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Identification of Residual Stresses after Machining a Gearwheel Made by Sintering Metal Powder

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SLS additive technology is an innovative method of metal components production, using a high material proportion. Currently, gearwheels are still one of the most used engineering parts, not only in the automotive, but also in other industries. For example, milling is used to reduce their weight, but the material can be distorted after this operation. The occurrence of cracks propagating in the transition region after induction hardening was the reason for conducting experiments with an alternative machining technology. The article deals with the identification of an influence of machining on residual stress change of a gearwheel made of sintered metal powder. The research focuses on the effect of boring on the residual stresses using a non-destructive measurement method using röntgene diffractometry.

Keywords: Additive Manufacturing, Selective Laser Sintering, Machining, Residual Stress

1 Introduction

Currently, the development of additive manufacturing (AM) focuses on the production of complex shaped functional metal parts to meet the demanding requirements of the aerospace, automotive and biomedical industries. [1] The eco-friendliness and cost-effectiveness of engineering production is another reason to exploit the potential of additive manufacturing, which achieves a high percentage of material utilization. Selective laser sintering (SLS) is one of the fastest growing AM techniques. [2]

A schematic of the SLS process is shown in Fig. 1. The part formation process consists of two main steps, i.e., powder layer deposition and laser sintering. The powder layers are deposited using a conventional roller or scraper system. The sintering step refers to the irradiation of the deposited powder layer by a selective scanning laser beam, which locally sinters the powder according to a predefined geometry of the part section. [3] Increasing competition and the need for productive machining of progressive materials is placing increasing demands on the quality and precision of production. In this paper, the stress state caused by drilling holes in a gear produced by additive SLS technology is investigated. [4,5,6]

However, the application of the technology has its difficulties. Compared to traditional material removal techniques, it causes deformations and micro cracks in the components. The quality of the parts produced with SLS technology is affected by a large number of printing parameters such as laser power, laser speed, scanning pitch, layer spacing, or the orientation of the structure or the flatness of the bed. [7,8] In addition, large residual stresses can pose a risk, in some applications, due to reduced load resistance compared to the stress-free state. [9] The effect of residual stresses can be eliminated to some extent after completion by heat treatment. However, for reliable fabrication completion and prevention of embrittlement, it is necessary to take into account the post-loading of residual stresses and to understand the mechanisms of its occurrence. [10,11]

X ray diffractometry is a non-destructive method that is used to analyze the atomic or molecular structure of materials. [12,13,14] In this paper, we evaluated the residual stresses using Proto XRD roentgen diffractometer. [15,16]

2 An experiment

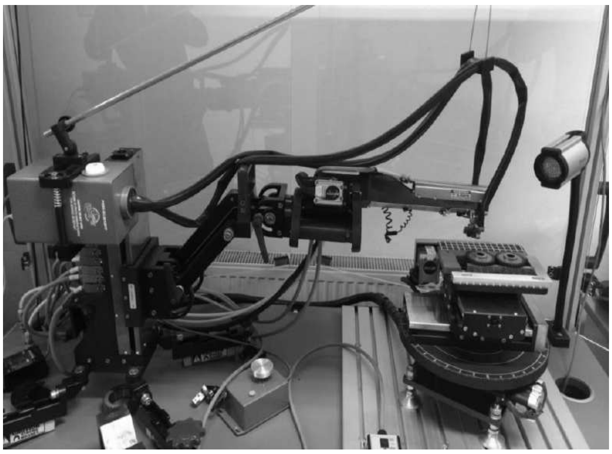

Fig. 1 *Measurement residual stress before machining*

The experiment consisted of measuring the residual stresses on the sprocket wheels before and after machining. The production of the gears consisted of pressing a metal powder (with a composition of Fe + 1.8% Cu + 0.7% C + 0.9% lubricant), followed by sintering, calibration, induction hardening and honing. Residual stresses were measured using a Proto XRD rontgen dicrograph (Fig. 1).

