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Laser Supported Optical Control of High Pressure Aluminium Cast Products

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We present a new method for surface quality control of aluminium high pressure cast products. By this method it is aimed to improve efficiently the existing practice of castings being only visually checked for surface defects such as laminations, non-fills and cold shots. The method is based on laser triangulation principle. The measured cloud of points is analysed using software designed specifically for automatic detection of surface defects. The paper describes a measurement system, measuring procedure focussed on the detection of surface defects and the comparison of the results with a visual inspection.

Keywords: aluminium pressure casting, surface quality control, laser 3D-measurement, optical control

0 INTRODUCTION

Today, the automotive industry requires complete traceability of each part used. This means that data on the exact date of production, production conditions and quality have to be provided for each part made [1] and [2]. The quality of a die-casting is determined by checking the precast final dimensions, casting quality, in particular with regard to porosity and surface defects, and the chemical composition of materials. The existing mechanical methods used for the purpose are the following: mechanical standard measurements, go-no-go gauges and 3D coordinate measuring machines (precast final dimensions), X-ray (porosity) and emission spectrometers (chemical composition of materials) [3] and [4]. In high pressure casting of aluminium, surface defects are relatively common. Normally, these occur on thin casting walls as laminations, non-fills and cold shots [5]. Surface defects may result from incorrect settings of the high pressure die-casting process, and the wear and cracks on die-casting tools. The traditional method of inspecting the quality of a die-casting is that a machine operator visually checks the quality of the product. The method depends on the skill of the operator and is as such highly subjective.

The paper proposes a new method for inspecting the surface quality of die castings, which is based on an optical measurement system and appropriate software to allow fast accurate measurement analyses. The new method shall be demonstrated on a cast product built for automobiles as an electronic component support (Fig. 1).

The support casting is made from aluminium alloy $AlSi_{12}$, and the casting dimensions are 190 x 150 x 10 mm with a minimum mean wall thickness of 1.5 mm. The inner surface of the casting has to be smooth to allow adhesion of an

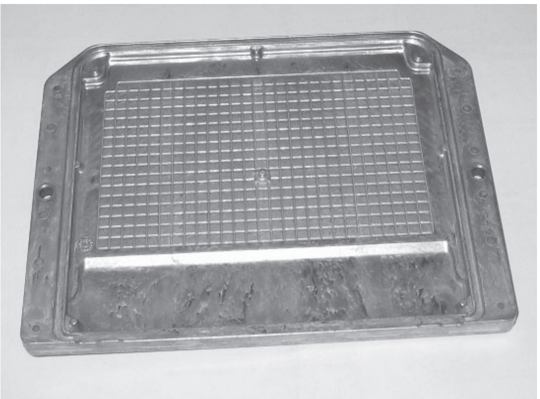

Fig. 1. *Electronic component support made by aluminium high pressure die-casting*

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electronic circuit board. Surface defects (e.g. small humps, slivers) protruding from the surface of the casting may cause short-circuit in the attached electronic circuit board and lead to the assembled set being rejected. According to the specifications, the maximum curvature of a casting shall not exceed 0.4 mm and the size of a surface defect shall not exceed 0.08 mm. Currently, three dimension prototypes are used in assessing casting quality: height, width and flatness. Assessment of surface defects, however, is entirely dependent on the visual capabilities of the assessor. On account of being highly subjective, this method is being replaced with a laser based measurement system which both ensures precise measurements of the casting surface quality and improves quality traceability.

