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Passive safety features of parts produced by rapid prototyping technologies

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S u m m a r y. The article presents a new tool for modeling parts produced by rapid prototyping (RP) technologies that has great potential for building structures with programmable properties, especially for items related to the energy dissipation during deformation. Using a wide variety of building materials and controllable part growing is the most important benefit for industry implementation of RP technology. Mass deployment is also hampered by the high price of equipment and materials for the technology.
K e y w o r d s: Rapid prototyping, passive safety, stress-strain diagram,

INTRODUCTION

Rapid prototyping (RP) is an advanced manufacturing technology commercialized since the middle of 80s. At present, RP technology is widely used in engineering for conceptual and functional models. There are many commercial RP systems available on the market today such as stereolithography (SLA) [Jacobs P.F., 1995], selective laser sintering (SLS) [Abe F., Osakada K., Shiomi M., 2001], fused deposition modelling (FDM) [Too M.H., Leong K.F., Chua C.K., Du Z.H., Yang S.F., Cheah C.M. and S.L. Ho, 2002], laminated object manufacturing (LOM) [Fazil O., Sonmez H., Thomas Hahn, 1998], three dimensional printing (3D printing) [Sachs E., Cima M., Cornie J., 1990] and etc [Luqi R., Steigerwald G., Hughes V., Berzin A., 1991, Herranz A., Moreno-Navarro J., 2003, Gil A., Kowalski P., Wańczyk K., 2011, Pysz S., Karwiski A., Czekaj E., 2009]. The main principle all of them is that machine is building the part by adding layers of new material to the previous one. This building goes under full computer control based on the 3 dimensional computer model of the part.

OBJECTS AND PROBLEMS

Processes description. All RP systems have a limit on type and properties of materials that can be used. Usually it is a wide range of polymers or even low temperature melting metals. It is possible to select some common properties for parts that will be built due to the common principals of building (layer by layer). In this work were described RP processes, that use the heat energy to melt the material, to bind two layers together (FDM, SLS).

FDM uses special head that is feed by the thermoplastic filament, then the head is melting thermoplastic and moving in X-Y plane to form the proper layer configuration on the table (fig. 1). After the layer is completed, the table lower in Z direction to the height of one layer (Z step) and machine begins the next layer according the 3D computer model.

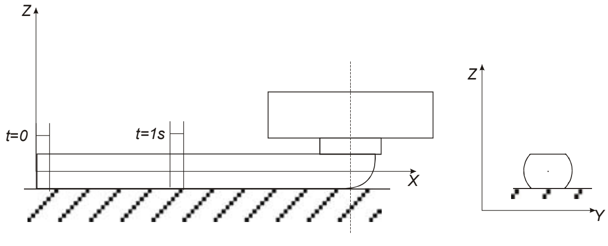


Fig. 1. FDM process scheme

SLS uses the layer of powder on the table that is melted by laser beam to form one layer configuration. On the next step the machine puts the next layer of powder on the table and process repeats till the height of powder will reach the actual part height.

Properties analysis. Even when the properties of original material are well known it is impossible to use it for future construction calculation (for example FEA). Parts will be anisotropic and material properties will depend on a lot of parameters [Rodrigues J.F., Thomas J.P. and Renaud J.E., 2001], such as the form of the construction (design), orientation of the part, original material properties, filling and regimes of the manufacturing.

Tests show the great difference in properties of parts made by casting (monolithic) and by RP from the same material [Ahn S.H., Montero M., Odell, 2002]. The ability to predict final properties, during the design and preparation stage allows to find an optimal way of manufacturing. Among the most significant data for future FEA stay the tensile strength and preliminary stresses in the part. Both depend on the strength of bonding two neighbor layers or paths. To predict this bonding the model of the process was built.

In the beginning of the process, the first path of melt material lays down on the foam foundation (fig. 2). This material comes out the FDM tip with diameter *D*, with the temperature near the liquid state ($T_0 = T_{liq}$). After distortion, material begins to cool, it brings the volume decreasing and creates temperature compress stress and shrinkage.