2.1 Before drilling

Before machining, we measured the residual stresses on the hardened gear and on the unhardened gear core. Six measurements were taken on each of the four gears. The measurements were set up so that the stresses were examined 3 times on the inductively hardened gear and 3 times in the center of the unhardened core. Measurements were taken at the designated locations (on 8x8 mm surfaces) as shown in Fig. 2.

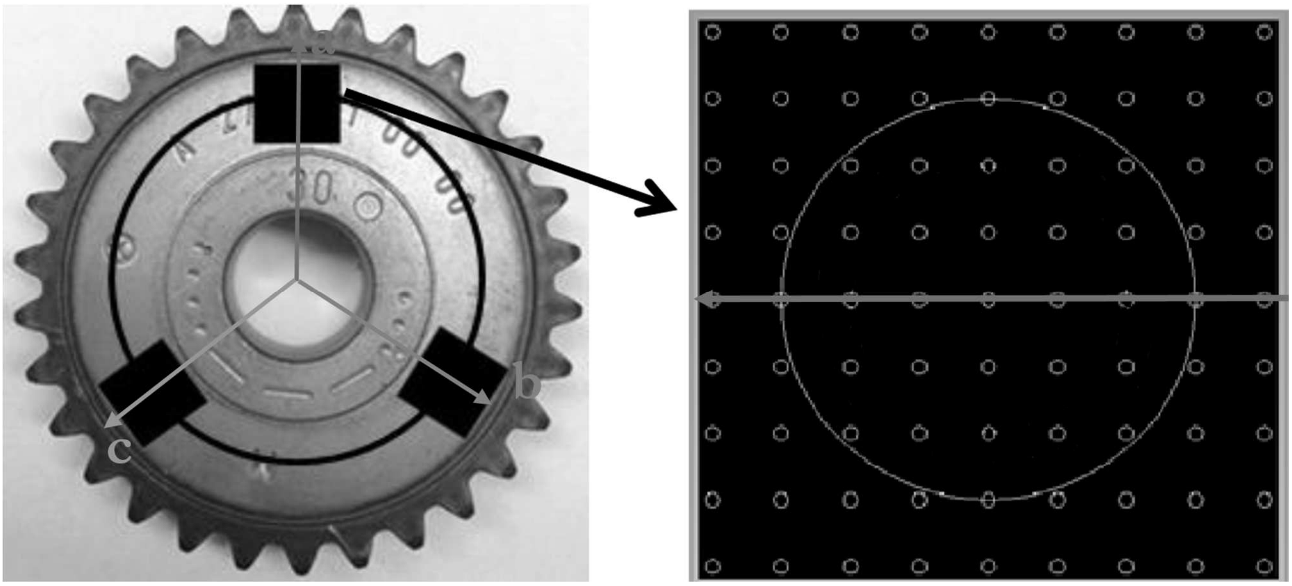

Fig. 2 *Scheme measurements on the area 8x8 with a circle, presenting drilled 6mm hole*

Measurement results of the residual stresses are displayed on the tense maps (Fig. 3). We can on them to see layout and size residual stress, on individual measured areas (a, b, c), so how they are illustrated on the picture above.