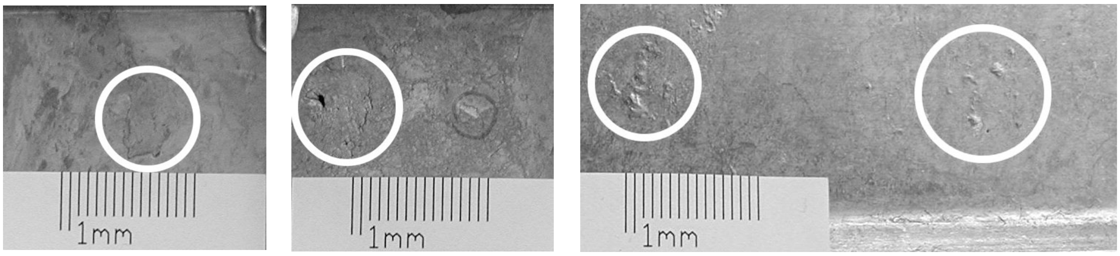
High pressure die-casting is a modern casting technique for mass production of complex components characterised by thin walls and good mechanical characteristics. The mentioned die-casting is made on a horizontal pressure die-casting machine with a closing force of 4000 kN with a cold chamber [5]. In pressure die-casting, temperature plays a very important role. It affects the time of solidifying, the quality of molten metal structure and the lifetime of pressure die-casting tools. Thermal cracks, which may occur on the surface of the main tool inserts, reduce the lifetime of the tools. These cracks are caused by high temperature differences (up to 500 °C) between the aggressive aluminium alloy and the cavity surface, alloy velocity at the gate area and the shape of the gate area.

The most common surface-visible die-casting defects include cold shots (Fig. 2-a), non-fills (Fig. 2-b) and laminations (Fig. 2-c, d). Cold shots are normally caused by high surface tension between the alloy and the inserts as well as from long filling time. In such a case, the alloy cools down and starts to solidify before the entire cavity has been fulfilled. Often the same reason also accounts for the occurrence of non-fills. Laminations are most commonly observed in die castings after sand blasting. This surface defect occurs when the top layer peels from the rest of the casting. It is caused by high velocity of the alloy or by a preheated surface of the cavity.

The most common defects in the die-casting of electronic component supports occur on the thinnest walls of the casting as cold shots or non-fills (cold die-casting tools). Laminations as another type of surface defect may occur as a result of preheated tools and is seen as humps or blisters appearing on the surface.

1 LASER SUPPORTED OPTICAL MEASUREMENT SYSTEM

The measuring system (Fig. 3) consists of an optical measuring instrument using the laser triangulation principle [6] and [7] and a movable table that changes the position of the measured product relative to the instrument. The casting contains precast blind holes which lean against three support balls when mounted onto the movable table, thereby ensuring repeatable mounting of the casting onto the table. The system set-up is made up of a laser projector which illuminates the casting with a thin laser plane, and a CDD camera (Basler 101f). At the point where the laser plane hits the casting, a thin bright line can be seen (intersection curve). The image is captured by the camera positioned at an angle with respect to the direction of illumination (laser triangulation). The process points to the 3D profile of the intersection curve. The image is then translated into a personal computer file, and the intersection curve is extracted and its maximum and minimum values are identified [8] and [9]. The result of one measurement is a profile representing a cross-



(a) (b) (c) (d)

Fig. 2. *A cold shot (a), non-fills (b), laminations (c, d)*

section of the light plane and the illuminated surface $(X,Y)_i$, where X and Y are the coordinates of a particular point, X along the intersection curve and Y perpendicular to the surface; index i runs from 1 to n, where n is the number of points within a profile (e.g. 1300). By changing the position of the table or the measured casting in several steps, new profiles are acquired and joined into a 3D surface image referred to as the cloud of points $(X,Y,Z)_{i,j}$. The Z-coordinate is the position of a particular profile in the direction of table positioning and index j runs from 1 to m (number of profiles). On account of the measurement technique applied, the cloud of points has a matrix structure {n, m}, which simplifies further operations for modelling and presentation of the measured surface. The measurement system (Fig. 4) incorporates built-in optics which magnifies the image 4.5 times more in the direction perpendicular to the casting surface than in the direction along the intersection curve. The optics is assembled from a spherical lens and two cylindrical lenses making up the cylindrical Keplerian telescope [10]. The optical system was set up to the measuring range of 200 x 35 mm (width x height) and a mean resolution of 0.15 mm along the intersection curve and 0.025 mm perpendicular to the measured surface. Measurement uncertainty in a particular measured point is 0.02 mm (σ). The existing system can capture 15 profiles per second, the speed being determined by the image size (1.3 MB) and bandwidth of the 1394 output (alias fire-wire). The measurement system has been set up to capture 750 profiles in 50 seconds. Further increasing of the speed of the system is only possible through development of a new camera supported by modern programmable logic, according to which the image will be processed by the camera and only the profile will be translated along the fire-wire.

