Materials Research Proceedings 44 (2024) 433-443 https://doi.org/10.21741/9781644903254-47

Semisolid deposition of metallic material by extrusion-base analytical and simulative methodologies

BRUNI Carlo

Università Politecnica delle Marche -DIISM, Via Brecce Bianche 3, 60100 Ancona, Italia

c.bruni@univpm.it

Keywords: FDM, Analytical Modeling, Finite Element Simulation, Magnesium Alloy

Abstract. The objective of the paper is the analytical and finite element simulation study of the material behaviour at temperatures of 400 - 450°C of AZ31 and ZM21 magnesium alloys tested for bulk metal working. In the extrusion, representing the main phase of the fused deposition modeling, the metal work material considered was a bulk magnesium alloy billet. The stress and deformation fields are reported in detail using analytical modeling to describe the material in a very small volume of a extruder. It is observed that the increase in the extrusion temperature also determined by the deformation and friction heat produces an increase in the thermal load particularly visible in the high deformed zone. This allows the obtaining of the semisolid condition for the material described by the temperature levels reported by the numerical simulations. Such technology results very useful for ribs deposition over flat surfaces.

Introduction

Today working of metal or polymeric materials requires the understanding of the material plastic flow in order to avoid all of the possible defects related with uncontrolled conditions getting voids and something similar in the bulk of the workpiece [1]. The material processes already known as additive manufacturing represent up today the most rapid way to realize physical models in different materials. When approaching metals the temperature managing represents the most important factor. That is why high temperature means shrinkage, warpage and oxide phenomena requiring subsequent treatments [2].

However the direct realization of a near net shape object under the additive manufacturing philosophy represents a useful task in order to realize fully metal parts with an effective layer by layer approach instead of the binder [3] or composite based ones. The latter requiring complex methodologies when separated materials are used.

But, the net shape realization of metal workpieces represents the real objective in such field. Different are the methods used that are SLS, SLM, jetting powder, fused filament and fused metal deposition to produce the desired metal object [4-8]. Even if the extrusion based one is the more simple to realize a semisolid filament to generate ribs and something similar [7-9]. Some studies appear also on microextrusion of material in which the tool is made by micro- EDM [10].

Of course the realization of extrusion trials at dimensions comparable with the millimiter and sub-millimiter order of magnitude could be sensitive to the friction conditions and subsequent heat generated. In general, the surface and bulk characteristics of the extruded object are function of the tool material contact interface [11-13]. Such contact in general increases the temperature of the extruded material by the nominal. The modeling of such behaviour can be found in literature and able to represent the micro-mesoscale. In particular, the thermal conditions for magnesium alloys as well as the modeling approaches whose variables, included the thermal-physical properties with temperature, is described by some researchers in [14-18].

Up today the FDM of metal material can be feasible not only for reduced complexity of tools and models typical of other technologies [19-20] in realizing components for high precision assemblies, but also for a traditional approach in working metals consisting of in temperature deformation and semisolid manufacturing in order to obtain the desired geometry of the filament. The pressure to material to feed can be imposed by a screw or a drum or a feed forward system in which a solid filament is heated by induction coil and deposited under semisolid condition.

Of course the process conditions need to be strictly monitored in order to avoid lack of respect of the filament requirements. Among the different variables such as deformation, strain rate, geometry of the container and of the tool, the most important is the temperature and temperature variation during working. The possibility to realize metal ribs by a semisolid filament could be a valid and sustainable solution in all of the situations in which metal powder is difficult to treat directly.

To do that the modeling of the extruding apparatus represents useful for understanding and controlling the manufacturing tools.

In literature different scientific works related to material behaviour [8-9,12] under extruding conditions and material flow description using analytical and non analytical methods such as numerical simulations in different conditions in terms of strain, strain rate, temperature and friction can be found. Some of them are concentrated on uniform and non uniform deformation, friction and subsliding effects in order to obtain the effective stress – strain conditions and the effective temperature values for load evaluation purposes.

