerning humidity, residual gas composition, vacuum pressure and air mass.
The sensor signals are acquired with a resolution of 1 kHz. The signals are displayed like the conventional shot curve with piston stroke, piston speed and machine pressure in a diagram with the time on the x-axis. Figure 6 gives an overview of all acquired sensor data. The used sensors were developed by the project partner electronics GmbH, Neuhausen, Germany.

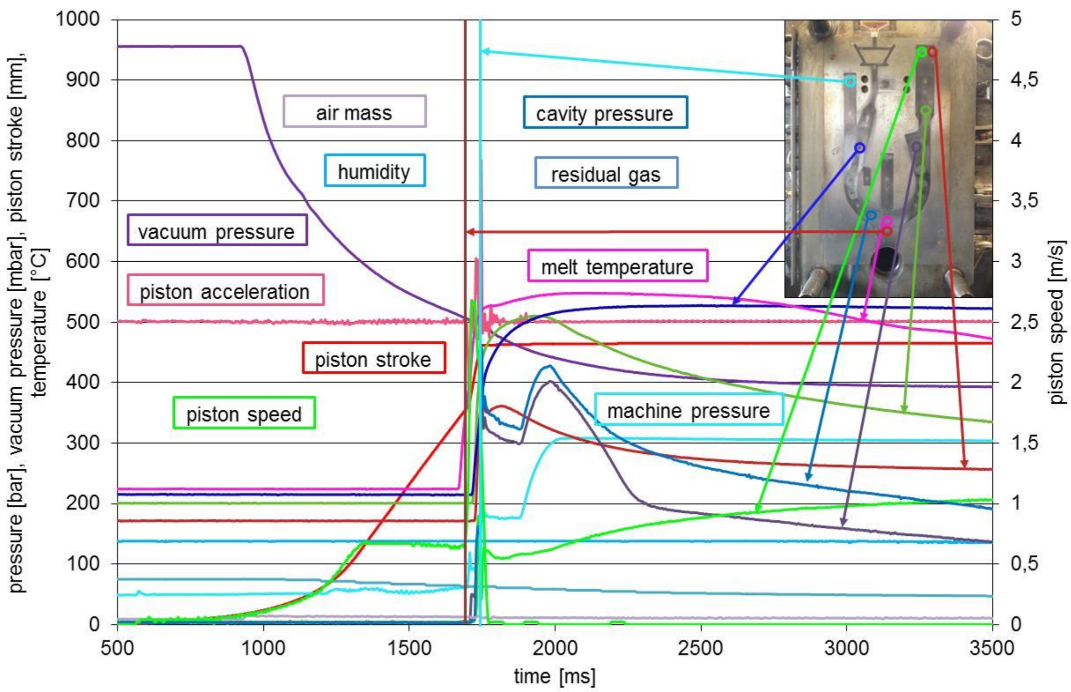

Figure 6: shot curve with additional sensor signals

QUALITY INVESTIGATIONS

To analyze the same criteria of all castings a quality control procedure was defined together with the University of Padua. First of all the whole cast part was evaluated by a visual inspection. The part was divided in seven areas. The areas with visible casting defects like cold shuts, incomplete filling or flow lines were rated with a value of four. Parts without visible external defects were rated with a value of one. Following the density of the whole cast part was measured by the Archimedean principle to quantify the amount of porosity inside the casting. The next step on the quality control procedure is the distortion measurement between the two arms of the casting. After the investigation of the part in its entirety the part was cut in 13 specimens.
Specimens 1-3 are the dome areas that were designed to have shrinkage porosity. These areas were also analyzed with x-ray and computer tomography to make the porosity visible. Figure 7 shows the average densities of the dome areas. Dome 1 near the gate has the highest density. Dome 2 and 3 are placed on the arms of the horseshoe part far away of the gate what leads to a worse feeding efficiency. The density of dome 3 is improved by a squeezer.