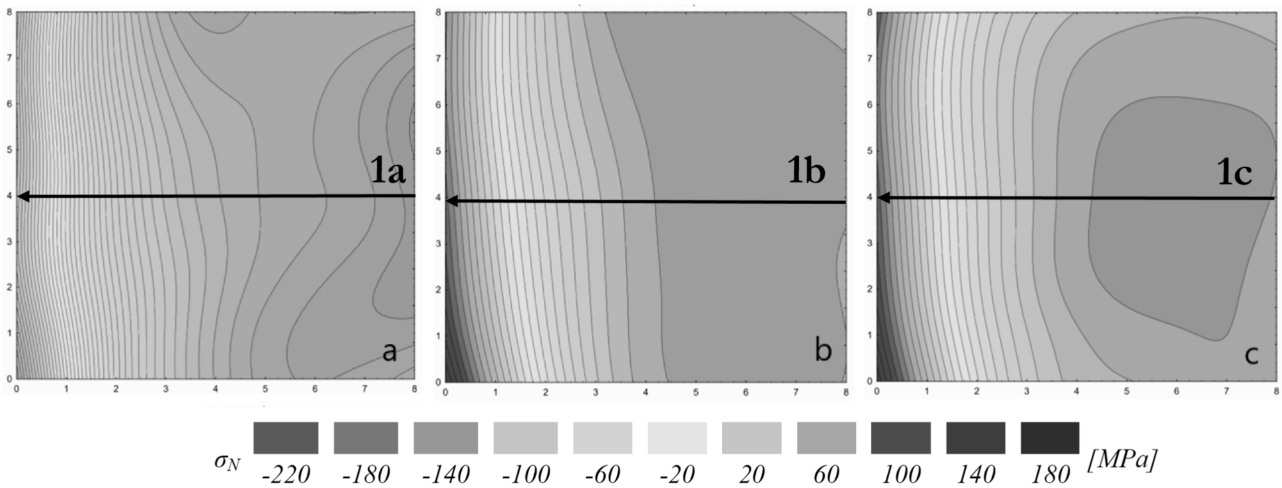

Fig. 3 *Residual normal stress on the the first gearwheel before machining holes (a – area No. 1, b – area No. 2, c – area No. 3)*

On the maps we can observe the normal tensile stresses on the left marked in red (the area close to the hardened part of the gear), the transition area where the residual stresses reach their minimum values. The stresses are therefore distributed in a robust manner and nothing disturbs their progression. The scattering of the measurement could be caused by pores in the material. This is a consequence of sintering since the sintering temperature does not reach the melting temperature of the material.

From the measurement results, it is clear that undesirable tensile stresses are generated on the cloudy gearing. This is caused by the hardening process itself, which produces a martensitic structure characterised by high internal stresses that weaken the material and cause the product to lose its toughness.

2.2 Drilling

The drilling of the holes was carried out on a Mazak Turn Nexus 100 II turning centre. The holes were drilled in three gears. The tool used was drill bits with diameters of 4, 5, 6 mm. The cutting parameters recommended by the tool manufacturer were selected when drilling all the holes diameters, these parameters are shown in Table 1.

***Tab. 1** Cutting parameters drilling*

Cutting parameter	Value	Units
Frequency turning spindle **n**	2500	min^{-1}
Speed displacement **vf**	3000	$mm.min^{-1}$

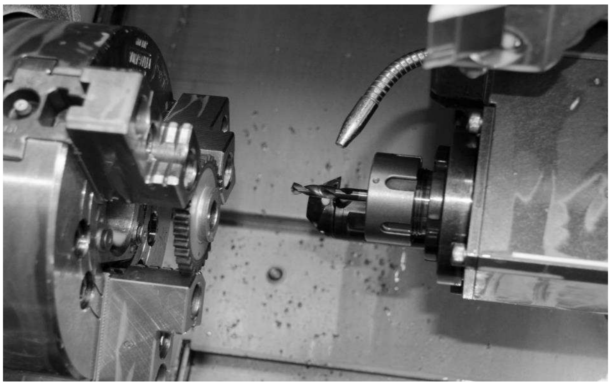

***Fig. 4** Drilling holes in the gearwheels*

Holes were drilled in the center of the marked locations (Fig. 2) to act as stress relievers and we observed how the residual stresses in their vicinity changed. We drilled different diameters of holes in the gears shown in Table 2.

***Tab. 2** Diameter of drilled holes*

Gear	Number of holes	Hole diameter [mm]
1	3	4
2	3	5
3	3	6

***Fig. 5** Gearedwheels after drilling holes*

2.3 Residual Stresses after Drilling

Similarly, to the pre-machining, after machining we measured the residual stresses at the 3 locations on the gears shown in Fig. 5. To illustrate this, we have selected some examples of measurements before and after machining.

In the maps (Figs. 6, 7, 8) we can see a comparison of the measured residual stresses of the investigated areas before and after boring holes of different diameters (Tab. 2). The drilled holes are represented by white spots on the maps, also taking into account the diameter of the drilled hole. Before drilling the holes, we can observe a uniform distribution of stresses with increasing tensile stresses towards the hardened gearing. The maximum values of tensile stress and compressive stress were 176.4 MPa and -105.4 MPa, respectively. After the holes were drilled, the measured values of residual stresses increased for tensile and compressive stresses to 139.6 MPa and -130.2 MPa, respectively.

