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Analysis of single tracks of IN718 produced by laser powder directed energy deposition process

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Abstract

Despite the powerful capabilities of the Laser Powder Directed Energy Deposition (LP-DED) process, the applications are limited almost to feasibility analyses of simple case studies. This arises from the knowledge gap in the process parameters identification and optimization of the deposition quality. A practical approach is to delineate the process parameters window by producing single tracks with different sets of parameter levels. This paper aims to study, through statistical analysis, the effect of process parameters on the characteristic dimensions of IN718 single tracks. Results will allow empirical relations to be identified between track geometry and the analysed parameters. These relations will support process optimization.

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Keywords: Additive Manufacturing; Directed Energy Deposition; Laser deposition; Single track; Statistical analysis; Melt pool

1. Introduction

The potentialities of Additive Manufacturing (AM) technologies are nowadays recognized as the future of manufacturing in different sectors such as aerospace, automotive and electronics [1-3]. Considering metal-based technologies, different AM techniques are available, among which Directed Energy Deposition (DED) opens up new perspectives. In Laser Powder-Directed Energy Deposition (LP-DED) metal powders are fed by means of a deposition head directly into a melt pool generated by a focused laser beam. When the laser moves away, the molten material solidifies, and a raised track is obtained [4]. The main potentialities of the LP-DED process are the ability to produce large components, the possibility to change material during the deposition process, thus producing multi-graded material parts, and the ability to repair damaged components [4-7].

In the LP-DED process, three fundamental mechanisms can be highlighted that are the powder stream, the melt pool

generation and the solidification process [8]. Among them, the melt pool generation represents the initialization of the track, and for this reason, its optimization and control are crucial aspects in process characterization [4,9].

A huge number of process parameters are involved in LP-DED, however, the parameters that most significantly influence the temperature distribution, and consequently the melt pool dimensions and the track geometry, are the powder feed rate, the travel speed, and the laser power [8]. Several studies have been performed in order to study the effect of these process parameters on the dimensions and the shape of the deposited track [10], that according to Toyserkani *et al.* [11] can be described by means of three geometrical parameters that are track width, track height and penetration depth.

In the literature, the effect of process parameters on the morphology of the deposited track has been investigated using both numerical simulations and experimental investigations [4]. Numerical simulations allow obtaining suitable results in a relatively short time. However, it should be noted that, in most

of the cases, numerical simulations use strong assumption and simplifications and the results obtained from these simulations suffer from these adjustments. Hence, the experimental investigation is always necessary to verify the assumptions used in the simulations. Moreover, it is also possible to highlight that significant phenomena cannot be observed using numerical simulations [12].

In the following, the main results obtained from experimental investigations are summarized. As concerns the laser power, available studies in the literature confirm that as the laser power increases, larger track width are obtained as a consequence of the higher temperature of the melt pool [13–19]. However, contradictory results are present in the literature regarding the effect of laser power on the track height. Pinkerton and Li [20] and Peyre *et al.* [17], observed that the values of the laser power did not influence the track height of steel and titanium alloys, and thus the track height remained almost constant. Conversely, Srivastava *et al.* [15], during the production of titanium alloy tracks, revealed that by increasing the value of laser power, a reduction of track height was obtained. Also, Lee *et al.* [16] and Pinkerton and Li [19] showed that the height of tool steel tracks increases with laser power. Sreekanth *et al.* [21], during the deposition of the IN718 track observed that, before a critical value, the track height decreases with increasing the laser power; however, after the critical value, the track height increases with laser power.

