ANALYSIS OF THE CAUSES OF DISTORTION CASTINGS AFTER HEAT TREATMENT

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Abstract
The article is focused on the use of Quality Management tools to identify causes of formation deviations dimensions in cylinder head castings. Moreover, methods of production of castings made from alloy AlSi9Cu1, heat treatment of castings, as well as requirements of their quality are described. Research of the influence heat treatment parameters on the changes of castings' dimensions, with using Quality Management tools (Ishikawa diagram) is described too. In order to optimize the process for eliminate of deviations, experiment for modelling parameters of heat treatment was designed. The results processed in the Pareto diagram clearly pointed out the causes. Dimensional deviations were created during the heat treatment process. We have found the largest distortions in castings were created during rapid cooling. The article gives important information about using of research results in the production of cylinder head castings.

Keywords: cylinder head castings; Aluminium alloy; heat treatment; dimension deviations; quality management tools

1 Introduction
Production of cylinder heads (**Fig. 1**) is achieved by the gravity casting of aluminium alloys AlSi9CuI into metal moulds. During gravity casting the melt is metallurgically treated in a holding furnace which is near to the moulds. The melted material for each casting is transported in a basin and is poured by tilting the basin to allow the material to flow to the system. The melted material fills the form from the bottom up until it can be seen above the casting in the system this is a tried and true technology for mass production which is used mainly to produce of the castings from alloys with lower melting temperature, such as Al, Cu, and Mg. The advantage of this method is that during pouring we can reach high dimensional accuracy and it lowers the number of faulty castings if the pouring production process is closely followed. A disadvantage of this method is the application of structural solutions requires a number of preliminary tasks and can only be used during higher production [1, 2]. Recently, Al-Si alloys find applications in such tribological components such as clutches, cylinder liners and pistons in the automotive industry [4].Companies that make products for the automotive industry adhere to the STN P ISO/TS 16 949:2009 norm - QMS, Individual Requirement for using norm ISO 9001:2008 in an organization production of automobiles and replacement parts, which specifies strict conditions for quality production. The goal of the technical specification is to prepare a

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QMS appropriate for continuous improvement with emphasis on prevention of defects and to limit deviations and losses within the supply chain [5].

2 Material and Methods

2.1 Quality of Production

Natural pressure to produce quality castings increases requirements for measuring qualitative characteristics. It is very challenging to produce high quality with reliability. Quality evaluation consists of observing the state of the surface and the interior of castings and measuring of values of mechanical characteristics. Observing and measurement is important in all production phases, in the research - development process, in the production process (observing quality of entry materials, raw materials, quality of production technology, environment, producers, measuring devices) in the process of entry control (evaluation of surface quality, dimensions, tightness, structure and mechanical characteristics of castings). Uncovering mistakes and analysis of causes their occurrence helps to decrease a number of nonconformal castings [2, 3, 9,].

Fig. 1 Production of head cylinder castings – gravity casting

Quality of cylinder heads firstly depends on adherence to a technological discipline during production and secondly on influences during heat treatment [4]. Below are examples of some specific influences that affect the quality of castings:

- impact of quality cores - cores quality affects the functionality of the casting, which is checked at every casting with using tightness tests,
- influence of the chemical composition of the poured melted alloy - lower quality of the alloy will be seen through the presence of non-metallic inclusions, heterogeneous microstructure and the casting's characteristics,
- influence of cleanliness of the cast-iron mould - presence of dirts on the surface of the metal form is manifested by surface defaults in the casting,
- influence of parameters of heat treatment - several risk factors exist, which can influence mainly the shape and dimensions of a casting, which would threaten the quality of functional areas of the cylinder heads and dimensions of the castings. It is very important to set heat treatment parameters so that the aforementioned influences are eliminated to the lowest possible measure [3, 7, 14].