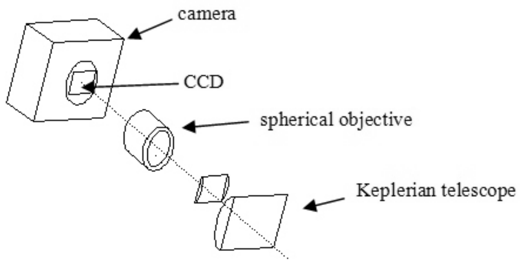


Fig. 4. *Keplerian cylindrical telescope increases measurement resolution in the direction perpendicular to the die-casting surface.*

2 DATA PROCESSING

In developing software for automated detection of surface defects, special emphasis was placed on the speed of action, since a measurement (an average measurement consists of 2×10^6 points) is to be made and processed within the casting cycle (approx. 60 seconds). The flowchart for detection of surface defects is presented in Figure 5.

Detection of die-casting defects is only performed in several different non-overlapping regions of interest (ROI). The number, shape and position of the studied regions of interest are

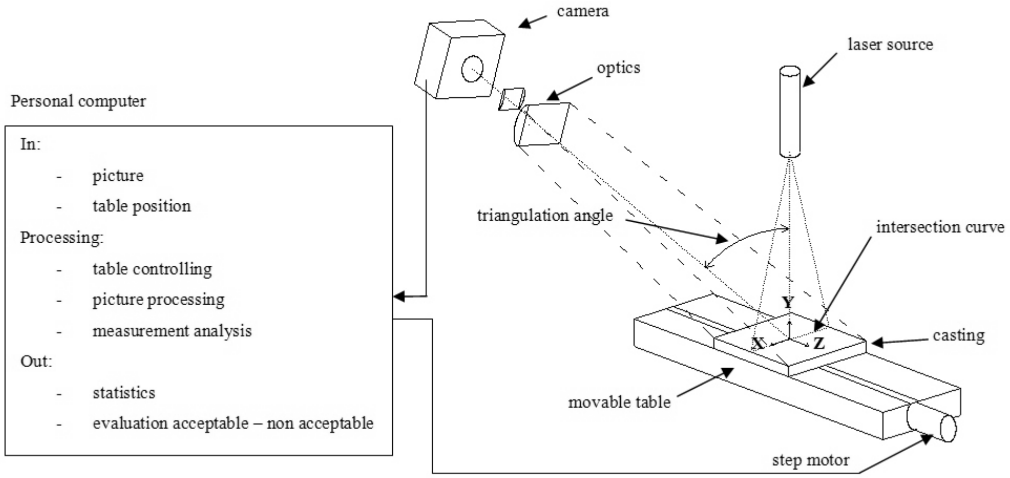


Fig. 3. *A schematic of the new method for inspecting the die-casting surface quality*

