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Improvement of Machining Thin-Walled Parts Generated by Hybrid Manufacturing Using Optimized Support

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Abstract

This paper is intended to show the problem in the production of thin-walled parts using hybrid manufacturing. It is necessary to machine the parts generated by 3D printing at certain stages of the production process. The problem can occur when machining thin-walled parts. This paper shows a way of change the critical depth of cut by adding a supporting structure instead of changing the cutting parameters.

Key words: Hybrid Manufacturing, Additive Manufacturing, Lattice Structure.

1. Introduction

The hybrid manufacturing has been on the rise for the past decade because it combines the benefits of machining process with an additive manufacturing. The machines for hybrid manufacturing are mostly five-axis rotary milling machines with an additional laser welding head either as a new axis or as a holder for clamping into spindle.

Figure 1. *Deposition of a nozzle for a rocket engine made of stainless steel (X5CrNiMo17-12-2): ø 450 × 470 mm, approx. 10 h machining time incl. 6-sided turn & mill complete machining. [1]*

The machines for hybrid manufacturing have no issue with final machining with respect to the roughness of surfaces and geometrical accuracy because the parts are machined during 3D printing. The Hosnedls [2] paper describes how thickness and height of the material play a major role in changing the critical depth of cut. There is thin-walled plate supported by several types of support structures. The author writes, that more suitable conditions for machining have been created by choose a suitable support structure.

The issue during the basic design of support structures lies in complexity of generating the support structures. Therefore, for the basic design, it is preferable to replace support structures by a body with a full volume of material but reduced density and reduced elastic module. (See Figure 2).

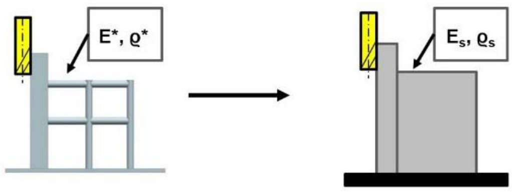

Figure 2*. Replacement of support structure by a solid body with a full volume of material*

Many papers deal with how accurate the replacement of foam or support structures (printing by additive manufacturing) by a one homogenic solid body is. One of the first papers defined the equation (1) by Gibson and Ashby [3].

$$\frac{E^*}{E_S} = C\left(\frac{\rho^*}{\rho_S}\right)^2 \qquad (1)$$

Here E^* is the elastic modulus of the support structure, E_s is the elastic modulus of the solid material, C is a constant that has been experimentally determined to have a value of 1 and q^* and q_s is the density of the support structure and solid material respectively.

The equation (1) has been used in many papers. Many papers dealt with the accuracy of the equation compared to the FEM calculations and the tests. It is worth mentioning that the work of K. Hazlehurst et al. [4], describing the differences between mechanical tests, FEM results and calculation according to Gibson. Hazlehurst came to an interesting result that the difference between the calculation according to Gibson and FEM varied by around 10%. But the difference

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between the mechanical test and the above-mentioned calculations was by tens of percent.

Most of the studies that compare the replacement of the lattice or the foam structures by solid material are intended for the base cells (same repeating elements) up to 1 mm in size. This paper is focused on the basic cells of tens of millimetres (eg 21 mm).

2. Designing a support structure using a solid body

In this study, the calculation is considered for a thin-walled plate that has been loaded with modal force. The modal force was vertical to the plate on its the upper surface. The dimension of the plate are: length 150 mm (L), height 150 mm (H) and thickness 5 mm (T). The density and mechanical properties were chosen for carbon steel.

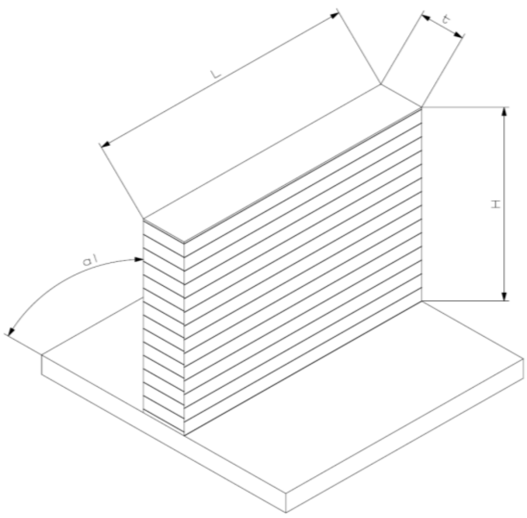

Figure 3. *The model of plate with dimension*

The support structure of thin-wall plate

This support structure consists of cubic cells that form a complete grid (see Figure 4). The dimensions of one cell are 21 x 21 x 21 mm. The bar diameter is 5,5 mm. The square cell was selected from a viewpoint of a more accessible shape on the three-axis machine which was available.