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2.2 Material Characteristic and Heat Treatment of Castings

Castings of the cylinder heads are made from AlSi9Cu1 alloy. It has under eutectic content of Si a structure consists of alpha solid solution and eutecticum (alpha+Si). Eutecticum in relatively large amounts (40-75%) gives the alloys Al-Si excellent melt flow. It also reduces their linear shrinkage and tendency to hot cracking and propensity to microporosity formation. This is for thermally stressed castings such as cylinder heads very important. The material characteristics of cylinder head are formed by heat treatment, which consists of:

- **homogenization annealing** – heating temperature depends on the chemical composition of the alloy approx. 530°C - in the solid solution effective amount of hard phases of alloy are dissolved by heating (these were excluded during solidification of the casting to the border of dendrites),
- **subsequent fast cooling** (called hardening) - cooling of casting in water, at room temperature, creates a heavy liquid (optimal conditions for precipitation hardening),
- **artificial or natural ageing – precipitation hardening** - after homogenization and hardening is achieved either by the temperature in the environment (natural ageing), or by precipitation heat treatment, which is called artificial ageing [2,14] (Temperature depends on chemical composition: interval of temperatures 165 - 220°C, for 3-6 hours).

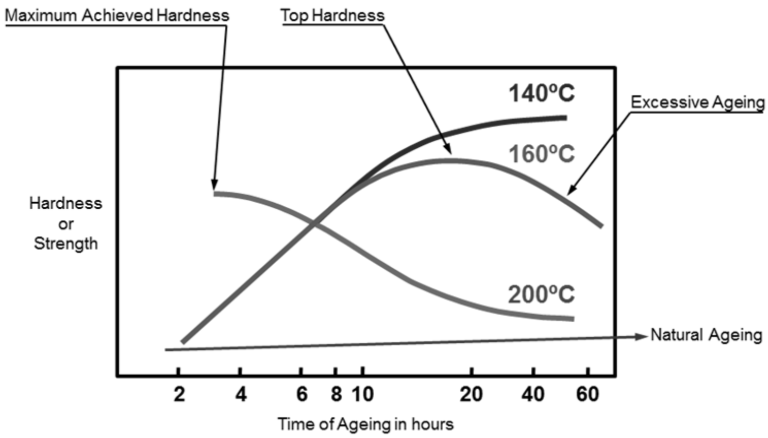

Fig. 2 Curves of the ageing process

Users of heat treatment follow diagrams of the relativity of parameters of heat treatment to achieve required levels of mechanical characteristics. The shape of aging curves (**Fig. 2**) is determined by the composition of alloys, by the speed of hardening, the temperature of hardening, the speed at which buds form, the speed of growth, the speed at which the corn is thickening, and the process of precipitation. **Fig. 2** portrays phases of aging in hours and achieved hardness. **Fig. 3** shows a diagram (processes of heat treatment marked from T4 to T7), indicating the temperature of aging and achieved a hardness of castings. For example, hardness 100HB, which a customer requires, has a necessary aging time of 3 - 4 hours at 200 °C. All values are approximate, and they differ based on the type of casting. Required combinations of hardness and toughness of castings depend on temperature and on the length of the aging period [14, 15].

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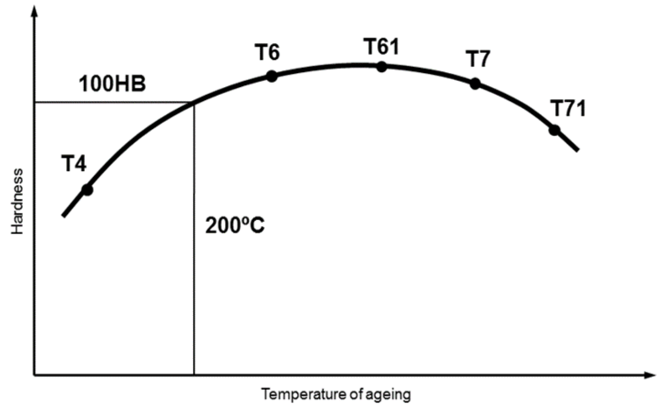

Fig. 3 Heat treatment process of castings **-** temperature of the ageing process and achieved hardness

After ageing the castings have a microstructure and mechanical characteristics, which ensure required quality and functionality [14, 15, 16]. Original pouring structure of the casting (**Fig. 4**) will be rafined, as you can see in **Fig. 5**.