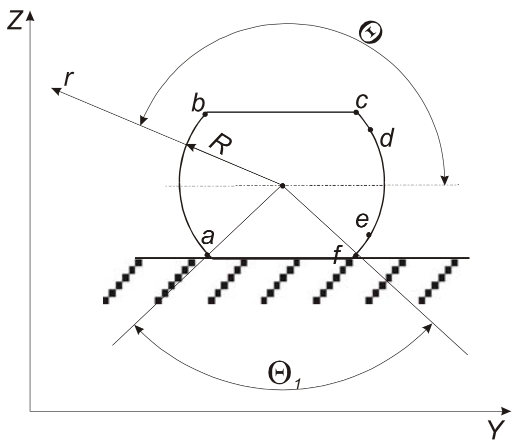


Fig. 2. Distorted material intersection (1 level)

During cooling, material gives out the heat energy to the air (*a-b-c-d-e-f surface*), to the foundation (*f-a surface*). Edge element *X=0* gives out the energy to the air, edge element on the other side $X=X_i$ contacts with the new, just distorted intersection.

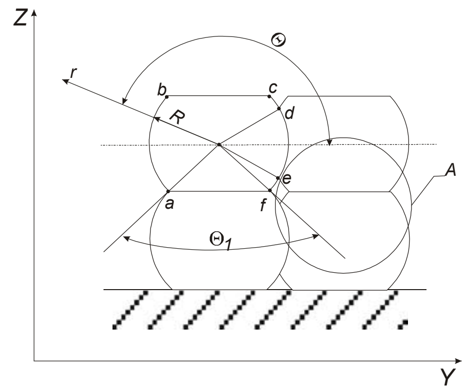


Fig. 3. Model of the process

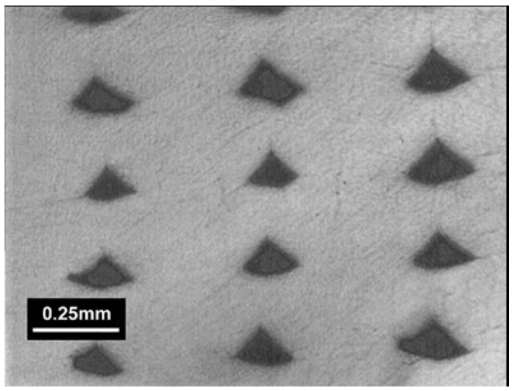


Fig. 4. Real part intersection

For the second (next) layer building (fig. 3), the surface *e-a* contacts with the previous slice. During this contact, the heat energy is melting the previous level (fig. 5). The depth of this melting d_{liq} is the main parameter, that defines the strength of layer binding. We can define three different material states: the liquid ($T>=T_{liq}$), with the depth d_{liq}; the transitional (d_t - d_{liq}); and the hard one ($T<T_{liq}$).

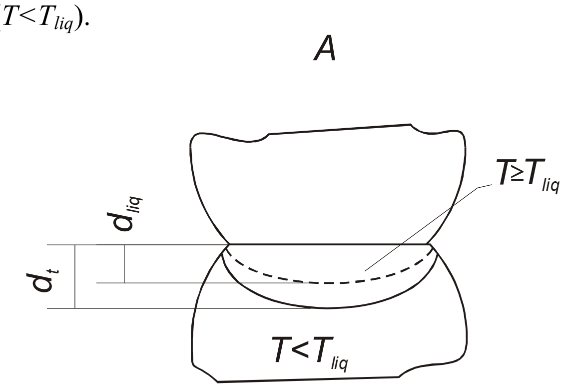


Fig. 5. Depth of material melting (penetration)

In side direction (*Y*) material will contact with the neighbour curve, on the surface d-e, and it will define the strength of side binding.

The value of bonding depends on the dliq and the length of contact (*d-e*). Sector (*d-e*) is in direct dependence on overlapping of curves and on other generates parameters (width, gap, etc.).

Temperature field in the materia

$$\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \Theta^2}+\frac{\partial^2 T}{\partial Y^2}=\frac{1}{a}\frac{\partial T}{\partial t}, \quad (1)$$

where: r,Θ,Y – cylindrical coordinate; a – coefficient of temperature conduction $\left(a=\lambda/c\right)$; λ – coefficient of heat conduction; c – specific thermal capacity; t – time.