The extrusion of lightweight alloys was investigated in the past by the author and other researches and the studied completed with the material behaviour knowledge [21, 22]. But the extrusion at millimeter and sub-millimiter order of magnitude, that is the filament metal deposition, at high temperatures is still under investigation being a promising technique to realize additive manufactured metal components. Under such conditions the understanding of the effect of the deformation and friction on the temperature represents still today an objective of the current research above all when low amount of material needs to be treated for filament deposition in particular for magnesium alloys.

The objective of the paper is the study through the analytical and finite element simulation of two magnesium alloys that are AZ31 and the ZM21 under extrusion conditions at elevated temperatures taking into consideration the effect of deformation and friction heating at 400-450°C. The stress and load obtained by an analytical modeling on both the materials and the temperature increase during forming is described. The thermal effect on the working tools studied by means of finite element simulation. It results that such methodology is very useful for determining the semisolid status for rib applications under the additive manufacturing philosophy.

Analytical and simulative procedures

The modeling of FDM for metal deposition of ribs is investigated by the realization of a proper procedural tool. Considering that the critical component of the system is represented by the extruder in which the material flow needs to be modeled two types of approaches are followed in such investigation. Fig. 1 shows the one based on the analytical modeling and the other one on the finite element simulation in order to describe both the tensional and the thermal behaviours inside the extruder. The billet of the initial radius of 3.5 mm was extruded to 2.5 mm over a length of about 14 mm included the cylindrical part of 10 mm.

By the analytical modeling the material flow during extrusion is described with the typical equations given by the slab method:

$$\sigma = \bar{\sigma} \cdot \frac{1+\mu cotg(\alpha)}{\mu cotg(\alpha)} \left(1 - \left(\frac{R_0}{R_f}\right)^{\mu \cot(\alpha)}\right). \quad (1)$$

$$\sigma_L = \sigma \cdot exp\left(\frac{2\mu}{R_0}\Delta l\right) \quad (2)$$

where:

σ: extrusion stress/tension

$\overline{\sigma}$: material flow

α : half cone angle

μ: friction coefficient

R_0: initial billet radius

R_f : final billet radius

σ_L : tension at the stem of the container

Δl: travel covered by the stem

The material behaviour is described by two models related to two different magnesium alloys that are the AZ31 magnesium and the ZM21 magnesium alloys. They are described by the two following equations proposed in [21, 22]:

$$\bar{\sigma} = K\varepsilon^n\dot{\varepsilon}^m \quad (3)$$

$$\bar{\sigma} = \beta_0 + \beta_1\varepsilon + \beta_2 \ln(\dot{\varepsilon}) + \beta_3 T^2 + \beta_4\left[exp\left(\frac{\varepsilon}{T}\right)\right]^2 + \beta_5\left[exp\left(\frac{\dot{\varepsilon}}{T}\right)\right]^2 + \beta_6\varepsilon^2 + \beta_7\dot{\varepsilon}^4 \quad (4)$$

with:

K: Material coefficient depending on Temperature

n: material coefficient depending on temperature

m: strain rate sensitivity depending on temperature

ε: deformation

$\dot{\varepsilon}$: strain rate

β_1, β_n : constant coefficients of equation.

By the previous equations the extrusion load can be calculated by using a 1.5/2 coefficient to consider the distortion effect with angles approaching 45°. The extrusion load calculated by the following:

$$L = \sigma_L \cdot \pi \cdot R_0^2 \quad (5)$$

The temperature increase due to deformation is obtained by balancing heat exchange as follows:

$$\Delta T_{def} = \frac{\beta\bar{\sigma}\Delta\bar{\varepsilon}}{\rho c} \quad (6)$$

Where $\beta=\beta_{hg}\beta_{hr}$ with β_{hg} is the percent of heat generated by deformation and β_{hr} is the percent of heat due remaining in the workpiece. $\Delta\varepsilon$ is deformation increment in the conical zone.