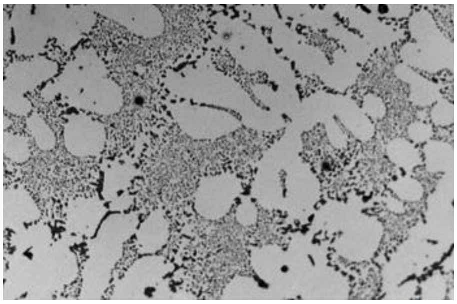

Fig. 4 Microstructure of the casting – AlSi9Cul before heat treatment

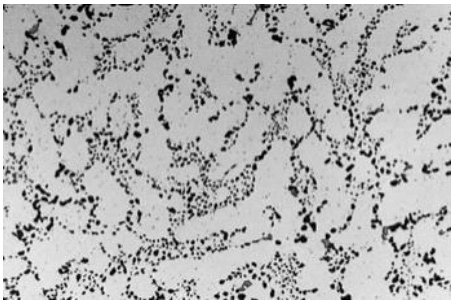

Fig. 5 Microstructure of the casting **-** AlSi9Cu1 after heat treatment

2.3 Methodology of Measuring Quality

To analyse reasons why discordant castings are made after heat treatment (hereafter HT), we used one of 7 basic Quality Management Tools – Ishikawa diagrams - Cause–and–Effect Diagram [9]. Ishikawa diagrams (also called fishbone diagram) are causal diagrams that show the causes of a specific event. Common uses of the Ishikawa diagram are product design and quality defect prevention, to identify potential factors causing an overall effect. Each cause or reason for imperfection is a source of variation. Causes are usually grouped into major categories to identify these sources of variation. **Fig. 6** portrays a diagram which features individual sources of problems, which during the heat treatment process affect the quality of the casting, specifically its dimensions. By specifying five main causes, which are closely identified with side effects, assumptions for modelling of individual processes are created and it results in optimization of parameters of the HT process. The featured diagram shows, from a dimensional perspective, factors that affect quality of the final product.

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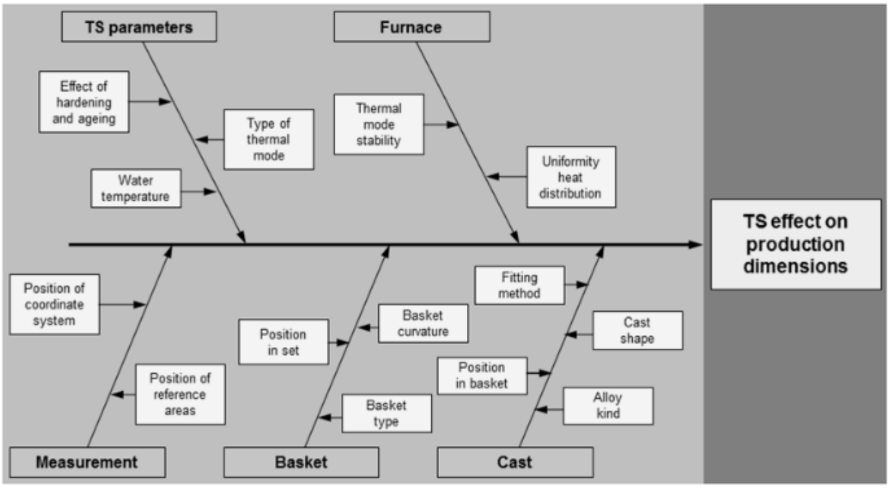

Fig. 6 Ishikawa diagram - dependence on influence of heat treatment process parameters on the castings' dimensions

Changes in microstructure after heat treatment of castings can cause undesired changes in dimensions. It is imperative to check dimensions before and after HT process to ensure that quality of castings is in accordance with customer's requirements. To check dimensions, we currently use 3D measuring devices, which is shown in **Fig. 7**.