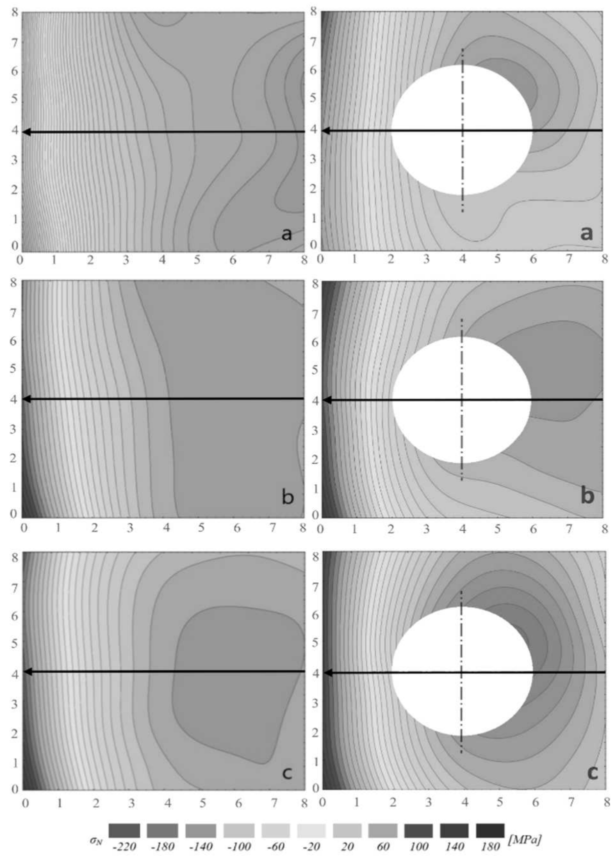

***Fig. 6** Residual stresses measured before and after machining on the first gearwheel*

A similar change in residual stresses was observed on the second gear, where the maximum values for compressive stresses and tensile stresses were -157.9 MPa and 142.3 MPa, respectively, before drilling. After drilling a 5 mm diameter hole, the values increased to 180.3 and -219.2 MPa for tensile and compressive stresses, respectively.

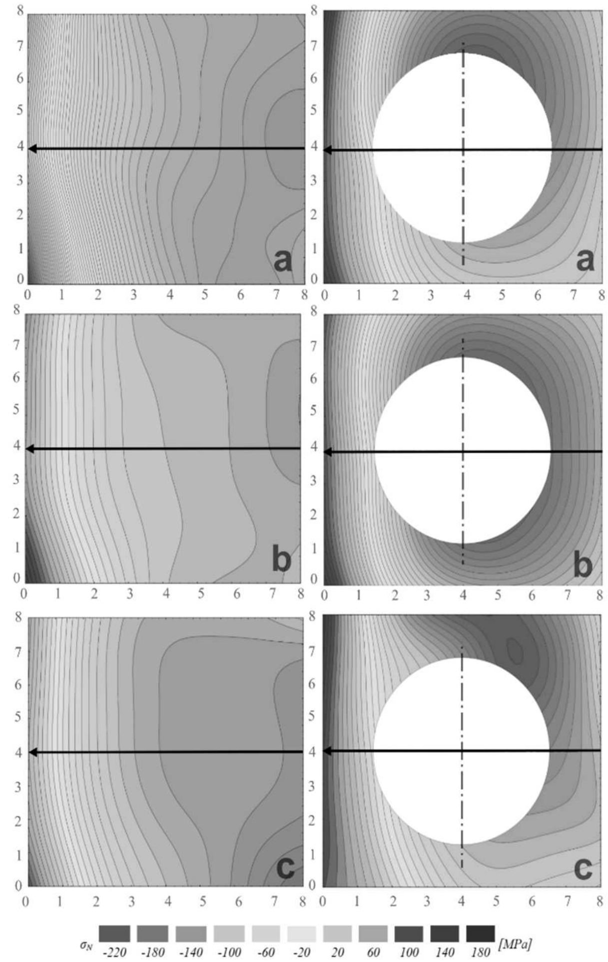

Fig. 7 *Residual stresses measured before and after machining on the second gearwheel*

For the third gear, where the drill bit with the largest diameter of 6 mm was used, the residual stresses can be seen in the graph (Fig. 8).

