Hot Isostatic Pressing of AISI 6150 Steel

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Abstract. Hot isostatic pressing (HIP) is a promising way to improve the quality of structural materials, and therefore the structures themselves. The article presents the results of experimental studies on the application of technology for processing critical products made of AISI 6150 steel in order to reduce the number of pores in material and formed weld. The influence of HIP process on the structure of AISI 6150 steel samples was investigated using x-ray computed tomography. The experimental results show a significant improvement in structure of material, a decrease in the number and size of pores relative to the initial values. The experiments presented in this work were carried out on the basis of a HIP setup located at Vladimir State University.

1. Introduction
At present, several methods are known for reducing the number of discontinuities formed in critical details. These include reductive heat treatment (HT) [1–4], mechanical-thermal treatment (MTT) [5–7] and electric pulse treatment (EPT) [8–10]. The action of HT and MTT is based on the fact that constant or cyclic heating or, in combination with it, mechanical and electro-impulse action (deformation) accelerate diffusion processes in the material of the part, which leads to the “healing” of some part of micropores and microcracks. However, these processes are characterized by a very long duration and low efficiency, only those discontinuities with a size of less than 1 μm are eliminated. At the same time, if tensile stresses arise in the discontinuity region, this can lead to an increase in these defects. Gas pores are not accessible for mechanical removal (stripping) and are stress concentrators, centers of nucleation of fatigue and thermal fatigue cracks.

The most effective way to eliminate internal pores and shells in full-crystalline castings of various alloys is hot isostatic pressing, which has been used for many years to process castings for critical purposes [11–14]. HIP has a number of advantages that determine its practical attractiveness. It is a complex technological process, the essence of which is the simultaneous exposure of a metal to high temperature and pressure obtained by pumping inert gas, more often argon, into a vessel. Under these conditions, processes characteristic of pressure sintering develop in a powder billet. In a monolithic workpiece with internal isolated defects such as pores, friability, cracks in the defect zone, plastic deformations occur, as a result of which the defect walls are closed. The development of diffusion processes leads to a gradual blurring of the interface and the disappearance of the defect [15, 16].

The combined effect on the workpiece of high pressures and temperatures can effectively eliminate (heal) micro- and macrodefects that occur in monolithic workpieces when they are obtained by traditional methods (casting, forging, stamping, rolling, welding) [17–20].
2. HIP processing of AISI 6150 steel

For the experiments, an automated hot isostatic press was used, designed for heat treatment of metal and ceramic products. The main technological parameters of the HIP setup used for the experiments are presented in Table 1.

| Parameter          | Value         |
|--------------------|---------------|
| Usefull diameter   | 250 mm        |
| Usefull height     | 350 mm        |
| Maximum filling mass | up to 30kg  |
| Camera type        | cylindrical   |
| Working pressure   | up to 2500 bar|
| Working temperature| up to 2000 °C |
| Temperature gradient| less than 3 °C |
| Heating / cooling speed | controlled  |
| Pressure medium    | argon         |
| Furnace type       | graphite      |
| Work mode          | manual, automatic |

As samples for investigating the effectiveness of hot isostatic pressing operation, was used a blank of a hydraulic equipment part operating at a pressure of up to 50 MPa. Sample material – AISI 6150 steel (after welding operation). Parts containing the maximum number of defects were used as samples. The aim of this approach was to study the effectiveness of eliminating various types of defects by hot isostatic pressing. In accordance with the literature, the application of HIP processing effectively eliminates pores, internal cracks in material, which do not have an exit to surface, increase material isotropy, which is widely used for processing parts obtained by SLM method [21–23]. The elimination of pores and cracks emerging on surface is possible when the part is encapsulated in a shell that prevents pores from filling with the medium (argon) used to increase pressure in vessel, however, this operation was not considered in this work.

The HIP process took place with the following parameters: working temperature – 1000 °C, working pressure 1500 bar, rate of rise and decrease in temperature – 6 °C/min, holding time – 7 hours. The graph of HIP processing is shown in figure 1.

Figure 2 shows the surface of the processed sample formed by a section of plane of the sleeve welded joint. The image was obtained by x-ray tomography. The same area was considered before and after HIP, orientation of the part is saved. The figure 2a shows many pores in the weld area.

As a result of HIP treatment, a significant improvement in the structure of material is observed. The pore content drops significantly, 5.39% before treatment and 0.21% after HIP. The total percentage of pores after the hot isostatic pressing operation in the weld area is comparable to the porosity of the base material. The pore content in the initial sample outside the weld pool before and after treatment in HIP is shown in figure 2. The nature of pores distribution in weld is different from the porosity of base material. Round pores with a diameter of up to 2 mm are recorded, which were probably formed as a result of the union of gas cavities. The presence of lack of fusion, uneven penetration corresponding to codes 403, 4013 [24] was not detected.

Despite the extremely positive result of processing, the gas-conditioning of welded joints must be treated with caution. With HIP, pores that have access to the seam surface or lie near it do not
close and can even open [25]. Non-discontinuities filled with air are also not welded. As a result of processing at high pressure, they only flatten. Subsequent heat treatment, due to expansion during heating of gas contained in discontinuities, they increase in volume and can break the metal. The latter, in particular, is characteristic of castings obtained by injection molding. In the case of filling defects with hydrogen (hydrogen porosity in castings, welds, etc.), it is dissolved in a solid solution and partial extraction into the atmosphere of the gas bath with successful welding of the defect itself.

Figure 1. Graph of HIP processing cycle.

Figure 2. Image of the seam cross-section: a - before HIP, b - after HIP.
3. Conclusion
Hot isostatic pressing is a relatively long and complex technological process associated with the use of expensive equipment. In this regard, the use of such technology was limited only to those branches of engineering – aerospace technology and nuclear energy, where high capital and operating costs are justified [26–30]. Analysis and generalization of the results achieved abroad allow to consider that HIP is an extremely effective and promising technological process. Intensively conducted research works are constantly expanding the scope of gas-static treatment and increase its efficiency in production conditions. However, hot isostatic pressing is not a tool that can and should be used for all materials and all types of products. Ultimately, the possibility of using this process is determined by the cost of the resulting product.

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