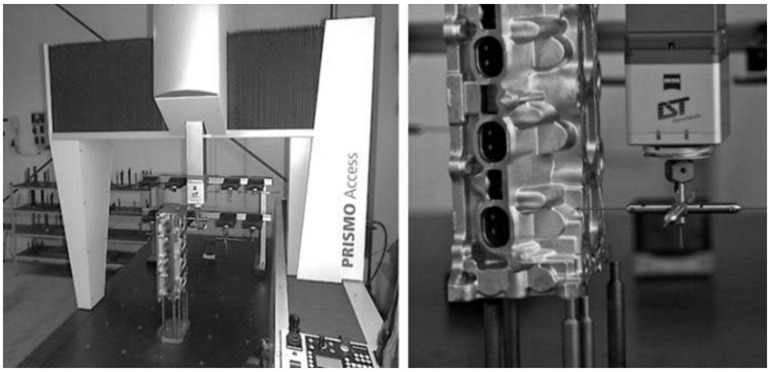

Fig. 7 Control of castings' dimensions - 3D measuring device

3 Experimental part

3.1 Process Modelling, Optimization of HT- Process Parameters

Due to an increase in the number of castings which come close to limits of tolerated dimensions and due to the formation of discordant castings, the influence of HT has become one of the key dimensions.

Based on this determination, an experiment was created. It consisted of 5 tests (**Fig. 8**). These were focused to control castings' position in bin and its affect to the distorsions. Also were aimed to monitoring of the bins shape (new bins, old bins), the HT phases, procedural parameters and their impact to the castings' dimensions. 3D measuring of selected dimensions was performed before and after conducted tests. The results were inserted into Pareto charts.

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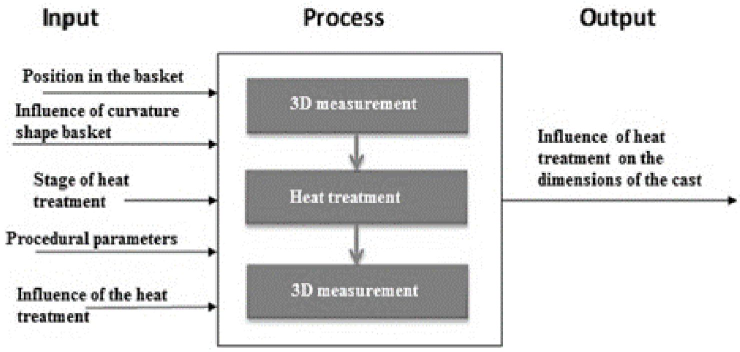

Fig. 8 Model experiment – the schema

Casting is a process which carries the risk of failure occurrence during all the process of accomplishment of the finished product. Hence necessary action should be taken while manufacturing of cast product so that defect free parts are obtained. Mostly casting defects are concerned with process parameters. Hence one has to control the process parameter to achieve zero defect parts. For controlling process parameter one must have knowledge about the effect of process parameter on casting and their influence on defect [10-14].
In following parts of the article we introduce only some of the five tests of the experiment and their results.

3.2 TEST No. 1- Position of Castings in a Bin

The aim of the first test was to find out the change in dimensions after heat treatment and to confirm reproduction of HT and discover deviations on three consecutive sets. **Fig. 9** shows the positioning of castings in bins, in which they are transported into a furnace for heat treatment.

Fig. 9 Positioning of castings in bin

Measured points on the casting are shown in **Fig. 10**. They are colour coded; the darkest stands for the highest and grey for the lowest influence of position in a bin on a casting's dimensions. **Fig. 11** shows most critical places in bins, where castings showed biggest deviations from required dimensions.

