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INFLUENCE OF THE TIME INTERVAL BETWEEN THE DEPOSITION OF LAYERS BY THE SLM TECHNOLOGY ON THE STRUCTURE AND PROPERTIES OF INCONEL 718 ALLOY

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We study the influence of a one-time stop in the course of manufacturing of products by the SLM technology on the structure and mechanical properties of specimens of Inconel 718 alloy with an aim to establish their serviceability. The specimens are produced on the equipment of different manufacturers both with stops in the process of printing and without stops. The mechanical properties are determined in tensile tests according to the requirements of GOST 1497 (ICO 6892-84). It is shown that they are improved both in the case of continuous technological processes and in the presence of a stop in the course of production of the specimens.

Keywords: SLM technology, mechanical properties, microstructure, Inconel 718 alloy, technological process.

Introduction

In modern industry, the so-called SLM (selective laser melting) method based on the procedure of layer-by-layer laser melting of powder particles when laser beams move along a given trajectory (Fig. 1) is now extensively used for the purposes of manufacturing of products made of metallic powders.

In the process of melting carried out on the corresponding equipment, components of complex geometries are formed layer by layer with the use of 3D digital models. The thickness of each layer varies from 15 up to 150 μm depending on the applied material. For the purposes of melting of the metal, it is customary to use ytterbium fiber lasers with powers of 200–1000 V, whose beams are focused with the help of mirrors mounted on a high-speed drive at the required site of formation of the component [1, 2]. The chamber is filled with inert gases (nitrogen or argon) in order to prevent the possibility of undesired oxidation of the component. Every next layer is obtained by lowering the platform with the component down to a depth equal to the height of the layer. After this, from a hopper feeding the powder, we apply a new layer by using a driving blade. The entire cycle is repeated up to the time of complete formation of the component in height. The productivity of the unit may vary from 10 to 50 cm^3/h depending on the geometry of the product, thickness of the working layer, and the strategy of construction.

In the SLM process, the metallic powders in a layer are rapidly melted by a laser beam and then instantaneously solidified in the melt bath (cooling rate varies from 10^3 up to 10^8 °K/sec [3]) with a short transition from

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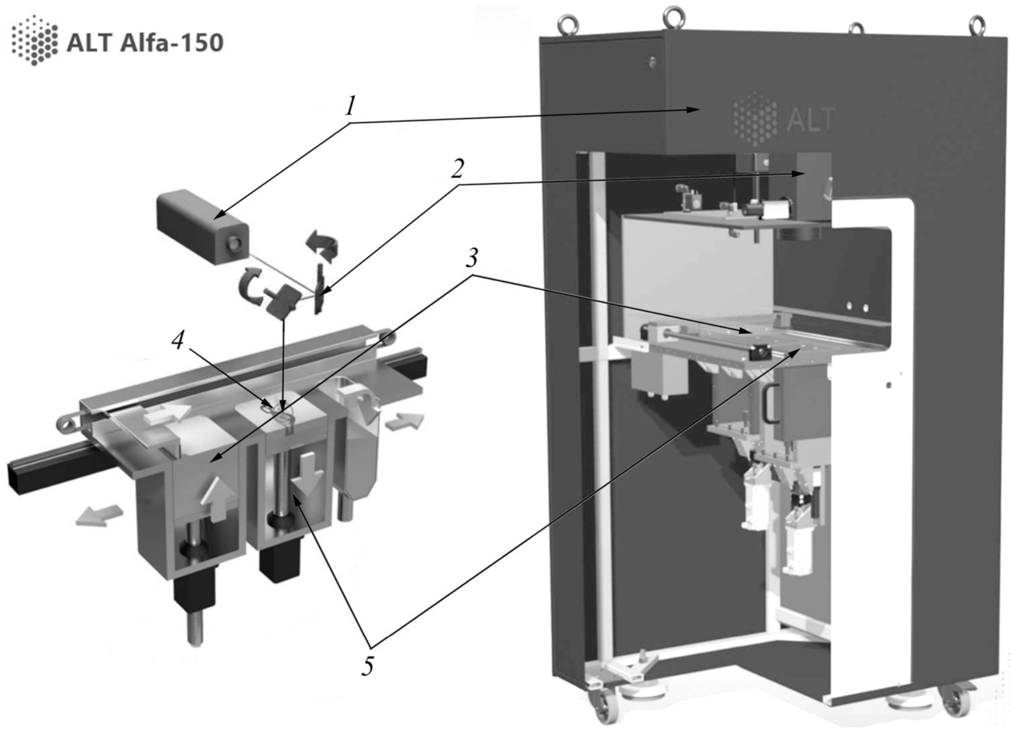