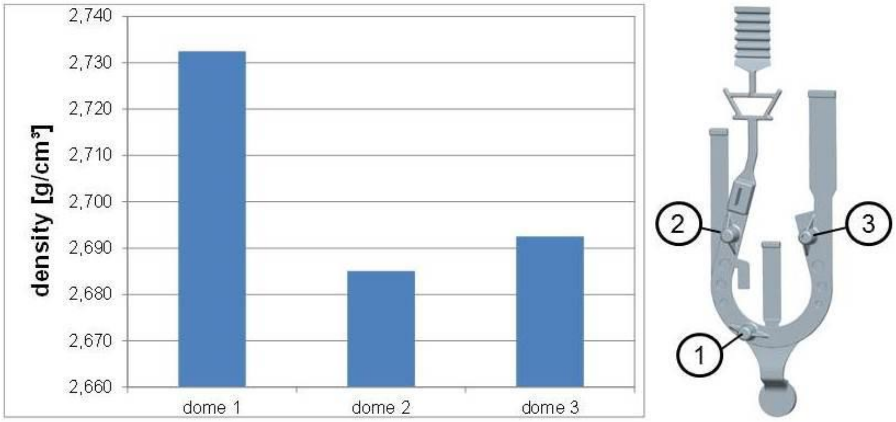

Figure 7: Comparison of the density of dome areas

To analyze the mechanical properties of the part the thin walled specimens marked in Figure 4 are used for a bending test.

RESULTS

CAVITY PRESSURE SENSOR

The cavity pressure sensor has been developed to measure the pressure that the metal applies in a precise position of the die in which the sensor is placed. This sensor allows to measure pressure of up to 2000 bar during the whole filling and solidification process. It is a membraneless pressure sensor based on quartz technology. The sensor can be used to control the reliability of the pressure transmission through the molten metal. It is important to consider that the sensor is able to provide a linear signal only for the first 5 seconds. Then the provided signal tends to drift away, the measurement is not confidential anymore. At each new cycle the new zero point is corrected and a new correct measurement is achieved. [3]

A comparison of the different cavity pressure signals is shown in Figure 8. Three pressure sensors are positioned in different regions of the die (left in Figure 8). Pressure sensor P1 is at the top of the casting in the overflow of the cold shut specimen. The pressure sensors P2 is placed at the shrinkage specimen ‘area P2’and pressure sensor P3 is placed at the shrinkage specimen ‘area P3’ close to the gate. Two different casting conditions are shown in the diagram. One part was casted with 140 bar machine pressure (third phase deselected) and the other part was casted with 320 bar machine pressure. To differentiate between the shots the curves with low intensification pressure are colored in shades of green and the curves with a high intensification are colored in shades of orange. The machine pressure curves are colored in blue like it is standard in the electronics monitoring software. The highest metal pressure is detected by the cavity pressure sensor P3 during the shot with high intensification pressure (orange curve, Figure 8). The pressure declines after a short peak at the end of the filling phase. When the intensification pressure is increased the pressure signal P3 raises again to a very high value what stands for a good intensification. The pressure sensor P2 shows the similar behavior but decreases in a shorter time due to the higher distance to the gate. The sensor signal P1 (yellow curve) shows a significant lower level than P2 and P3 because it is placed in a thin-walled area and the solidification process is finished in a very short time before the intensification pressure starts. The density diagram on the top left in Figure 8 shows as expected that the intensified part has a higher density than the part without intensification pressure. The density of the ‘area P2’ and ‘area P3’ is lower than the density of the whole part because they were designed especially to show shrinkage porosities. The ‘area P3’ has a higher density because it is close to the gating section where the pressure affects the specimen longer. With the low intensification pressure the pressure curve of sensor P3 (light green curve, Figure 8) shows nearly the same trend before the intensification starts depicted in the orange P3 curve. The green curves of P2 and P3 are falling after the end of the filling because the low pressure has no effect on the sensor regions. The curves of the cavity pressure sensors are monitoring the pressure in different regions of the casting. They provide information about the feeding efficiency and are helping to predict the density especially in thick areas of a cast part.