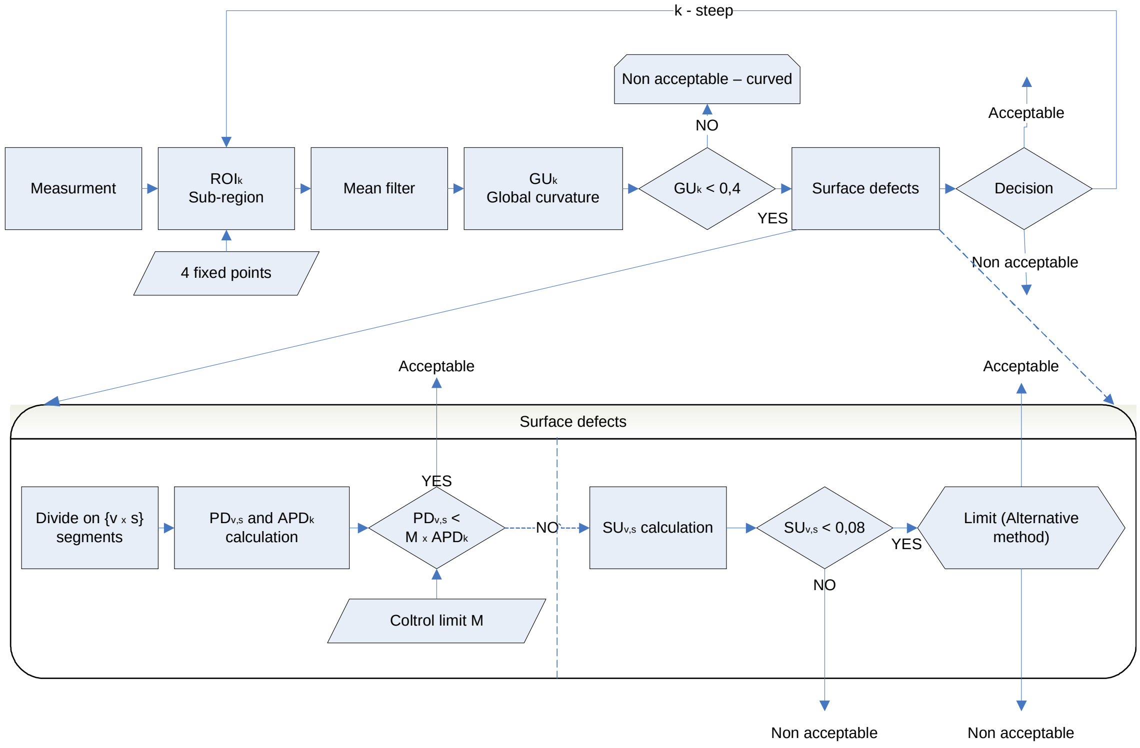


Fig. 5. *The flowchart for detection of surface defects*

selected with regard to the functionality or purpose of various casting surfaces. To this aim, the cloud of points is first divided into several sub-regions $ROI_k = \{(X, Y, Z)_{i,j};\ i,j \in k\}$, where $k = 0, 1,..., K$ (K is the number of all ROI). Figure 6 shows OI_1, for which the process of detecting casting defects will be demonstrated in the continuation of the paper. Each ROI is defined with a boundary consisting of four fixed points, positioned into a rectangular pattern. Fixed points are used to ensure that the casting measured maintains the same position at all times, which significantly speeds up data processing as it enables us to avoid the invariant analysis.

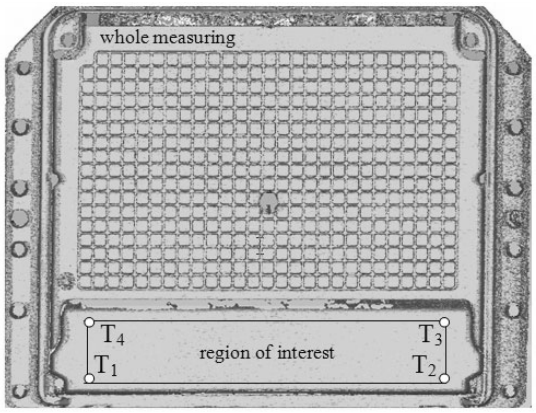


Fig. 6. *A particular region of interest (ROI_k) is defined with four fixed points.*

In the first processing step, the region of interest is filtered.