Fig. 1. Schematic diagram of operation of a 3D printer: (1) laser; (2) scanning system; (3) powder supply; (4) printed object; (5) platform with the object.

liquid into the solid state and formation of highly dispersed microstructures. This method enables one to produce components of complex shapes without special technological equipment, reduce the range of the required equipment, lower the number of assembly operations, guarantee the required accuracy of sizes and shapes according to the design-basis documentation, minimize the necessity of subsequent mechanical treatment, and make the utilization factor of the material maximally close to 100%.

The main producers of the equipment aimed at the manufacturing the components according to the SLM technology are located in Europe and America [these are, e.g., 3D Systems (USA), Electro-Optical Systems (EOS, Germany), and Concept Laser GmbH (Germany)]. The decisions proposed in the market are quite costly, require the development of special additional software for different materials, and moreover, the required powders should be purchased from the producer of the equipment.

In Ukraine, the "Additive Laser Technology of Ukraine," LLC, Firm is engaged in the development of equipment of this kind. In this case, it is most important to develop a procedure for choosing the parameter of the process of melting of powders guaranteeing the required technological, mechanical, and operating properties of the components.

In the present paper, we discuss one aspect of this problem connected with changes in the properties of the material caused either by unexpected shutdowns of the equipment or by scheduled pauses in the course of printing prior to completion of the process of formation of the component.

Statement of the Problem

In the additive production, it is customary to use equipment characterized by high flexibility and adjustability, i.e., perfect for the conditions of pilot and single-piece production.

Table 1
Chemical Composition of the Inconel 718 Alloy (wt.%)

Ni	53.5	Mo	3.00	Si	0.07	S	< 0.0003
Cr	17.82	Ti	0.94	Mn	0.08	Pb	< 0.0003
Fe	18.03	B	0.0026	Cu	0.06	Ta	< 0.020
Nb	5.50	C	0.026	N	0.005	Bi	< 0.00003
Al	0.55	Co	0.32	P	0.011	Se	< 0.0003

In the production of carrier rockets, the processes of manufacturing of combustion chambers of the engines occupy a special place. Moreover, the applied technologies are laborious and quite complicated mainly due to the complexity of created structures. In this case, the SLM technology that enables one to produce components with complex geometries, internal cavities, and cooling channels without using costly special equipment, the operations of forge-rolling, stamping, bending, as well as the assembly operations of soldering and welding proves to be quite promising. Units of rocket engines are most often produced of refractory nickel alloys. In particular, thermally loaded structures are made of Inconel 718 nickel alloy.

This is why we studied the influence of the laser power and the distance between the lines of scanning on the porosity and range of particle dimensions in the microstructure of the components made of powders of the analyzed alloy [4]. However, for some reasons, the process of manufacturing may be sometimes paused. It is believed that this may lead to the deterioration of the mechanical properties and substantial changes in the microstructure and, hence, can negatively affect the operating reliability of components. It is known that, in the case of small intervals between the formations of layers, the subsequent layers inherit the texture of the previous layer and, hence, we observed the formation of grains elongated along the Z-axis whose sizes correspond to thicknesses of the dozens of layers. The presence of so large grains leads to the deterioration of the mechanical properties of the metal. At the same time, there exists an opinion that, in the layer-by-layer production of the components, the presence of regulated intervals between the formations of layers favorably affects the structure and properties, which promotes the formation of fine-grained structures.