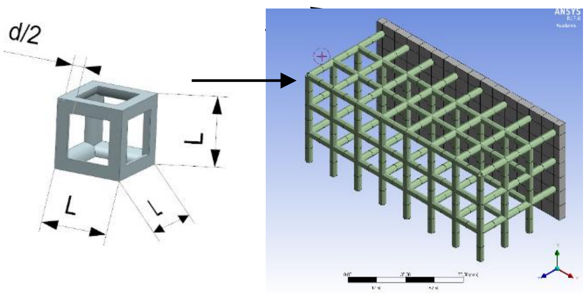

Figure 4 *The sample of the support structure*

Mechanical properties of the solid body

In the first phase, it was necessary to solve the correct ratio of the density and the elastic modulus of the supporting structure to the spare full volume.

The density was taken from ratio (2).

$$\frac{V^*}{V_s} = \frac{\rho^*}{\rho_S} \qquad (2)$$

Here V^* is the volume of the support structure (measured from the CAD model). V_S is the volume of solid material enveloping of the support structure. ϱ^* is the density of the support structure and ϱ_S is the reduced density of solid material.

The elastic modulus of solid material has been solved in software Ansys. In the first phase, the critical depth of cut was calculated for the chosen thin-wall plate supported by grid of square cells. In the second phase, the grid of square cells was replaced by solid material with reduced density embedded in the envelope of the support structure and elastic modulus was calculated for the known critical depth of cut from the previous calculation. The results are in the Table 1.

Table 1 *The density and the elastic modulus for the support structure and the solid body*

	Density [kg/m^3]	Elastic modulus [Pa]
Support structure	7850	2,1*10^9
Solid body	1000	8,1*10^8

The parametric model of solid body

The parameter-controlled volume of material with modified properties was attached to the thin-wall plate to determine the optimal dimension of envelope of support structure. It was calculated in Ansys. On the Figure 5 there is a sketch of parametric model which has four parameters for changing shape (height - B, length - A, length of chamfer – A2 and height of chamfer – B2).

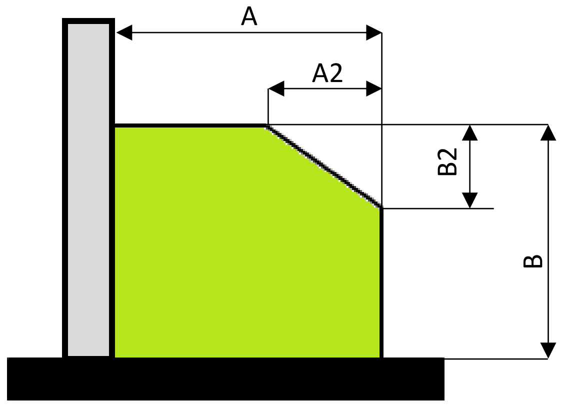

Figure 5 *A sketch of parametric model of solid body*

The optimization program was set to look for the optimal shape of a support. The support must meet of criteria: Minimum weight of support system and the limit depth of cut around 0,5 millimetres for thin-walled plate. Where all the dimension of parametric model be able to change only in 21 millimetres increments. Which corresponds to the chosen grid. The assumption of depth of cut around 0,5 mm is based on consideration that machining is only considered to improve surface roughness and geometric accuracy. This assumption indicates that this is only a final machining. It can also be assumed that the height of the printed layer can be aligned by machining. The depth of cut for aligned of height by machining is less than 0,5 mm, it follows from the tests at the Department of production machines and equipment.

The dimensions for parametric model are A = 105 mm, A2 = 63 mm, B = 126 mm, B2 = 42 mm. The next phase, the support structure with dimensions according to the parametric model was created with in CAD software (see Figure 6). The mechanical properties of the support structure were calculated. The results are in the Table 2.