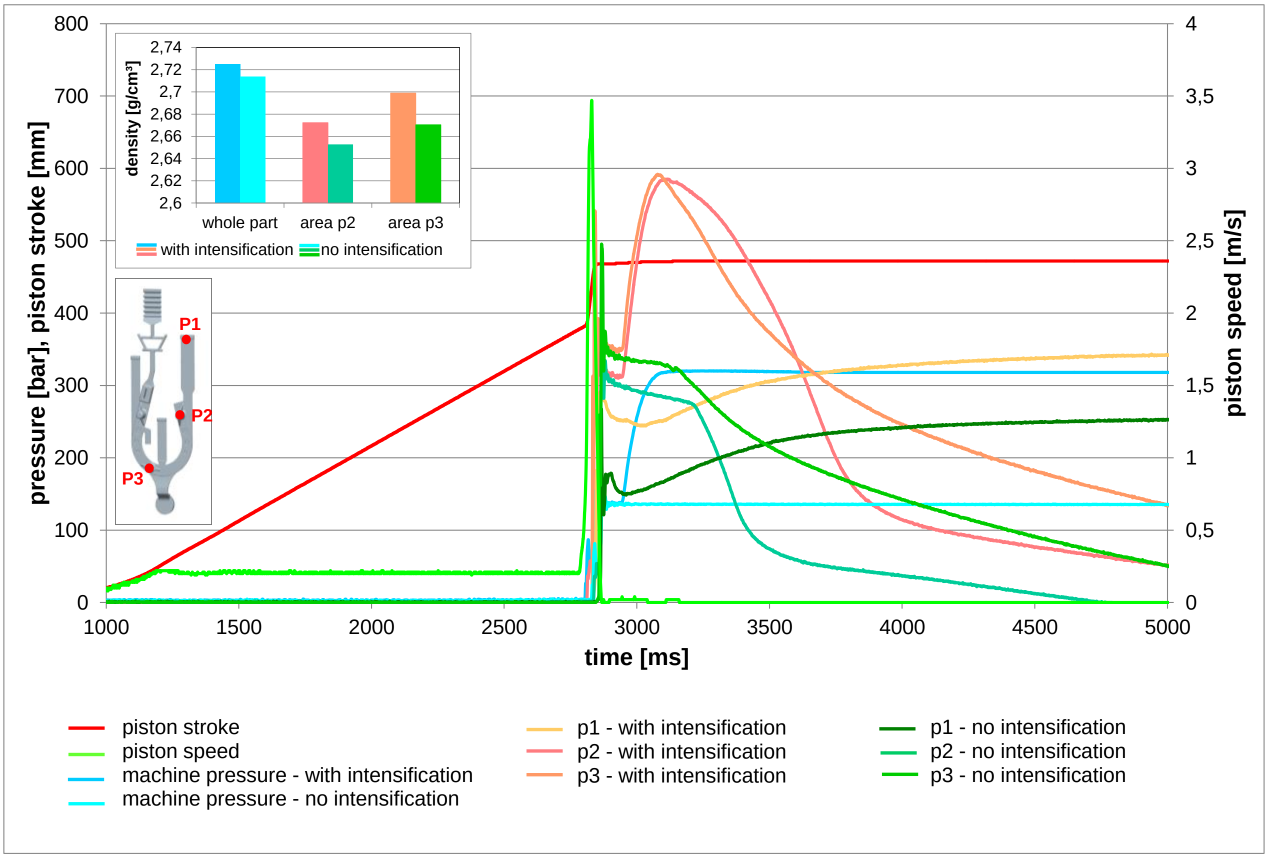

Figure 8: Shot curve with cavity pressure sensor signal with intensification pressure (orange color of sensor signals) and without intensification pressure (green color of sensor signals)

AIR MASS SENSOR

The air mass sensor that was developed by electronics GmbH to measure the mass flow during air extraction carried out from a venturi vacuum system in order to gather information on air extraction effectiveness. Moreover this sensor can be used to detect a failure in the vacuum system. [3] The Multi-airpipe sensor-system is connected to the vacuum channel. Figure 9 shows the sensor system attached on the machine plate of the 750 t cold chamber machine of the foundry laboratory in Aalen.

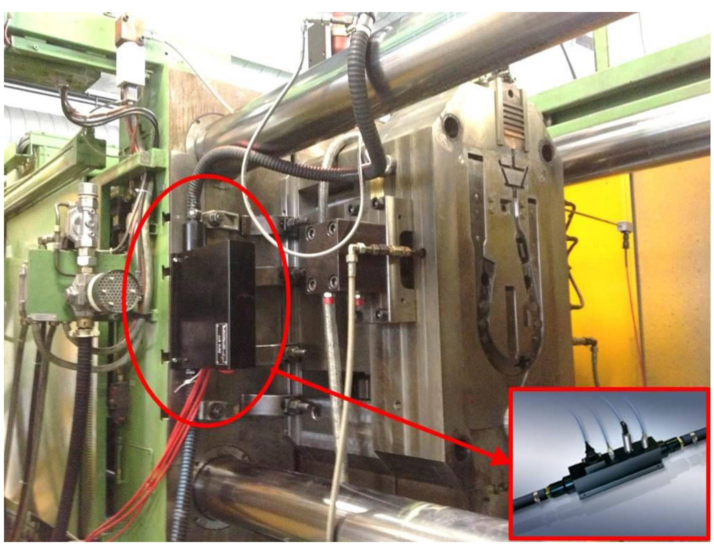

Figure 9: Multi-airpipe-sensor-system assembled on the 750 t cold chamber machine of the foundry laboratory in Aalen [4]