As regards the travel speed, there is large evidence that it strongly influences the geometry of the deposited track. According to Hua *et al.* [13], by increasing the travel speed, the maximum temperature reached in the melt pool decreases, and as a consequence, a smaller melt pool width is expected. Yellup [18], during the deposition of 304 stainless steel, confirmed that at low laser power values, the track width slightly decreased by increasing the travel speed. This result was confirmed by Hu *et al.* [14], Srivastava *et al.* [15], Pinkerton and Li [20] and Lee *et al.* [16] during the deposition of 1050 steel, Ti48Al2Mn2Nb, 316L stainless steel and M4 tool steel, respectively. However, it was observed that for 304 stainless steel and IN718, at high levels of laser power, the dimension of track width was not significantly affected by the travel speed [18,21]. On this point,

Hu *et al.* [14] identified a threshold value of the travel speed at which the layer width is almost unaffected by the variation of process conditions and was equal to laser beam diameter. Similarly, Yellup [18] and Srivastava *et al.* [15] found that before a critical value, the layer height increased by increasing the travel speed. After this critical value, a decreasing trend was observed, increasing the travel speed. The critical value depends on the feedstock material, laser power and deposition head z-increment. Accordingly, Hu *et al.* [14] and Pinkerton and Li [20] reported that the track height was inversely proportional to the travel speed.

From the literature emerges that most of the studies have been implemented on the steel or titanium alloys, and only few studies analysed the effect of process parameters on the geometry of the melt pool in the nickel-based superalloys.

In this work, IN718 single tracks were produced by means of the LP-DED process by varying process parameters following a Design of Experiments (DoE) approach. The statistical analysis allowed us to investigate the effect of laser power and travel speed on the geometry of the deposited single tracks. Regression analysis was performed to relate process parameters and deposited track geometry.

2. Materials and methods

In the following sections, the equipment and the procedures used to carry out the experimental investigation are described.

2.1. Material

Single tracks 20 mm long were deposited using a Prima Additive Laserdyne 430 system. The system is characterized by a working area of $585 \times 400 \times 500 \text{ mm}^3$ and it is equipped with a 1 kW fiber laser. In this work, single tracks of IN718 were deposited on a substrate of the same material. The substrate was a disk with a diameter of 100 mm and a thickness of 10 mm. Gas atomized IN718 powders with a spherical shape and with a diameter ranging between $44 \mu\text{m}$ and $106 \mu\text{m}$ were used as feedstock material. From the micrograph of powder particles at 500x magnification, which is reported in Fig. 1, it was possible to observe that on the powder particles surface, satellites and partially melted small particles can be embedded.

2.2. Single tracks production

Single tracks were deposited with different combinations of laser power, P , and travel speed, v , according to a full factorial DoE plan. The DoE included two factors, three levels each and two replicates, for a total of 18 tests. The factors and the corresponding levels are reported in Table 1. In this study, the powder feed rate was taken constant to exclude the effect of the flow inertia. As a matter of fact, this is a preliminary study on IN718 by LP-DED with the main focus of analysing the effect of the input energy density on the deposited track.

Table 1. Process parameters and their values used in DoE.

Factors	Levels
Laser power, P (W)	300 – 500 – 700
Travel speed, v (mm/min)	450 – 900 – 1350

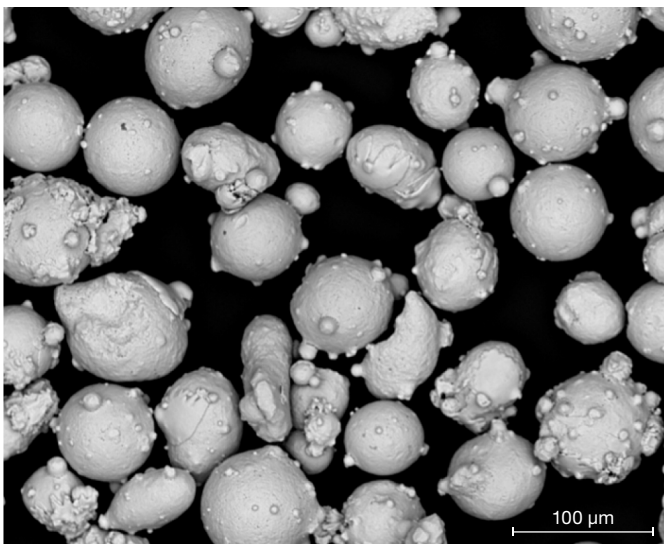


Fig. 1. SEM micrograph of IN718 powder particles (500x magnification).