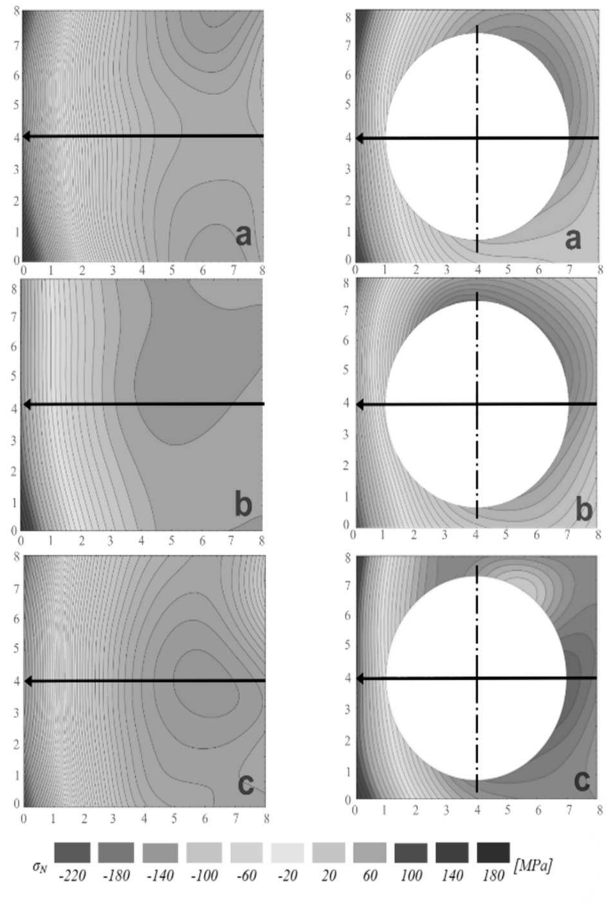

Fig. 8 *Residual stresses measured before and after machining on the third gearwheel*

3 Summary results measurements

Table 3 presents the numerical values of the maximum residual stresses.

Tab. 3 *Maximum values residual stresses measured after drilling holes (in MPa)*

		I. Gearwheel			II. Gearwheel			III. Gearwheel		
		I	II	III	I	II	III	I	II	III
Before machining	Max. Tensile stresses	90.8	176.4	152.1	142.4	147.3	142.3	150.8	156.4	120.7
	Max. Compressive stresses	-107.2	-105.4	-120.3	-106.3	-124.9	-157.9	-110.5	-112.2	-113.1
After machining	Max. Tensile stresses	141.7	139.6	125.5	148.5	155.9	180.3	148.2	119.4	170.2
	Max. Compressive stresses	-138.6	-130.2	-175	-192.6	-194.7	-219.2	-148.1	-186.1	-204.7

A summary of the results of the residual stress measurements is shown in the graphs below. The graphs show the maximum measured values of residual stresses in the individual areas before and after machining. The Fig. 9 we can see the decrease of the maximum values of residual stresses.