The air mass sensor has to be used in combination with a vacuum system. To the shot curve in Figure 10 the signal of the vacuum sensor (blue) and of the air mass sensor (grey) was added. Figure 10 shows a regular shot. The air mass signal is rising with the starting of the vacuum when the filling hole of the shot sleeve is passed by the piston. After the injection when the chill vent is blocked by the metal the signal falls to the starting value zero.

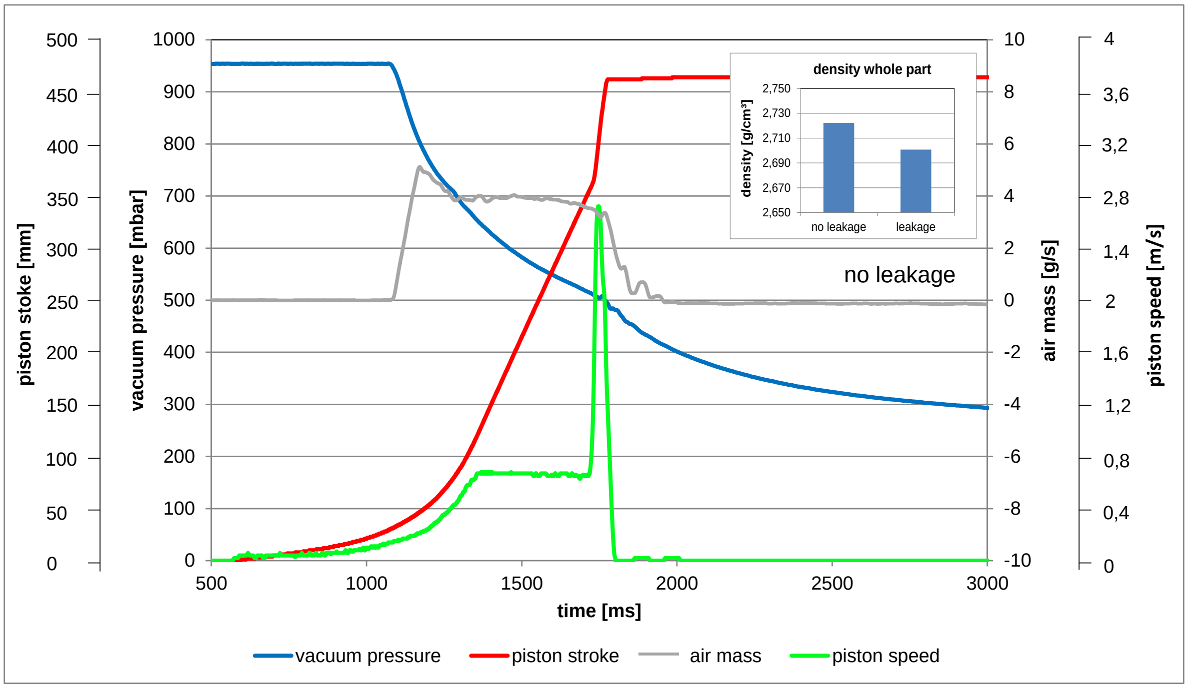

Figure 10: Shot curve with vacuum and air mass signal showing no leakage in the vacuum channel

Figure 11 shows the sensor signals acquired during a casting cycle with the same process parameters. The air mass signal is rising with the starting of the vacuum as in Figure 10. After the injection the curve does not fall to zero like expected. The signal reaches a final value of 3 g/s. This means that the air is still flowing despite the chill vent is blocked by aluminum. The reason for the air flow is a leakage in the vacuum channel that can be detected by the air mass sensor signal.