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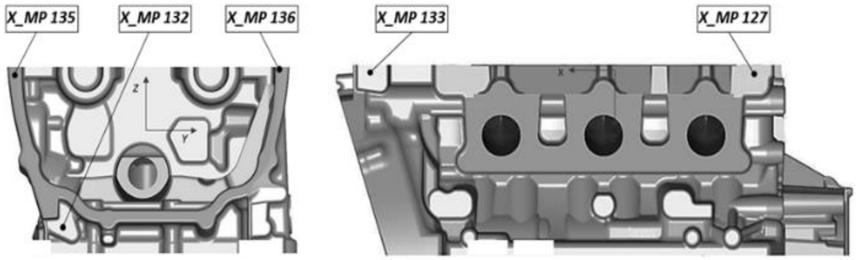

Fig. 10 Measured points on the casting

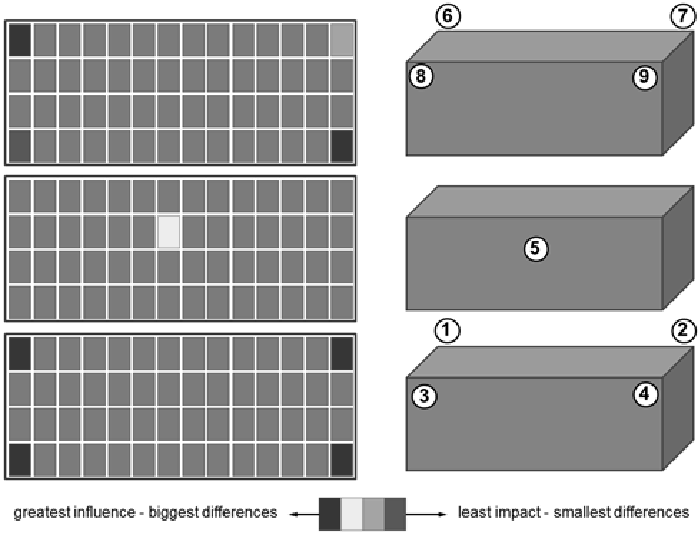

Fig. 11 The most critical places in the bins and colour range of intensity of influence on the dimensions

Conditions for evaluation in a test:

- one set contains nine castings,
- test of influence HT on casting dimensions has been done in three sets - old bins,
- by analysing measured data it was confirmed the most critical places are points which are shown on indicated places of **Fig. 11**: X_MP127, X_MP132, X_MP133, X_MP135 and X_MP136,
- on axis "X" the maximum measured deviation was 0.53 mm (MP136),
- on axis "Y" the maximum measured deviation was 0.28 mm (MP143),
- on axis "Z" the maximum measured deviation was 0.24 mm (MP25-2).

After verification of dimensions, the results were analysed with the help of the Pareto diagram, which operates on the 80-20 principle (20% of factors cause 80% of effects). From the diagram it is seen, 20% controlled castings are marked as the darkest columns. There are the most critical places in the bin where dimensional changes were found. (**Fig. 12**).

Lorenzo's curve completes the diagram and explains the importance of the relative scale on the right side of the diagram. The final point of the cumulative curve presents 100% and all data. This is shown left of the indicated points and is considered to be essential.

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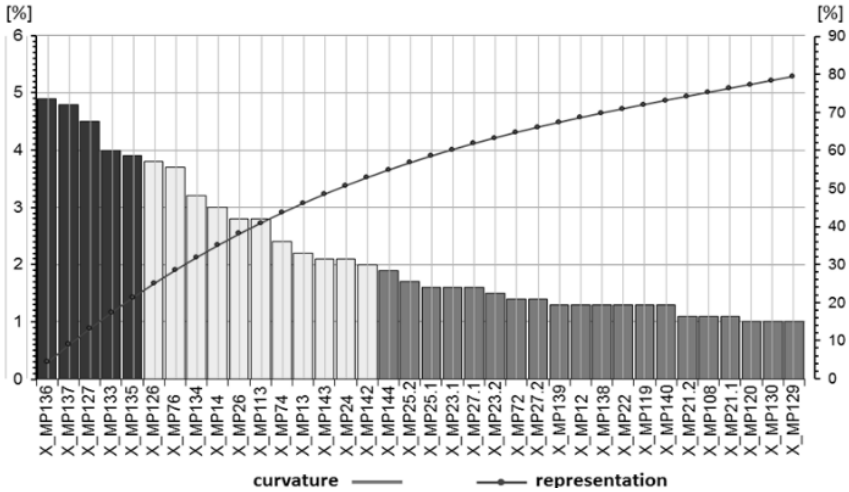