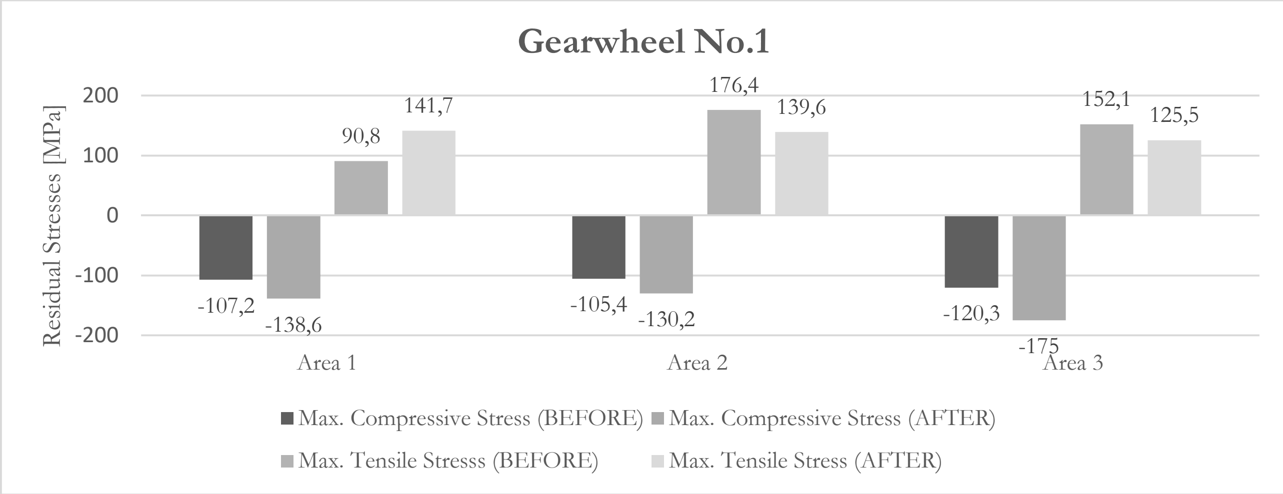

Fig. 9 *Maximum residual stresses measured before and after machining on the first gearwheel (in three areas)*

Gear No.2 (Fig. 10) in the individual measured areas showed unstable residual stresses during the measurement. The tensile stresses did not change significantly, whereas the compressive stresses increased radically. In the third measured region, the measured stresses increased by more than 30 %.

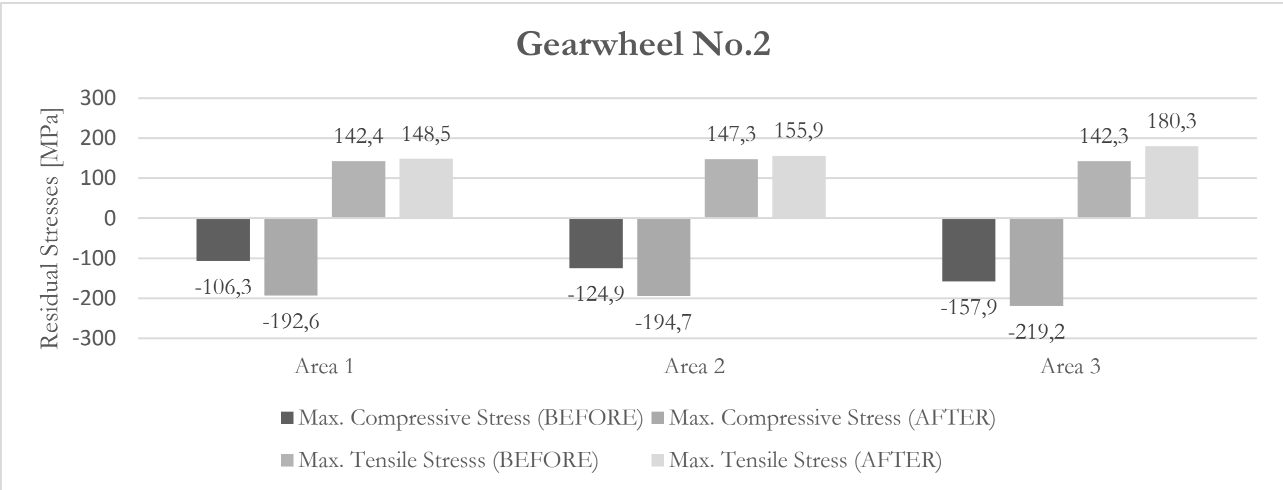

Fig. 10 *Maximum residual stresses measured before and after machining on the second gearwheel (in three areas)*

The third wheel, with a 6 mm hole (Fig. 11), shows the greatest differences before and after drilling the holes. Increases in compressive stresses were observed in all measured regions. In the third measured area, the maximum values of compressive stresses increased up to almost 100%.