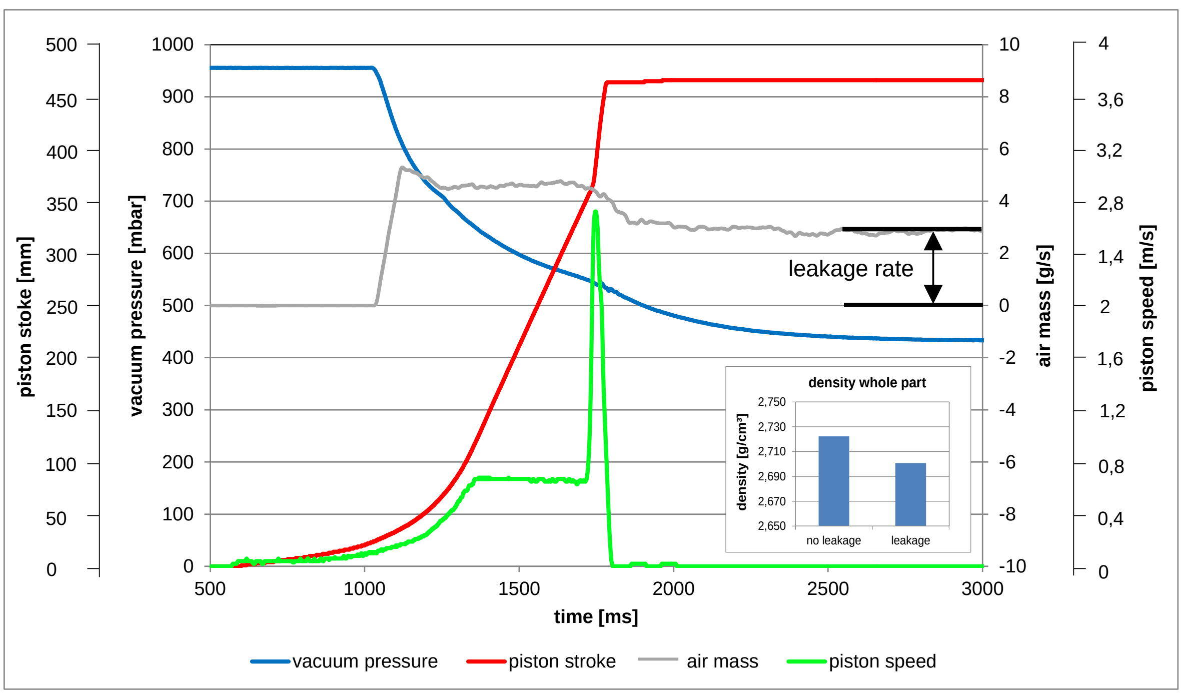

Figure 11: Shot curve with vacuum and air mass signal showing a leakage in the vacuum channel

On a closer inspection of the vacuum signal a degradation of the vacuum during the injection of 50 mbar can be detected. In the small diagram on the bottom right in Figure 11 the density of the cast parts produced during the cycle without leakage and with leakage is compared. The air mass sensor allows measuring the amount of air that is evacuated and detects leakages in the vacuum channel. It helps to predict the density of a cast part with regard to entrapped air due to poor evacuation.

HUMIDITY SENSOR

The humidity sensor measures the percentage of humidity in the air flow coming out from the die during the evacuation process. This sensor exploits a capacitor to measure the amount of humidity during air extraction. This measure uses the capacity variation of the capacitor cause of humidity variations in the outgoing air flow. [3] The sensor is also included in the Multi-airpipe-system shown in Figure 9. To test the sensor function the spraying program was varied. Figure 12 shows the humidity sensor signals after a long and a short spraying cycle. Before the acquisition of the blue curve the die was sprayed very long with a lower moving velocity of the spray head. The yellow curve was acquired after a minimal spray cycle time. The comparison between the signals confirms that after a long spraying cycle more humidity is remaining in the die. The vacuum helps to decrease the remaining humidity in the die. With the sensor an improvement of the spraying cycle with a minimization of the remaining humidity in the die can be reached.