A mean filter [11] is used to clean up isolated points protruding from the die-casting surface, which have probably been caused by second reflection of the transmitted laser beam on the die-casting. The first important parameter used in assessing the die-casting surface quality is global curvature (GU) of a particular ROI_k. In calculating this parameter, the plane (R_k) is first adjusted to the ROI_k, using the method of least squares [11]. In the next processing step, perpendicular distances D_k are calculated from the points of ROI_k to the plane R_k (Fig. 7). Global curvature GU_k is then determined as a distance between the maximum and the minimum of the D_k. According to the specifications, GU_k of a particular ROI_k may not exceed 0.4 mm.

In the second processing step, detection of surface defects is performed. To this purpose, ROI_k is sub-divided into small segments (Fig. 8), the surface area of which corresponds in size to a

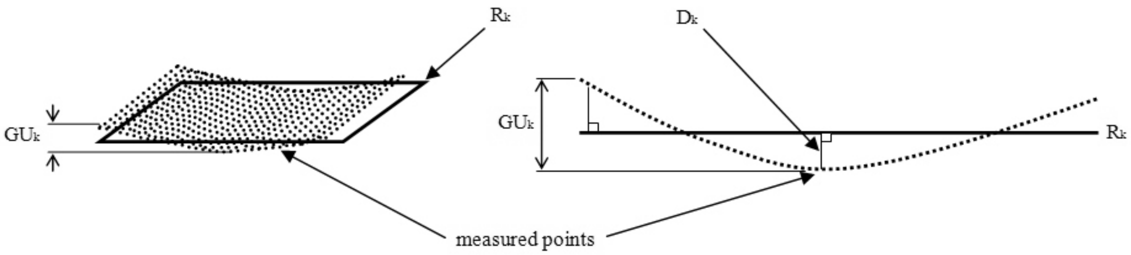


Fig. 7. *Definition of global curvature (GU)*

typical casting defect (e.g. 5 x 5 mm). The underlying idea of segmentation is to perform narrow-band filtering on ROI_k surface to detect geometrical shapes the size of the segment. Figure 8 shows a sample segmentation of ROI_k.

In detecting surface defects, certain parameters are first calculated for each segment and then a statistical analysis of the values obtained is carried out for the entire ROI_k. Calculation of parameters by segment is similar to the calculation of global curvature GU. On every segment $S_{k,v,s} = \{(X, Y, Z)_{i,j};\ i,j \in (k \wedge v \wedge s)\}$, ($v$ = 1, 2, .. V (number of rows) and s = 1, 2, .. S (number of columns)) a plane $R_{v,s}$ is fitted in a least-square sense, and the perpendicular distances $D_{v,s}$ of the $S_{k,v,s}$ points to the plane $R_{v,s}$ are calculated.

The first parameter to be calculated for each segment is local curvature of the matrix segment ($SU_{v,s}$) which is defined similarly as the global curvature GU_k, as a distance between the maximum and the minimum of $D_{v,s}$. Local curvature of the matrix segment $SU_{v,s}$ defines the size of a surface defect.

The second parameter describes the average deviation $PD_{v,s}$ of perpendicular distances $D_{v,s}$

$$PD_{v,s} = \frac{\sum D_{v,s}^{\ 2}}{npts_{v,s}} \quad (1),$$

where $npts_{v,s}$ is the number of points within a particular matrix segment $S_{k,v,s}$. Both parameters are then statistically analysed along the entire ROI_k.

The research has shown that defect identification through the average deviation $PD_{v,s}$ is considerably more reliable than the detection based on the local curvature of a matrix segment $SU_{v,s}$. In the light of this fact, the mean value of $PD_{v,s}$ is first calculated for all the matrix segments within a ROI_k, generating the average value APD_k, whose multiple M is set as the upper control limit for detection of surface defects. In conclusion, a surface defect is likely to be located in a segment where $PD_{v,s} > M * APD_k$. The multiple M of the upper control limit is determined experimentally; in our case M = 2. The defect found is confirmed by the parameter $SU_{v,s}$ indicating an absolute defect size. When $SU_{v,s}$ exceeds 0.08 mm (specification of surface defect size), the matrix segment {v, s} contains a surface defect, and the casting is marked as »Not acceptable«. Otherwise, the defect is on the verge of acceptance; the casting is marked as "Limit" and needs to be inspected using an alternative method (also visual inspection).