This is why, we studied the influence of a one-time stop in the process of production of components made of Inconel 718 alloy by the SLM technology on the structure and mechanical properties of specimens with an aim to establish their serviceability.

Materials and Testing Methods

We studied specimens manufactured in an ALT Alfa-150 installation produced by "Additive Laser Technology of Ukraine," LLC, from powders of Inconel 718 refractory alloy (Table 1) under the following conditions: a distance between tracks equal to 0.10 mm (and the overlapping of tracks equal to ~ 30%); the power of a laser of 175 W; its traverse speed of 800 mm/sec, a thickness of the layer of 0.050 mm, and a diameter of the beam of 0.050 mm.

The first batch was printed according to the specified parameters without pauses, while the second batch was prepared with a stop in the process of printing made at a height corresponding to the working part of the specimen used for tensile testing. For the sake of comparison, we also tested the specimens produced in Germany by the Böhler GmbH Firm.

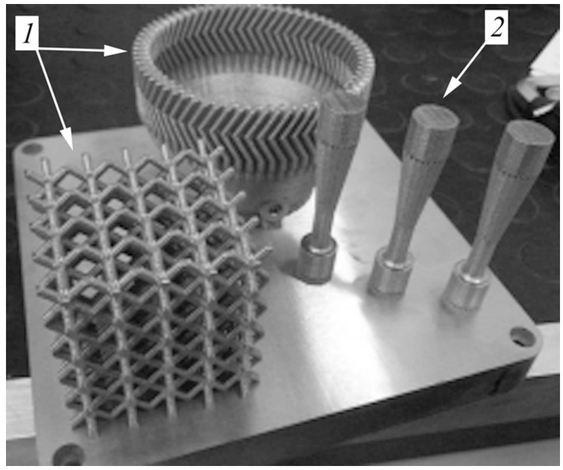

Fig. 2. General view of the tensile specimens produced by selective laser melting: (1) finished components; (2) test specimens.

Table 2.
Mechanical Properties of the Inconel 718 Alloy after Manufacture by Different Methods

Manufacturing method	σ_u	$\sigma_{0.2}$	δ_5, %
	MPa		
After 3D printing [8]	980 ± 50	700 ± 50	28 ± 3
In the as-cast state [7]	790	400	90

The mechanical properties were determined in a TTDM–5004 Instron machine under normal conditions in tension. The sizes and shapes of the specimens, and test methods met the requirements of GOST 1497 (ICO 6892-84) (Fig. 2). The microstructure was studied in an AXIOVERT-200M MAT (Carl Zeiss) optical microscope, on the "heads" of specimens both in planes $X-Y$ parallel to and in planes $X-Z$ perpendicular to the direction of manufacturing of the product, and at the site of pause in the process of printing.

Results and Discussion

In the development of the SLM technology, it is important to guarantee the required mechanical characteristics. Under the influence of highly concentrated energy sources and elevated temperatures, a special complex of mechanical properties is formed in special alloys and alloyed steels [5, 6] (Table 2).

It was established (Table 3) that the difference between the mechanical properties the specimens manufactured with a pause made in the technological process and without pauses does not exceed 5% and is comparable with the mechanical characteristics of specimens made in Germany [8]. It should be emphasized that, in the presence of pause in the course of printing, the specimens failed just at the site of this pause (Fig. 3).

The mechanical properties of the products in tension directly depend on the internal structure of the material. For the investigation of changes in its structure caused by a pause in the process of printing, we used the metallographic analysis. Special attention was given to defects and, in particular, pores, which may play the role

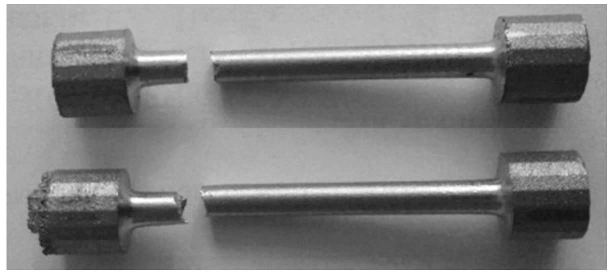

Fig. 3. Tensile test specimens after fracture.