Initial conditions for this problem are the following

$$\text{when } t=0, T(r,\Theta,Y,t)=T^0_{\Pi Л}. \quad (2)$$

Boundary conditions are the following:

- there is convectional heat exchange on the area $a-b-c-d$ (fig.3) when

$$r=R\cdot f(\Theta), \Theta'_a \le \Theta \le \Theta'_d, \frac{\partial T}{\partial r}+\frac{\alpha_1}{\lambda}\left(T-T'_0\right)=0, \quad (3)$$

where: α_1 – coefficient of heat release; T'_0 – build envelope temperature (environment temperature);

– on the area $a-c$ and $d-e$ material contacts with foundation or with the cool material

$$\lambda\left(\frac{\partial T}{\partial r}\right)_{r=+R}=\lambda_\Pi\left(\frac{\partial T_\Pi}{\partial r}\right)_{r=-R}, \Theta''_d \le \Theta \le \Theta''_e, or, \Theta''_c \le \Theta \le \Theta''_a, \quad (4)$$

where: λ_Π – coefficient of heat conductivity of foundation (or cool material); T_Π – foundation (old material) temperature;

– on the left side

$$\text{when } X=0,, \frac{\partial T}{\partial X}+\frac{\alpha_2}{\lambda}\left(T-T''_0\right)=0, \quad (5)$$

where: α_2 – coefficient of heat release of this side;

– on the right side for contact with new material

$$Y=l,, \lambda\left(\frac{\partial T}{\partial Y}\right)_{Y=+l}=\lambda\left(\frac{\partial T^0_{\Pi Л}}{\partial Y}\right)_{Y=-l}. \quad (6)$$

It is convenient to seek the solution of problem (1)-(6) in form:

$$T(r,\Theta,Y,t)=\sum_{n=0}^{N}\Phi_n(r)a_n\cos n\Theta\cdot\exp(-k_0 t)Y^n, \quad (7)$$

where: $\Phi_n(r)$ – the function of only r argument ; a_n, k – undefined coefficients.

It is possible to reach a solution of this equation, based on Bessel function of first and second kinds.

This decision defines the temperature distribution in the part. This allows to create simulation of cooling process. Temperature inequality causes the non-linear deformation of form. Using the apparatus of thermo elasticity, it is possible to predict the elementary volume deformation

$$\varepsilon_x=\frac{1}{E}\left[\sigma_x-\gamma(\sigma_y+\sigma_z)\right]+\alpha T;$$
$$\varepsilon_y=\frac{1}{E}\left[\sigma_y-\gamma(\sigma_x+\sigma_z)\right]+\alpha T;$$
$$\varepsilon_z=\frac{1}{E}\left[\sigma_z-\gamma(\sigma_x+\sigma_y)\right]+\alpha T; \quad (8)$$
$$\gamma_{xy}=\frac{\tau_{xy}}{G};$$
$$\gamma_{yz}=\frac{\tau_{yz}}{G};$$
$$\gamma_{xz}=\frac{\tau_{xz}}{G},$$

where: ε_{ij} - deformation of elementary volume, %; σ - stress, MPa; γ,α - coefficients; γ_{ij} - shearing; E - elastic (Young's) modulus, MPa; G – shear modulus, MPa; T – temperature field $T(x,y,z,t)$, obtained before. It is necessary to point that this model will work properly for amorphous materials and not good for crystalline due to the great specific volume variation during the solidification [Gibson I. Shi,D, 1997]. But especially this reason limits the application of such materials in RP.

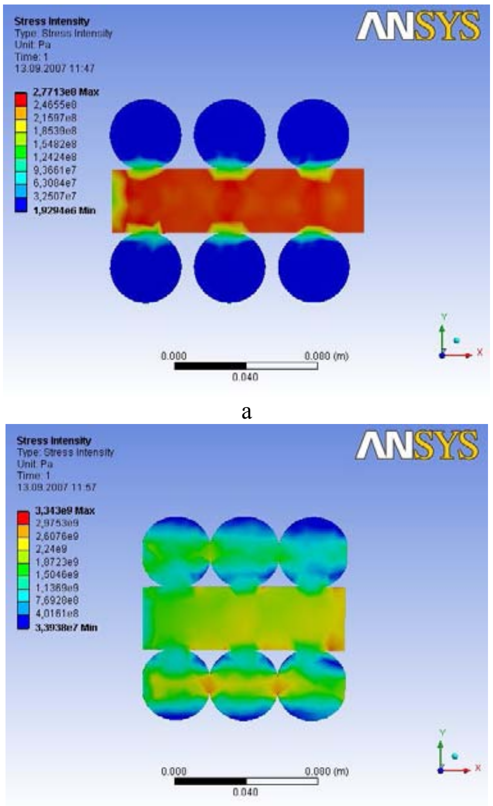
To receive stress and shearing, it is convenient to use the potential energy of deformation. Final deformation (shrinkage) of the part will be resulted as a sum of elementary volume deformations

$$u_x=\int\varepsilon_x dx+C_1; \quad (9)$$
$$u_y=\int\varepsilon_y dy+C_2;$$
$$u_z=\int\varepsilon_z dz+C_3,$$

where: C_1, C_2, C_3 – are defined by the boundary conditions.