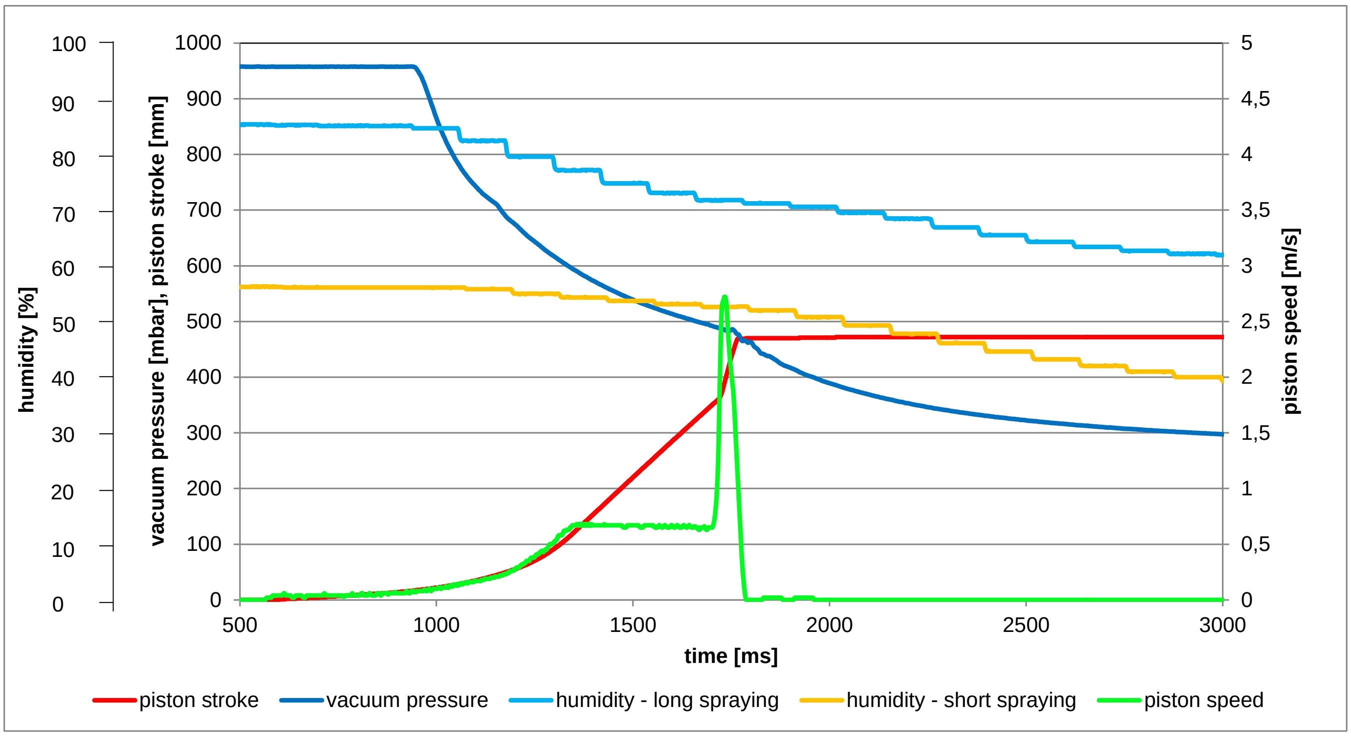

Figure 12: Shot curve with vacuum and humidity sensor signal showing measured after a long (blue) and a short (yellow) spraying cycle

CORRELATION OF SENSOR DATA

For the correlation analysis of the data the most significant points of the shot curve were extracted and summarized in one common table. The data in the table can be divided in ‘sensor measurements’, ‘process parameters’ and ‘quality values’. Examples for the most important points for the sensor measurements are the maximum values of the temperature signals at the die surface, the maximum cavity pressure or the integral of the air mass curve. Examples for the process parameters are the piston speed in the first phase v_1 , the piston speed in the second phase v_2 and the intensification pressure p_n. The quality indexes are described in the chapter above.

The table was used to generate a correlation matrix to see the dependencies of the parameters, the sensor data and the quality results. A little extract of the complete correlation matrix that has more than fifty columns is presented in Table 1. A good correlation is indicated by a correlation coefficient that is 1 or -1. If the correlation coefficient is 0 there is no correlation.