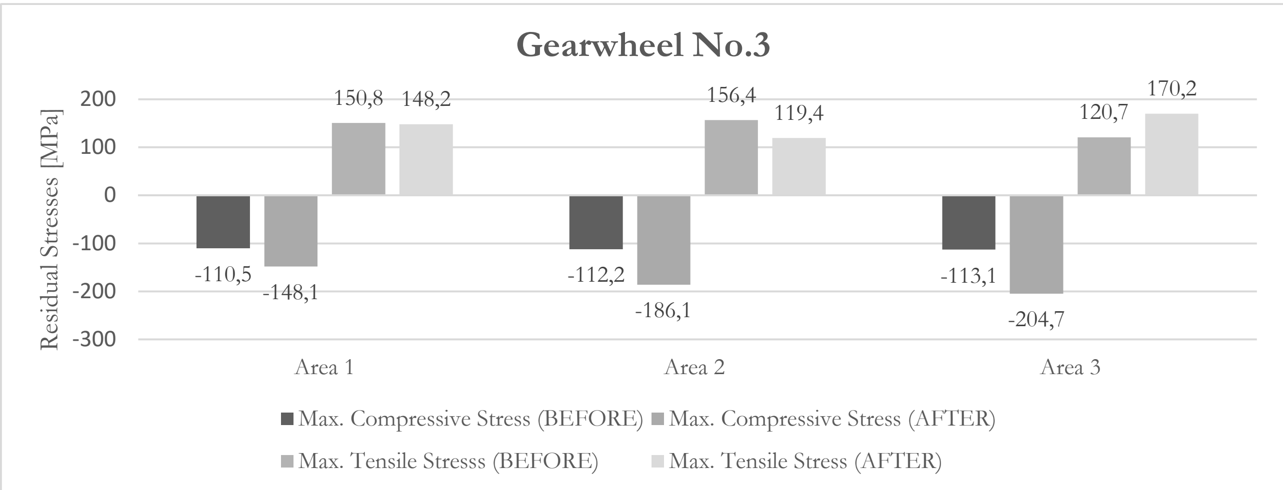

Fig. 11 *Maximum residual stresses measured before and after machining on the third gearwheel (in three areas)*

The results demonstrate the effect of the drilled holes diameter on the magnitude of change in residual stresses. As the hole diameter rises, the effect on the increase in stresses also moves upwards.

4 Evaluation and conclusion

The paper deals with the investigation of residual stresses in surface layers since there was a requirement for non-destructive measurements in terms of the actual manufacturing process. The problem was the occurrence of cracks, which were formed in the area affected by induction hardening weakened after milling, due to weight reduction. By replacing milling with drilling and the proposed non-destructive analysis of its effect on surface stresses, the problem was solved.

The research consisted in investigating the stress states around the circumference of the wheels (on the face of the gearing) and also on the unhardened part of the wheel. We found that due to the structure of the component, produced by sintering the material, relatively high variance of the nominal values can occur. The hardened gearing was characterized by tensile and the unhardened gear core by compressive residual stresses. After subsequent drilling, in order to reduce the weight of the gear, changes in the stress states around the drilled holes were demonstrated.

The drilling the selected hole diameters (4, 5 and 6 mm) did not fundamentally affect the functionality of the component. A problem could arise with larger drilled hole sizes or by changing the cutting parameters during drilling. The measured values of residual stresses show some dependence, with the magnitude of the change also depending on the size of the drilled hole. The largest increase was observed when drilling a 6 mm diameter hole, when the stress values increased by 80%. As the diameter of the drilled hole increases, the likelihood of tensile stresses increases, with an associated increase in the risk of damage to the component. The bills of materials indicate a tensile strength of Rm= 475 MPa and since a maximum tensile stress of 180 MPa has been measured, it can be assumed that the gears have sufficient tensile reserve before gear failure (breakage) occurs. Of course, this fact depends on the total load on the gear itself in real operation. However, it can be assumed that the compressive stress values (max. -220 MPa) should have a more significant effect on the required service life of the wheel.

The presented research demonstrated the effect of machining on the formation of residual stresses. Weight reduction is applicable in several industries, making the work not only theoretical but also of practical relevance to practice.

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