From one side, the temperature field gives the opportunity to find the depth of penetration of one layer to another. It will depends on the boundary of $T=T_{liq}$ (temperature of liquid state). From other side, slicing process (RP preparation stage) arranges almost all necessary data for analysing the part as a sum of elementary volumes. These two details allow to predict the tensile strength in different directions.

The analyse of compression behaviour of specimen produced by FDM technology is possible with the help of FEA (fig. 6). The strength of filaments bonding was calculated according to the value of d_{liq} and the length of contact (*d-e*) (fig. 5).



a

b

Fig. 6. Deformation of FDM structures: a – initial state, b – final state

Two different mechanisms work during compression that produces bilinear stress-strain diagram in elastic mode. First slope (fig. 7) is caused by elastic behaviour of interlayer links (fig. 6a). The same slope continues till neighbour filaments meet each other and start theirs compression (fig. 6b). In the point of theirs meeting will be the breakpoint of stress-strain diagram, because two different mechanisms produce the force of deformation.

Honeycomb structure of RP parts (fig. 4) gives a unique opportunity to create constructions with controllable passive safety characteristics. The energy of deformation can be easily calculated with the help of stress-strain diagram of specimen compression.

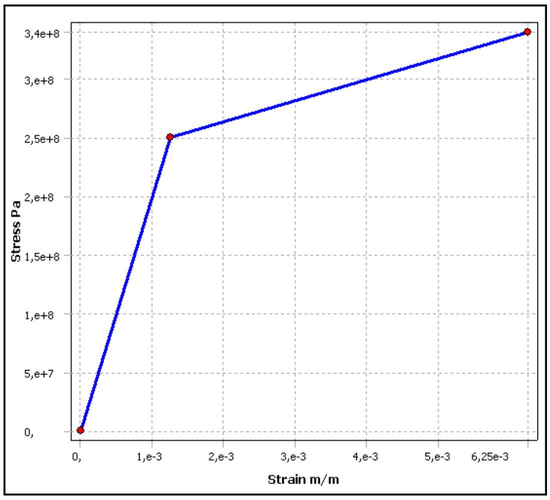


Fig. 7. Stress-strain diagram of RP specimen during compression test

CONCLUSIONS

RP technology is pretty new instrument of parts building and has a great potential for building constructions with programmable properties, especially for a lot of applications connected with energy dissipation during deformation. Ability to control all bindings in the part individually gives an opportunity to create very flexible programs of deformation, even programs that will be very close to optimal ones. Interlayer links determine the first slope of stress-strain diagram and can be changed by regimes of part building. The second slope connects with material characteristics and can be changed only for the part at all. Building material is the most critical factor that breaks the development of RP technology in industrial area. The second factor that breaks mass implementation is the high price for equipment and material for real rapid manufacturing applications.

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СВОЙСТВА ПАССИВНОЙ БЕЗОПАСНОСТИ ДЕТАЛЕЙ, ИЗГОТОВЛЕННЫХ ТЕХНОЛОГИЯМИ БЫСТРОГО ПРОТОТИПИРОВАНИЯ

Андрей Фалалеев, Елена Ноженко

Аннотация. В статье рассмотрен новый инструмент для моделирования деталей, произведенных с использованием технологий быстрого прототипирования, которые имеют большой потенциал для создания конструкций с программируемыми свойствами, особенно для элементов, связанных с диссипацией энергии при деформации. Возможность использования большого разнообразия материалов и управляемой схемы выращивания деталей является наибольшим преимуществом данной технологии, в то время как массовому внедрению технологий в промышленность препятствует высокая цена на оборудование и материалы.

Ключевые слова: RP технология, пассивная безопасность, диаграмма деформация

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