2.3. Characterization and analysis

The substrates with the deposited single tracks were cut using TR 100S (Remet S.a.s, Italy) cutting machine in order to obtain the cross-sections of the single tracks. Subsequently, the cross-section of each single track was ground and polished using a Minitech 233 (PRESI Sàrl, Switzerland) polishing machine. In fact, the metallography of the single track started with the grinding using different SiC abrasive paper, with a grain between #180 and #4000, followed by final polishing with diamond pastes 3 μm and 1 μm . Thereafter, the as-polished surface was chemically etched using Kaling No.2 etchant to facilitate the measurement of the dimensional features of the melt pool. Afterwards, an optical microscope was used to acquire the optical micrographs of the melt pools. The dimensions of the deposited tracks were measured, namely the track width, w , the track height, h , and penetration depth, d .

Analysis of variance (ANOVA) was also applied to the DoE in order to evaluate if the variation on the track dimensions, selected as the responses, is explained by the variation of process parameters selected in this study, and to evaluate which parameters are statistically significant. Lastly, a regression analysis was performed to model the relationship between the track dimensions and the process parameters. The full factorial

DoE definition and the experimental analysis were performed using Minitab® 20 Statistical Software (Minitab LLC, USA).

3. Results and discussion

In this paragraph, the main results obtained in the present paper will be illustrated. Firstly, the results of ANOVA for the dimensions of the tracks are described. Then, the analytical relationships between track dimensions and the selected process parameters are presented.

3.1. Single tracks production

All the single tracks were successfully deposited using the process parameters reported in Table 1. From the visual analysis performed on the top view, the single tracks looked stable and showed a good regularity. In fact, it was observed that all the tracks were characterized by an almost constant value of track width, and no macro defects such as particle agglomerates were observed. Therefore, to avoid the influence of the edge effects, it was decided to cut and analyse the single tracks from the middle of their length. Top views and cross-sections after the chemical attack of the single tracks, obtained from the two replicates, are reported in Fig. 2. From cross-