Table 3
Mechanical Properties of the Experimental Specimens Made of Inconel 718 Alloy

Batch of specimens	Specimen No.	F, mm^2	P_{max}, N	σ_u, MPa	$P_{0.2}$, N	$\sigma_{0.2}$, MPa	δ_5, %
"ALT of Ukraine," LLC, without pauses	1	19.23	2000	1019.073	1410	718.91	40.0
	2	18.85	2050	1066.67	1400	728.45	39.8
	3	19.23	2005	1022.28	1405	716.36	42.3
"ALT of Ukraine," LLC, with pause	1	20.41	2125	1021.01	1493	717.38	41.4
	2	20.41	2094	1006.20	1487	714.44	40.0
"Böhler" (Germany), without pauses	1	19.63	2070	1034.42	1431	715.10	35.6
	2	20.02	2090	1023.84	1451	710.81	35.6

of fracture concentrators in the alloy, and to the grain size because the refinement of grains leads to the increase in strength and plasticity of the material according to the Hall–Petch equation [9] (Fig. 4).

The chosen parameters of manufacturing of the products make it possible to get the minimum porosity of the specimens (Figs. 4a, d), which positively affects their strength. The pores have regular rounded shapes, i.e., they are caused by insignificant amount of gases penetrating into the molten bath with powder particles. The granular structure of the specimen is well visible (Figs. 4b–e).

The grains are stretched by the SLM method in the direction of manufacturing of the products, which may lead to the anisotropy of their properties. The mean grain sizes along the X- and Z-axis are equal to 59.0 μm and 87.2 μm, respectively. According to the data presented in [7], in the as-cast state, the Inconel 718 alloy has a dendritic structure with mean grain sizes of 500 μm. As the grains are refined, the ultimate tensile strength and the yield strength increase. The specimens produced in Germany (Fig. 5) are more porous, and the grain size corresponds to the grain size of the specimens obtained on the equipment of the "Additive Laser Technology of Ukraine," LLC Firm. This explains a decrease in the relative elongation in the course of the tests.

In order to deeper understand the influence of unpredicted pauses in the operation of equipment on the structure of the alloy, we analyzed the sections of specimens in the direction of the X–Z-axis at the site of the pause in printing (Fig. 6).