Fig. 12 Pareto`s diagram – critical places of castings' distortion

Test results: As a result of test 1, it can be seen that not all castings within a bin are processed under the same conditions. Since a set has 168 units and each casting reacts differently to heat within a tolerable scope, within a set, the interval is up to 30 minutes. Therefore 9 castings were chosen where is presumed the greatest interval of time to obtain the required temperature. This test showed the casting no. 9 has a faster onset of temperature and its heat loading is the highest, therefore its dimensions are influenced the most.

3.3 TEST No. 2 - Procedural Parameters of Heat Treatment

The aim of the second test was to find out the deviation in temperature in various parts of the casting from a selected unit in position no. 9 in the bin. Three thermocouples were placed into the observed cast in position no. 9. (**Fig. 13**), which aimed to find out the temperature of the cast.

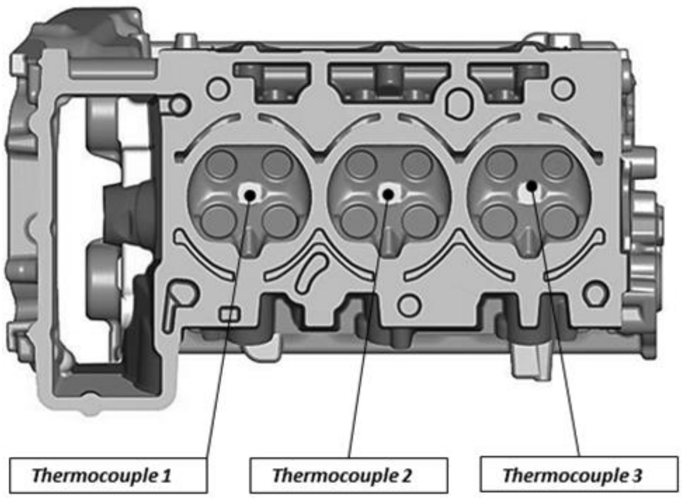

Fig. 13 Thermocouples situated in a casting

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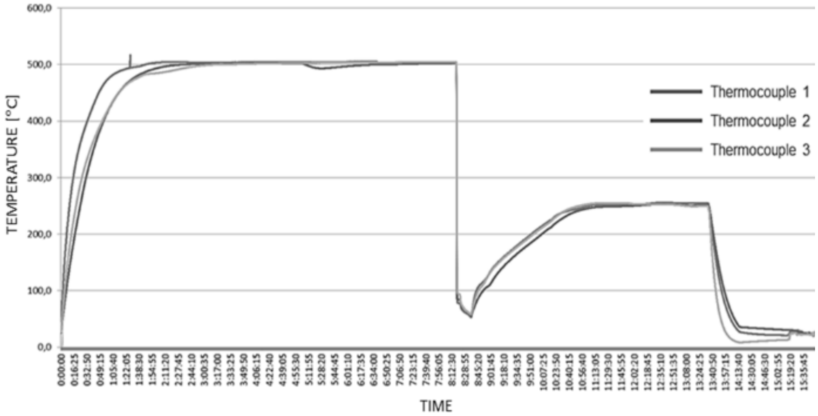

Fig. 14 Behaviour of temperature in the casting – position no. 9

Fig. 14 is a graphical process of temperature in the observed position no. 9. The final temperature of the sample is shown in the diagram, temperature – time relationship.

Test results: Temperature distribution in various parts of the casting was up to 2.5°C. The customer requires distribution of up to ± 5°C within the entire set, which means that temperature in the bin meets customer's requirements. Due to this fact, we did not dedicate any more tests to this influence.