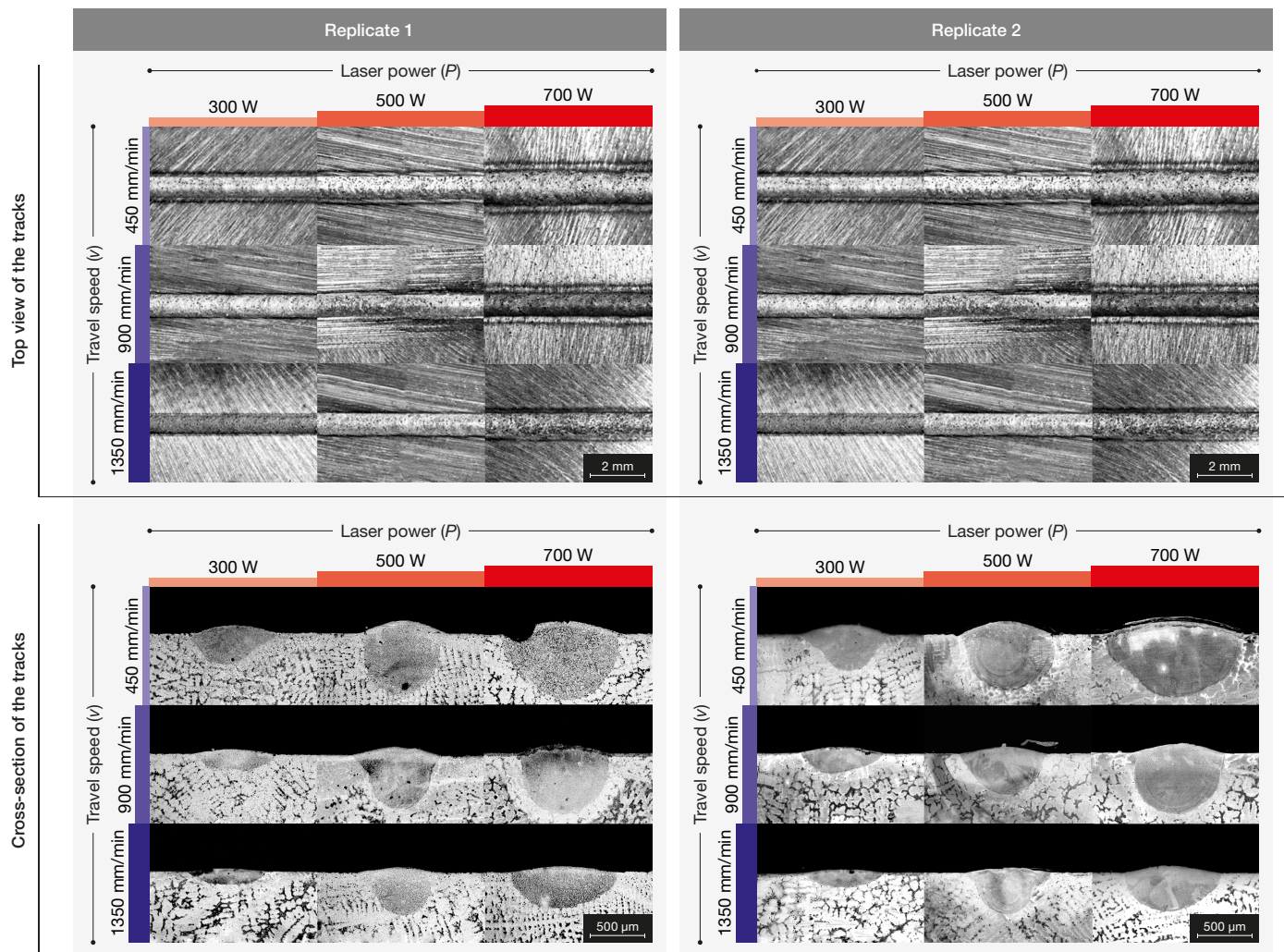


Fig. 2. Top view and cross-section of IN718 single tracks obtained from the two replicates.

Table 2. Results of the analysis of variance for the track width, *w*.

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	8	556019	69502	22.67	0.000
Linear	4	435118	108780	35.48	0.000
<i>P</i>	2	279571	139786	45.60	0.000
<i>v</i>	2	155547	77773	25.37	0.000
2-Way interactions	4	120901	30225	9.86	0.002
<i>P</i> · <i>v</i>	4	120901	30225	9.86	0.002
Error	9	27590	3066		
Total	17	583609			

S	R-sq	R-sq(adj)	R-sq(pred)
55.3675	95.27%	91.07%	81.09%

section analysis, it was observed that all the tracks had a good adhesion with the substrate. Thus, the selected process parameters are suitable for the deposition of the single tracks.

3.2. Analysis of variance on the track width

Table 2 reports the outcome of ANOVA on track width, and it was observed that the DoE was able to explain over 91% of the width variation. Results showed that both laser power and travel speed significantly influenced the variation of the track width, being both factors characterized by a p-value lower than 0.05. Moreover, the interaction between the two selected factors was statistically significant in the analysis.

From the main effect plot represented in Fig. 3 it is possible to see that the track width continuously increased with increasing the laser power. Moreover, it could be observed that a sharp variation of track width was obtained when the laser power varied from 500 W to 700 W.

Considering the travel speed, it was revealed that the mean value of the track width sharply decreased when the speed value varied from 450 mm/min to 900 mm/min. A further increase of the travel speed to 1350 mm/min did not induce a significant track width variation. This can be attributed to the fact that through the variation of the travel speed from 900 mm/min to 1350 mm/min, the Marangoni thermocapillary force increased significantly and consequently enlarged the melt pool dimension.

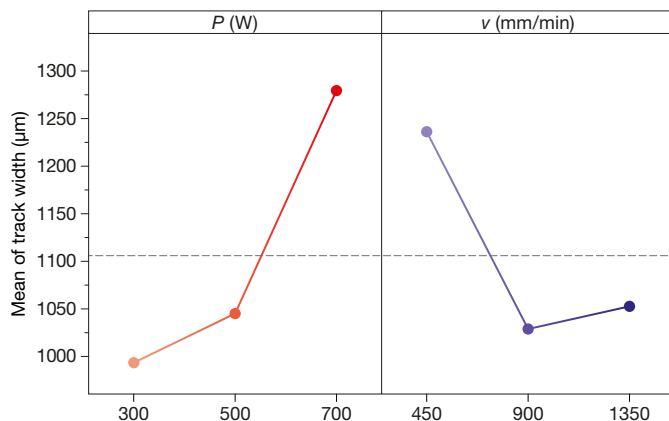


Fig. 3. Main effect plot for the track width, *w*.