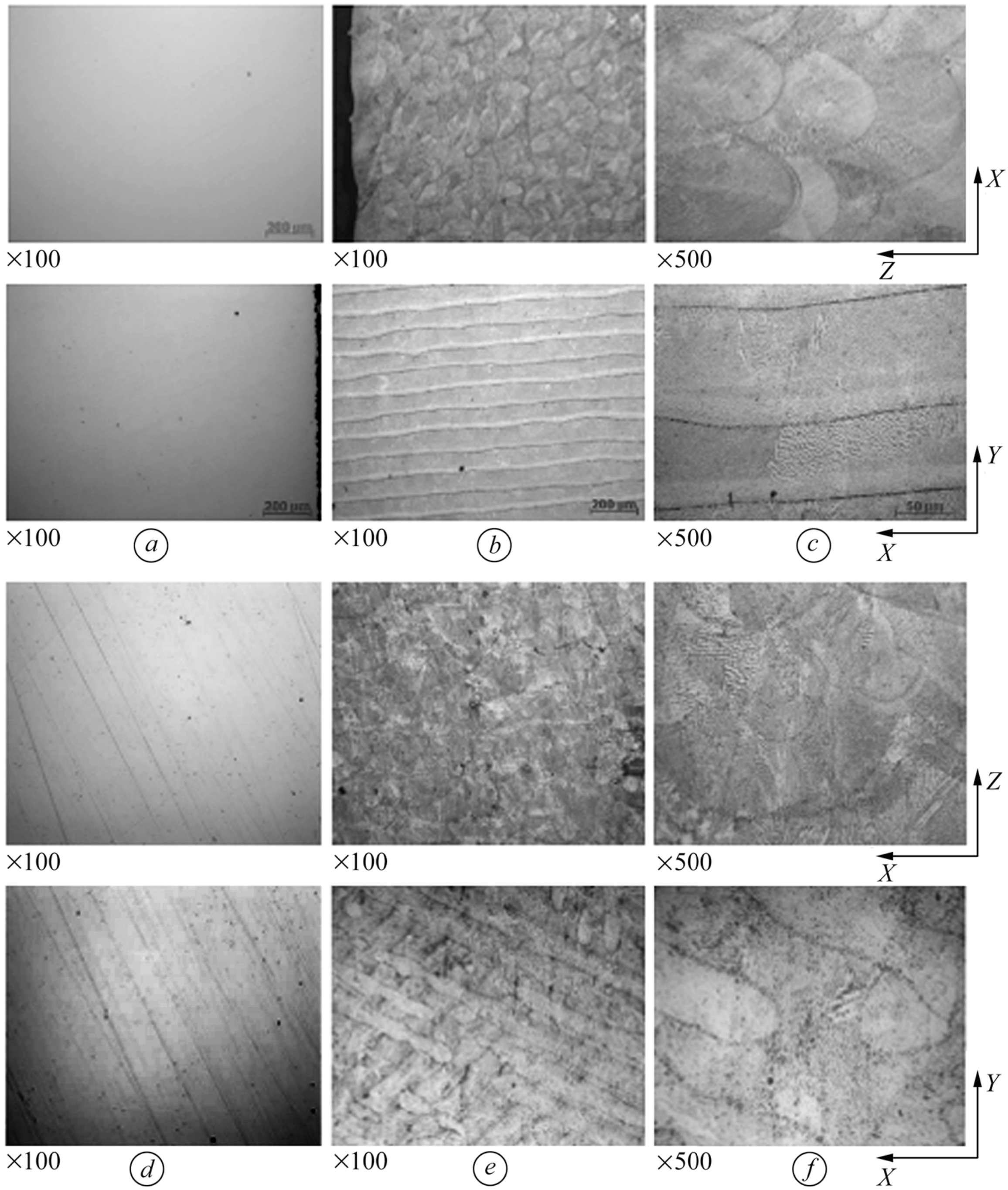

Fig. 4. Microstructures of the specimens: (a–c) without pauses; (d–e) with a pause made in the process of manufacturing; × 100 and × 500.

The pause in course of printing does not affect the microstructure of the specimen and grain sizes. The structure also contains grains elongated in the direction of the Z-axis. During the pause in the process of printing, the last layer has time to cool and solidify. Therefore, when the process of printing is resumed, the conditions of melting of the metal of the new layer differ from the conditions of the process without termination due to the lower amount of heat transferred from the previous layer. The volume of the bath for a new layer