3.4 TEST No. 3 - Influence of the Heat Treatment Regime

Parameters were changed in the third test: kind of casting in the HT regime. The test was divided into 3 micro tests. The types of castings and types of HT changed, as seen in **Fig. 3**. An example layout of the 1st micro test and its results are shown below:

- casting MPI - casting V6 and HT MPT T7 - change of one variable
- critical places of distortion of a casting in this alloy are shown in **Fig. 15**
- measured deviations are shown in **Fig. 16**

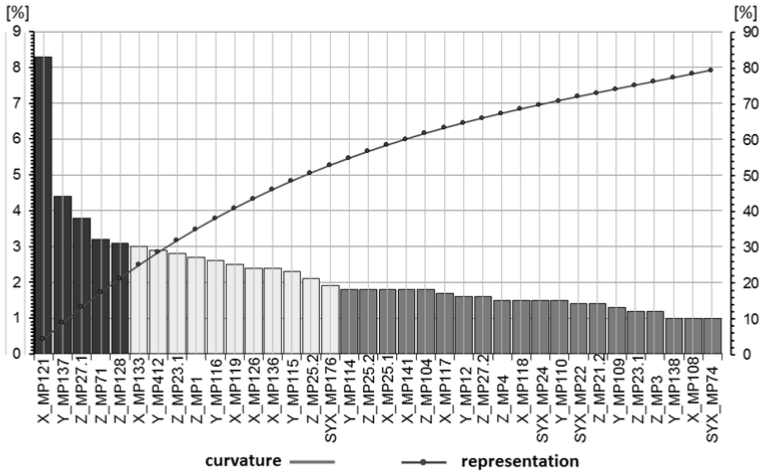

Fig. 15 Pareto`s diagram – critical places of casting's distortion after hardening MPI – alloy V6, heat treatment MPI T7

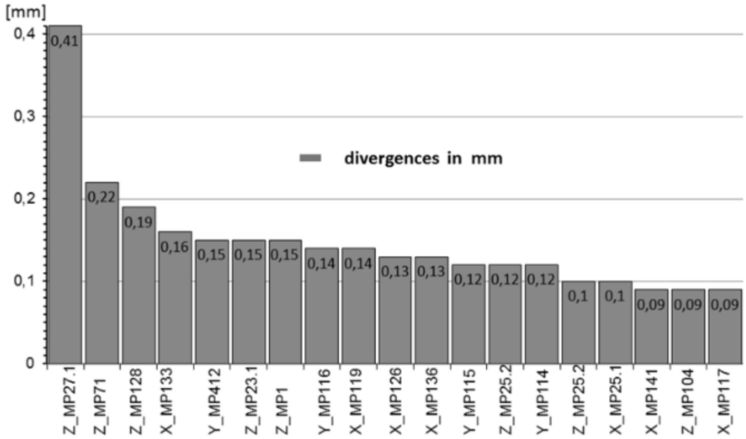

Fig. 16 Deviations of measured dimensions - alloy MPI V6; heat treatment MPI T7

Test results: The goal of the third test was to find out, if change of the sort alloy or change of HT from T6 to T7 will affect of the dimensional stability. When both parameters were changed in the 3rd micro test (change of type of alloy and change in HT regime) dimensional stability improved by so much, that the difference in dimensions of all controlled points was, on average, within the 0.1 mm, which would satisfy the customer without any adjustments to the equipment.

4 Conclusion

We researched that the most distortion in castings occurs during the fast cooling process from annealing. We conducted tests to find out the influence of individual HT phases on the castings' dimensions. Control of dimension by 3D measuring took place before HT, after fast cooling of castings (hardening) and after completion of the precipitation hardening.

Based on the results, we can conclude that within various regimes of heat treatment (T6 and T7) occurs a change in dimensions within various phases of the process. In the T6 process, we found changes in dimension after cooling in water and in the T7 process a change occurred after artificial aging.

Our model experiment based on the use of modern Management Quality Tools confirmed a prediction and discovered intensity of some factors of heat treatment on the quality of cylinder head castings. Implementation of the results of our research and experiments in the production process of castings manufacturer we brought the effect in terms of reducing the number of nonconforming castings and associated cost savings.

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