Table 3. Results of the analysis of variance for the track height, *h*.

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	8	35933	4492	39.65	0.000
Linear	4	35378	8844	78.08	0.000
<i>P</i>	2	8977	4489	39.63	0.000
<i>v</i>	2	8977	13200	116.53	0.000
2-Way interactions	4	555	139	1.23	0.366
<i>P</i> · <i>v</i>	4	555	139	1.23	0.366
Error	9	1020	113		
Total	17	36952			

S	R-sq	R-sq(adj)	R-sq(pred)
10.6432	97.24%	94.79%	88.96%

3.3. Analysis of variance on the track height

The results of ANOVA obtained for the track height are summarized in Table 3. Results showed that the present DoE explained approximately 89% of the variation of the track height. From these results, it can be seen that both the laser power and the travel speed were statistically significant. However, the interaction between the selected factors, from a statistical point of view, did not significantly influence the variation of the analysed response. This means that the overall effect of a factor is completely independent from another one, and as a result, it is possible to study each factor, i.e. laser power or travel speed, individually.

The main effect plot in Fig. 4 illustrates the effect of laser power and travel speed on the main value of the track height. Results showed that the highest values of the track height were obtained when the high values of the laser power and low values of the travel speed were adopted. From the graph, it was also possible to observe that the track height increased with laser power almost linearly.

The travel speed had an opposite effect, and by increasing the travel speed, the track height decreased with an almost linear trend. From a physical point of view, as the laser power increased or as the travel speed decreased, a higher level of thermal energy density was available to melt the material. Consequently, a larger amount of powder was melted, and a higher track height was obtained.

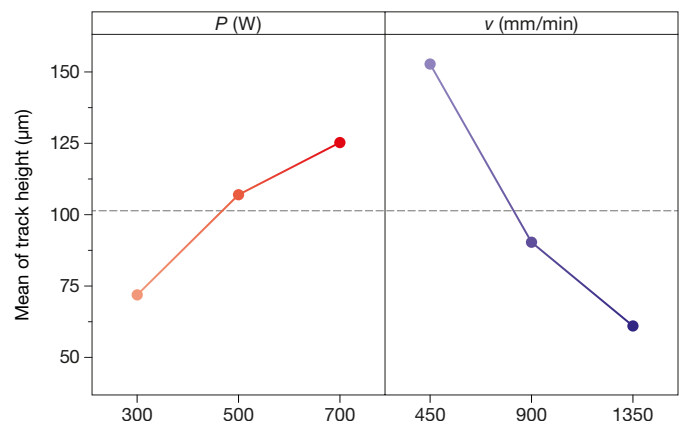


Fig. 4. Main effect plot for the track height, *h*.

Table 4. Results of the analysis of variance for the penetration depth, d .

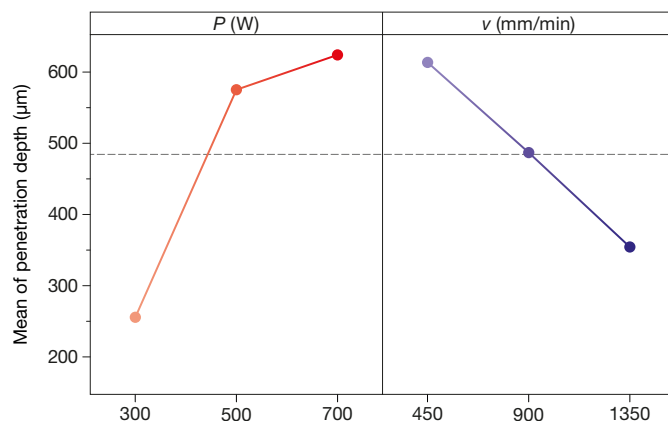
Source	DF	Adj SS	Adj MS	F-value	P-value
Model	8	716720	89590	20.93	0.000
Linear	4	684529	171132	39.99	0.000
P	2	482482	241241	56.37	0.000
v	2	202047	101024	23.60	0.000
2-Way interactions	4	32191	8048	1.88	0.198
$P \cdot v$	4	32191	8048	1.88	0.198
Error	9	38519	4280		
Total	17	755239			