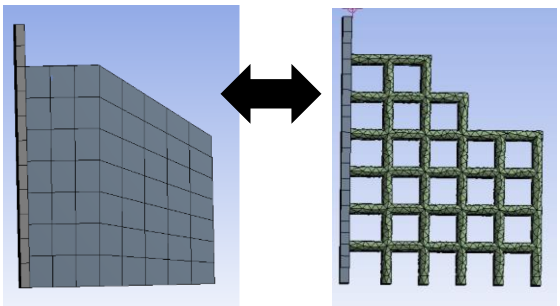

Figure 6. *Difference between the solid body and the support structure from the calculated optimal model*

Table 2 *The density and the elastic modulus for the support structure and the solid body*

	Weight [kg]	Limit depth of cut [mm]
Support structure	1,95	0,46
Solid body	1,79	0,41

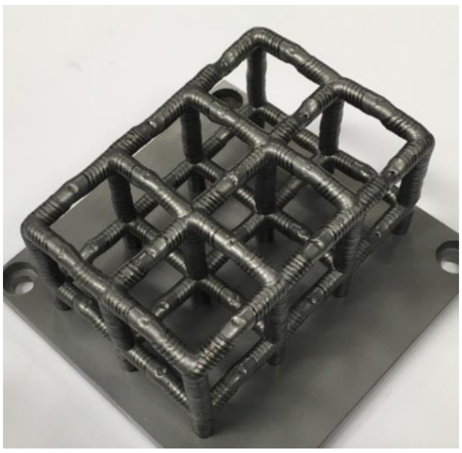

Figure 7 *The support structure from the first tests*

Treatise on price and time-consuming

Generally, for small parts, which are simple in shape are not pay off printing in terms of the difficulty of preparing NC programs, and printing times. This claim may not apply for complex shape parts or parts from hard-to-cut material.

If we do not consider the programming time of the NC program, but only the printing time, we get to the production time of about one hour for the structure shown in Figure 7. The weight of this support structure is about 0,2 kg. The printing cost for the machine tool, which it is at the department, is from 2 500 to 3 000 Kč/kg. The thin-walled plate is not as time consuming as support structure. On the Figure 8 is printed thin-walled plate with dimension: length 60 mm, height 70 mm and thickness 5,5 mm and the height was machined for each printed layer. The printing time for this plate is about one hour.

We can conclude from this information that the printing and machining time for the calculated optimal model may be about ten hours and the price may be about nine thousand Czech crowns. The weight of the plate is about nine hundred grams and the weight of the support structure is about two kilos.

3. Conclusion

Thin-wall plate, which is generated by 3D printer on hybrid machine, is supported by the grid square cells. This support is intended to improve the mechanical properties of the thin plate support system. The production time is prolonged by 3D printing (this is true for both the thin-wall plate and the support structures). The price of the product increases with the printing time. But on the other hand, if the thin-wall plate is not supported and is only machined, there is a possibility that it will not be possible to machine the part for large heights, or the machining time will enormously increase.

This paper shows what procedure can be chosen for the design of the support mechanism. This procedure is a replacement of the support structure by the full volume

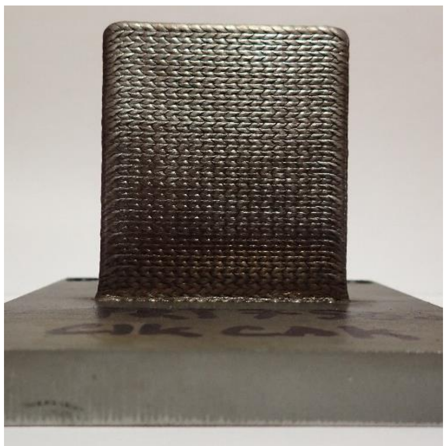

Figure 8 *The thin-walled plate from the first tests*

of material embedded in the envelope of the support structure. This paper shows what procedure can be chosen for the design of the support mechanism. This procedure is a replacement of the support structure by the full volume of material embedded in the envelope of the support structure. This new solid body has reduced density and reduced elastic modulus in comparison with the real support structure.

When comparing the FEM results of a substitute model of a beam structure with a designed support structure in the CAD program, the difference in the depth of cut is within a tenth of a millimetre. It can be assumed that a substitute model of the support structure can be taken into account for the rapid determination of optimal support from the point of view of FEM.

Acknowledgements

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The list of symbols

A	The length of solid body (mm)
A2	The length of chamfer (mm)
B	The height of solid body (mm)
B2	The height of chamfer (mm)
C	Constant (-)
d	The diameter of rod of cell (mm)
E^*	The elastic modulus for the support structure (Pa)
E_S	The elastic modulus for the solid body (Pa)
FEM	Finite element method
H	Height of plate (mm)
L	Length of plate or cell (mm)
T	Thickness of plate (mm)
V^*	The value of the support structure (mm3)
V_s	The value of the solid body (mm3)
α	Rotation angle of plate (°)
ρ^*	The density for the support structure (kg/mm3)
ρ_S	The density for the solid body (kg/mm3)

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