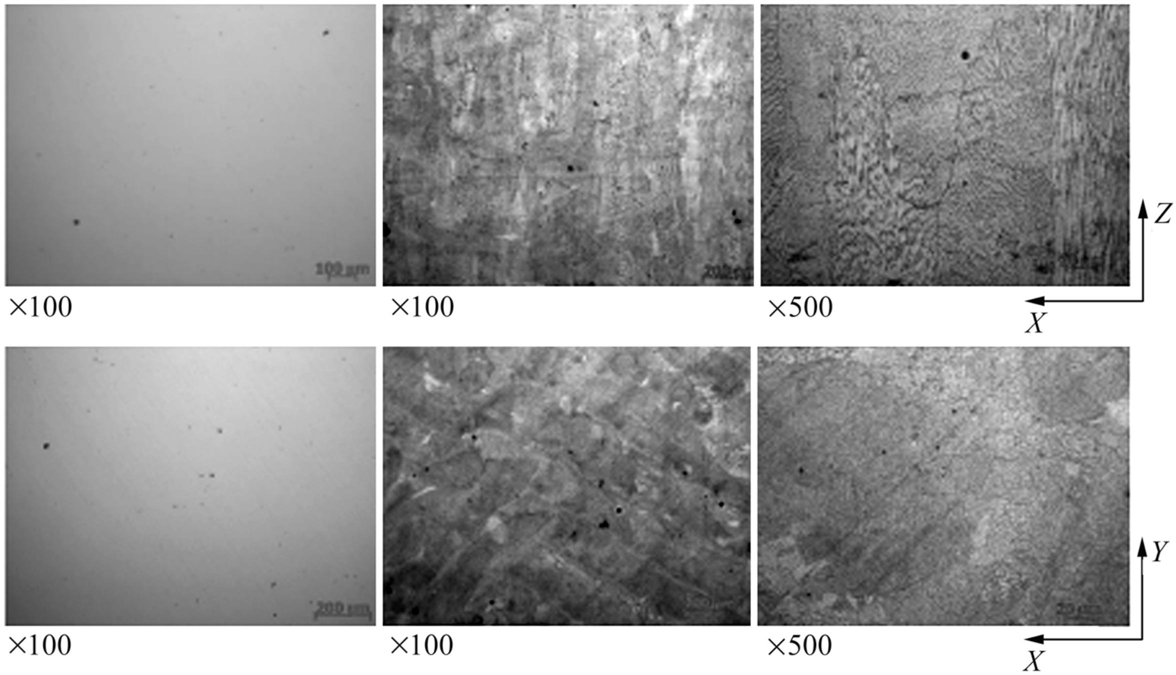

Fig. 5. Comparison of the specimens produced in Germany.

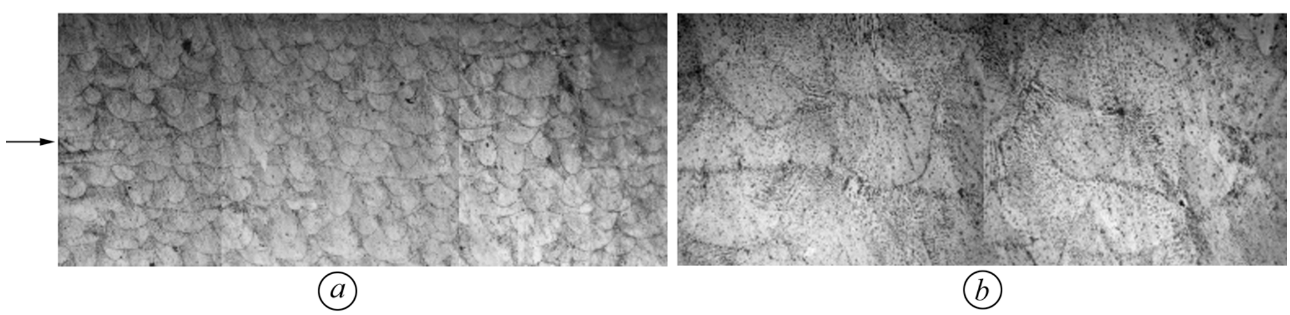

Fig. 6. Microstructures of the specimen in the zone of pause in the process of printing (indicated by the arrow): (a) × 100; (b) × 500.

melted by the laser after termination is somewhat lower. Therefore, as a result of termination, the lower layers of the melt have smaller thicknesses and, hence, fracture occurs through the indicated section but under admissible levels of the load.

CONCLUSIONS

We performed the comparison of the mechanical properties of the specimens of Inconel 718 alloy produced both as a result of a continuous technological process and in the presence of a pause. The ultimate strength, yield strength, and relative elongations are high and differ for different conditions of preparation of the specimens by less than 5%, which corresponds to the values obtained for foreign analogs. The specimens produced by the "Additive Laser Technology of Ukraine," LLC, Firm are less porous than the specimens manufactured by the Böhler GmbH Firm (Germany). The grain sizes of the specimens produced by the method of selective laser melting are lower (by an order of magnitude) than that for the specimens produced by casting. This fact may justify the improvement of the mechanical properties of material in tension. In the case of unpredicted termination of the process, the size of the zone of melting of the material decreases, which leads to fracture just in the indicated zone. However, this fact is uncritical and the products remain suitable for subsequent testing.

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