S	R-sq	R-sq(adj)	R-sq(pred)
65.4204	94.90%	90.37%	79.60%

3.4. Analysis of variance on the penetration depth

Finally, the outcomes of ANOVA related to penetration depth are reported in Table 4. Analogously to track height, the penetration depth was highly influenced by laser power and travel speed, and their interaction was not statistically significant. The DoE explained about 90% of the variation of the penetration depth.

The main effect plot represented in Fig. 5 shows how the selected factors influenced the penetration depth. It was possible to observe that the maximum value of penetration depth was associated with the maximum laser power and the minimum travel speed corresponding to the highest value of specific energy. In particular, from the graph, it was possible to observe that the penetration depth decreased linearly when increasing the travel speed. The laser power strongly influenced the value of the penetration depth by varying the value from 300 W to 500 W. Then, from 500 W to 700 W, only a slight increase was observed. This behaviour confirmed the thermal mechanisms described above. In fact, in the range of laser power between 300 W and 500 W, the main phenomenon was the thermal conduction, and the heat was transferred downwards to the substrate, increasing the penetration depth. Varying the laser power from 500 W to 700 W, the thermal behaviour was governed by the convective flows caused by Marangoni forces, and the heat was transferred laterally acting on the track width. In other words, the surplus of energy

Fig. 5. Main effect plot for the penetration depth, d .

introduced in the system from 500 W to 700 W does not significantly change the depth of penetration but acts on the width of the molten pool, allowing for larger tracks.

3.5. Regression equations

Considering the evidence from the ANOVA analysis, a linear regression analysis was performed in order to model the mathematical relations between the process parameters and the analysed responses. The regression analysis performed on the selected data sets led to the following equations:

$$w = 932.0 + 0.716 \cdot P - 0.2044 \cdot v \quad (1)$$

$$h = 125.9 + 0.135 \cdot P - 0.1020 \cdot v \quad (2)$$

$$d = 282.8 + 0.923 \cdot P - 0.2883 \cdot v \quad (3)$$

Results of regression analysis showed that the obtained equation allows predicting the value of the track height, Eq. (2), and the penetration depth, Eq. (3), with a good approximation. In fact, the R-sq of these equations was 90% and 78%, respectively. On the contrary, the regression equation of the track width, Eq. (1), was characterized by a R-sq of 54%. This means almost half of the variation of the track width was explained by the variation of the selected parameters P and v .

4. Conclusion

In this work, the effect of laser power and travel speed on the characteristic dimensions of IN718 single tracks were analysed. Several tracks were deposited on an IN718 substrate according to the design of experiment, and the track sections were observed to extract dimensional data. All the tracks were successfully produced, characterized and then statistically analysed. All in all, the following conclusions can be drawn:

- Both laser power and travel speed statistically had a significant influence on the values of the track width, the track height, and the penetration depth. The interaction between the two factors was statistically relevant only for the variation of the track width
- A threshold value of the laser power of 500 W was defined at which a change in thermal behaviour was observed. Before the threshold, the thermal behaviour was mainly influenced by conduction. After the threshold, the thermal behaviour was mainly governed by Marangoni flows
- Regression equations were identified in order to identify analytical relations between the track dimensions and the process parameters. The equations were able to describe with a good fit the trend of track dimensions, namely the track width, w , the track height, h , and penetration depth, d . In the range of process parameters analysed in this work, regression equations could be used to estimate the effect of process parameters on track dimensions in order to reduce expenses in experiments for process optimization

Future works should include the effect of powder feed rate on the geometry of the deposited tracks. Moreover, other variables that it is necessary to investigate are the standoff distance, the shielding gas flow and the powders average size.

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