3 EXPERIMENTS

The new method is demonstrated through the shape measurement and surface quality control of a group of 32 castings, which had been visually inspected following production. The method's performance is demonstrated on two castings, focusing in both only on the first region of interest (ROI_1). The first casting E_2 successfully passed visual inspection in the production. Using the new method, the calculated global curvature is GU_1 = 0.15 mm (Fig. 9).

The process of averaging $PD_{v,s}$ generates the value APD_1 = 0.0032 mm; perception threshold for surface defects is 0.0064 mm (M = 2). The graph of perpendicular distances PD (Fig. 10) shows that

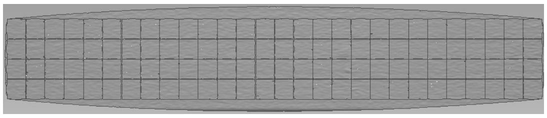


Fig. 8. *ROI_1 divided to a matrix of 28 x 4 segments whose average size is 5 x 5 mm*

Fig. 9. *Visualization of D_1 on casting E_2. (light: +0.7 mm above R_k, dark: -0.7 mm below R_k)*

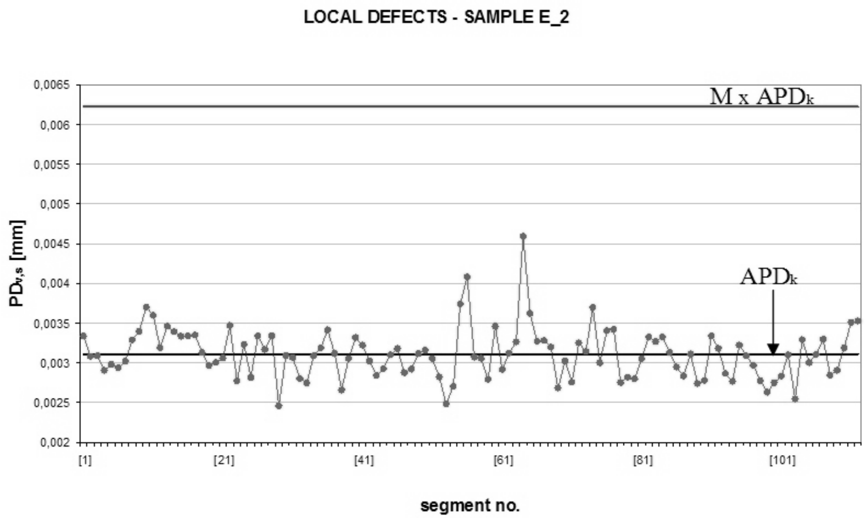


Fig. 10. *Control chart of* $PD_{v,s}$ *(segment number = (v-1)*S+s)*

all $PD_{v,s}$ are lower than 0.0064 mm indicating there are no surface defects. In cases where such results are obtained, no further analysis of the local curvature SU is performed.

The second casting E_4 is marked as conditionally acceptable in the production visual control. The region of interest ROI_1 shows signs of laminations (cf. Fig. 2 c and d). Using the new method, global curvature is calculated at GU_1 = 0.08 mm (Fig. 11), and found to be within the control limits (< 0. 4 mm). The mean of $PD_{v,s}$ values is APD_1 = 0.0038 mm; perception threshold for surface defects is 0.0074 mm (M = 2). The graph of the parameter PD (Fig. 12) indicates that PD exceeds the perception threshold in segments 46, 53 and 74, indicating occurrence of potential surface defects in these segments. In such cases, the local curvature parameter SU (Fig. 13) is analysed further. It can be observed that in the

Fig. 11. *Visualization of* D_k *on casting E_4. (light: +0.04 mm above* R_k*, dark: -0.04 mm below* R_k*)*