Table 1: Examples for correlations between process parameters, sensor data and quality results

	v_1	v_2 max.	p_n max.	T1	p3	p1	p2	density	density 1	density 2	density 3	Flash	A
v_1	1,00												
v_2 max.	-0,08	1,00											
p_n max.	0,00	0,16	1,00										
T1	0,04	0,77	0,29	1,00									
p3	0,10	0,27	0,91	0,45	1,00								
p1	-0,08	0,80	0,09	0,71	0,24	1,00							
p2	0,22	0,35	0,82	0,54	0,95	0,34	1,00						
density	-0,19	-0,14	0,62	0,07	0,51	0,05	0,41	1,00					
density 1	-0,05	-0,02	0,71	0,18	0,60	0,10	0,56	0,78	1,00				
density 2	-0,20	0,20	0,61	0,24	0,61	0,23	0,61	0,50	0,54	1,00			
density 3	-0,25	-0,01	0,70	0,08	0,65	0,07	0,58	0,68	0,51	0,53	1,00		
Flash	-0,22	0,77	0,04	0,65	0,12	0,73	0,19	0,05	0,10	0,21	0,03	1,00	
A	0,20	-0,58	0,10	-0,50	-0,05	-0,56	-0,14	0,19	0,11	-0,08	0,09	-0,56	1,00

The DoE was also evaluated with the statistic software Design-Expert®. This software allows illustrating the interactions in a graphic 3D diagram. The example in Figure 13 shows the dependency between the quality index of the cold shut specimen in area 'A', the maximum temperature signal of metal front temperature sensor T1 and the piston speed in the second phase v_2 that is also highlighted in green color in the correlation matrix. In the pictures of the real castings left in Figure 13 the quality of the parts is illustrated. If the velocity in the second phase is too low and the sensor T1 measures a too low temperature in area 'A' the part shows cold shuts and incomplete filling. With a high piston speed and a high temperature in region 'A' a good quality of the specimen is expected.

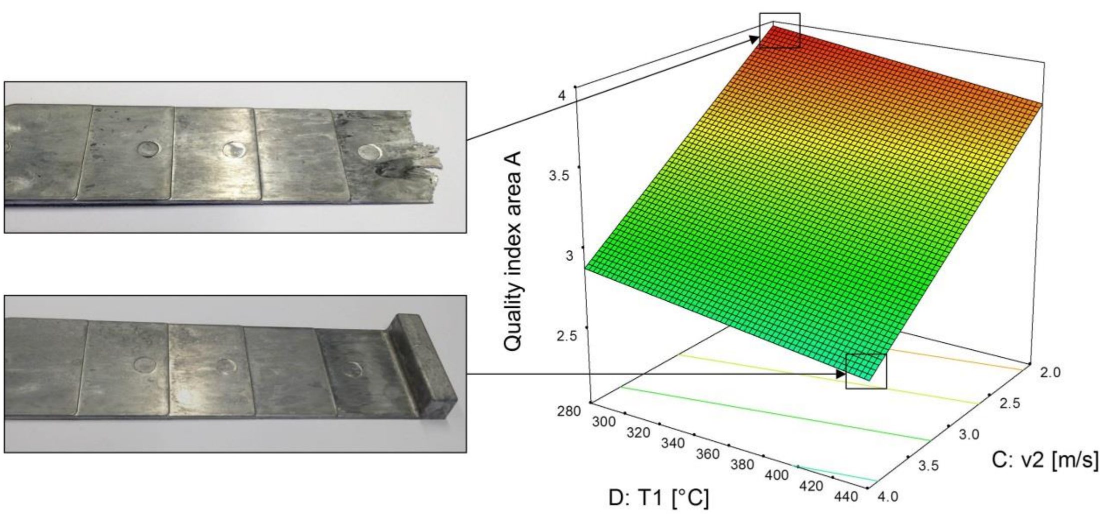

Figure 13: Interrelation between the quality index in area 'A', piston speed in the 2nd phase and temperature sensor signal T1

Summarizing the data as described in the previous section leads to a loss of data. For each sensor 10000 values per shot are stored in the database. For the correlation only a few significant values were used. To minimize the loss of information it is important to deal with a bigger amount of data. To reach an exacter model other evaluation methods using data mining algorithms are in progress.

Correlations like given in the example help to train the cognitive model and to predict the quality of the cast parts without quality investigation. This is a great opportunity to decrease the effort of quality controls and to reduce the scrap rates. The software of the cognitive system will be developed by the Italian project partner Enginsoft S.p.A.

A further aim of the project is not only the prediction of the process variables but also the reaction on the prediction of the cognitive model. The connection of all devices via OPC-UA allows not only the acquisition of data but also to send input variables to the control of the HPDC machine and the peripheral devices. This means that the system will be able to regulate the process by adjusting certain quality influencing parameters within defined thresholds to optimize the process.

PROJECT INFORMATION

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