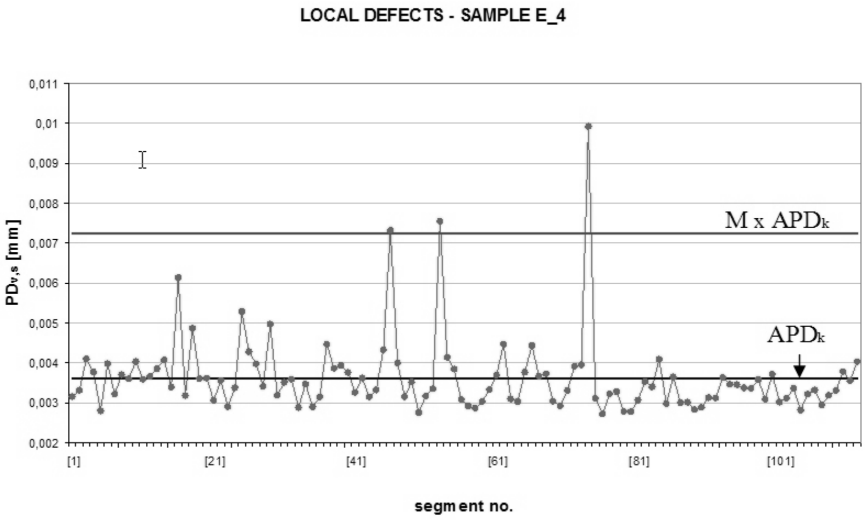


Fig. 12. *Control chart of* $PD_{v,s}$

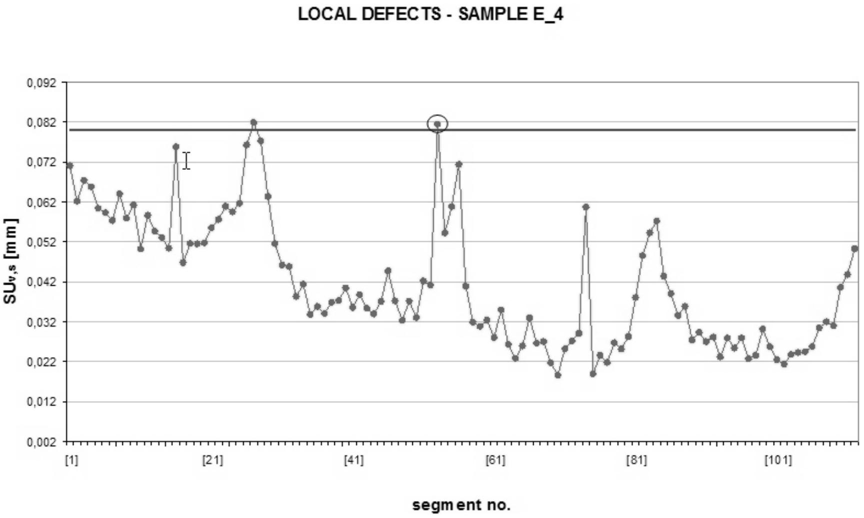


Fig. 13. *Control chart of* $SU_{v,s}$

segment 53 SU exceeds the control limit of 0.08 mm and is therefore marked as containing a surface defect. In segments 45 and 74 SU is below 0.08 mm and these segments are marked as defect limit. As the matrix segment 53 contains a surface defect, the casting is marked "not acceptable" (defective).

The same procedure is used for analysing the remaining die-castings. The results are given in Table 1. The second column presents visual inspection results. Castings containing no defects are marked "Acceptable"; conditionally acceptable castings are marked "Limit" and defective castings are marked "Not acceptable". The results of the new method are given in the third, fourth and fifth columns. The third column indicates segments with surface defects, the fourth column states global curvature and the fifth column states the decision regarding the surface quality of the casting.

A comparison into the columns Visual Inspection and Decision shows that the new method is stricter in inspecting the castings. All the castings which have been marked as defective in the production, have been recognized as such by the new method; additionally, the method yielded several castings with small defects and marked them as "limit" defects. The reason for stricter control lies in currently low control limits (M = 2 and SU = 0.08 mm). If these are increased, the strictness of quality control decreases. Stricter control causes production costs to rise as it increases reject rates and requires additional checking of conditionally acceptable die castings. The results call for an additional fine setting of control limits in the phase of introducing the new method for casting quality control into the production process.

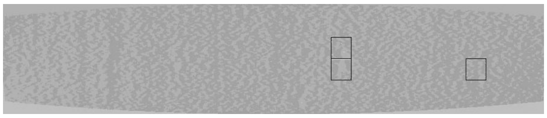


Fig. 14. *Segments with surface defects (46, 53, 74)*

4 CONCLUSIONS

The paper presents the development of a new method for control of die-casting surface quality, which is based on a 3D measurement of the die-casting shape with a laser supported optical measurement system and on analysing the 3D measured shape. In using the new method, the measured shape is sub-divided into several non-overlapping regions of interest, whose size and position are selected with respect to the casting functionality. For each of these regions, global curvature and the position and size of surface defects are calculated. Casting surface quality is assessed by checking whether the calculated values fall within the set control limits. Through this approach, casting surface quality is assigned numerical values and is time-independent, unlike the currently used visual inspection where a worker decides on the

Table 1. *Comparison of the classic (visual) and a new method for quality control*

		New method		
Casting	Visual inspection	Segment with defects	Global curvature [mm]	Decision
E_1	Acceptable	15	0.14	Limit
E_2	Acceptable		0.15	Acceptable
E_3	Acceptable		0.11	Acceptable
E_4	Limit	46,53,74	0.08	Non acceptable
E_5	Non acceptable	19,48,49	0.15	Non acceptable
U_1	Non acceptable	74	0.16	Non acceptable
U_2	Acceptable		0.11	Acceptable
U_3	Acceptable	27	0.17	Limit
U_4	Non acceptable	46,54,67,74 etc.	0.22	Non acceptable
U_5	Non acceptable	2,8,9,10,12 etc.	0.33	Non acceptable
U_6	Acceptable	75	0.14	Limit
U_7	Acceptable		0.15	Acceptable
U_8	Non acceptable	58	0.20	Non acceptable
U_9	Non acceptable	10, 28, 53, 54 etc.	0.33	Non acceptable
U_12	Acceptable		0.11	Acceptable
U_13	Acceptable	8	0.10	Limit
U_14	Acceptable		0.10	Acceptable
A_1	Acceptable		0.11	Acceptable
A_2	Acceptable		0.11	Acceptable
A_3	Acceptable		0.11	Acceptable
A_4	Acceptable		0.12	Acceptable
A_5	Limit	76	0.11	Limit
A_6	Acceptable		0.10	Acceptable
A_7	Acceptable		0.12	Acceptable
A_8	Acceptable		0.09	Acceptable
A_9	Acceptable		0.10	Acceptable
A_10	Acceptable		0.10	Acceptable
A_11	Acceptable		0.12	Acceptable
A_12	Acceptable		0.08	Acceptable
A_13	Acceptable		0.11	Acceptable
A_14	Acceptable	81, 82	0.10	Non acceptable
A_15	Acceptable	37, 65	0.14	Non acceptable

acceptability of a cast product relative to his/her subjective experience.

Tests have proven that the measurement system achieves sufficiently high measurement precision and accuracy (0.025 ± 0.02 mm perpendicular to the casting surface) and that the current speed of measurement (15 profiles per second) is too low to accommodate introduction of the new measurement method into the production process and will therefore need to be increased. Furthermore, a comparison into the results of the quality of test castings has pointed to the need for an additional fine setting of control limits in the phase of introducing the new method for casting quality control into the production process in order to achieve the balance between technological requirements and increasing of costs on the one hand and stricter casting quality control on the other.

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