Materials Research Proceedings 44 (2024) 433-443 https://doi.org/10.21741/9781644903254-47

The friction heating is calculated by the following equation:

$$\Delta T_{attr} = \frac{\tau 2\pi R_0 \Delta l \cdot v \cdot t}{\rho V c} + \frac{\tau\pi(R_0^2 - R_f^2)\sqrt{\frac{tg\alpha^2+1}{tg\alpha^2}} \cdot \left(\frac{R_0 - R_f}{sin\alpha}\right)}{\rho V c} \quad (7)$$

while the temperature of the billet during cooling by tool contact calculated as:

$$T = T_{sup} + \left(T_0 - T_{sup}\right) exp\left(\frac{-\alpha A(t - t_0)}{\rho c V}\right). \quad (8)$$

Finally the total temperature of the billet due to different contributions given by:

$$T_f = \Delta T_{def} + \Delta T_{attr} + T \quad (9)$$

where:

t_0: initial time

v: velocity of the stem

t: time of displacement

ρ: density of material

c: specific heat

V: volume of the material

ΔT: temperature increment

T_{sup}: surface temperature of container and stem

T_0: initial temperature of the billet

ΔT_{def}: actual temperature increment of the billet due to deformation

ΔT_{attr}:actual temperature increment of the billet for the friction

T: actual temperature due to tool contact

T_f : total actual temperature of workpiece.

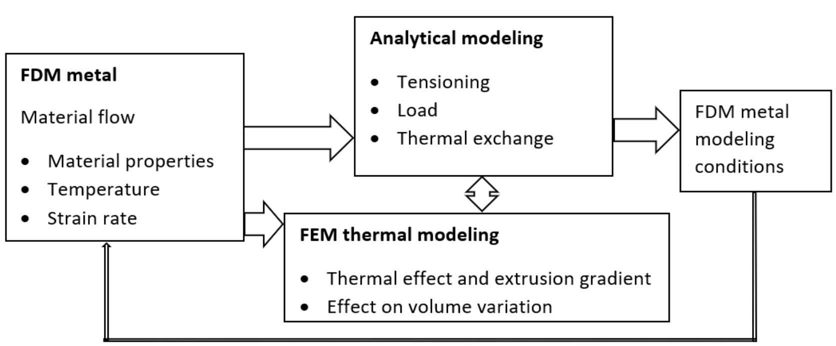


Figure 1 Procedure.

The previous equations by (1) to (9) are used to quantify the stress of the material inside the container and under the action of the stem. By those the temperature increase, under two nominal temperatures investigated that are 400° and 450°C, due to the deformation and friction heating was calculated and computed in a finite element simulation model.

The finite element analysis of the extruder behaviour was performed mainly in terms of the thermal load obtained by the imposed and during working generated temperature. The built model is characterized by an adaptive re-meshing. The heat flow and the thermal dilatation of the material and of the container in order to take chance to quantify elastic deformation and its effect on the extrusion are obtained. The material used for the stem and for the container was conventional tool steel. In Fig.2 a scheme of the extruding model is given.

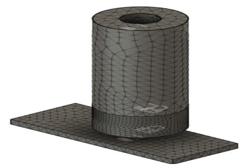


Figure 2 Extruding system model.

Results

For the temperatures considered in the study the equation (1) and (2) using the material models (3) and (4) proposed in previous works produce the results in terms of stress reported in Figs. 3 and 4. At 400° and 450°C for AZ31 magnesium alloy a slight decrease and then an increase in the stress vs. displacement curve is given in particular in the conical zone of the extruder in which the main deformation appears. In detail Fig. 3 reports the values at different levels of the displacement, while the Fig. 4 shows the same values increased to consider at the beginning the final stress values at the end of the extrusion phase. This provides useful information for project design evaluations at the extruder level.

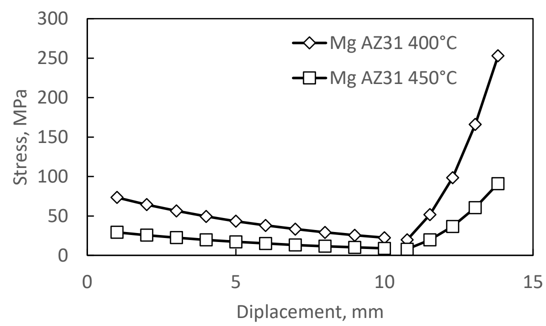


Figure 3 Stress behaviour for AZ31 Mg alloy during extrusion at 400° and 450°C.

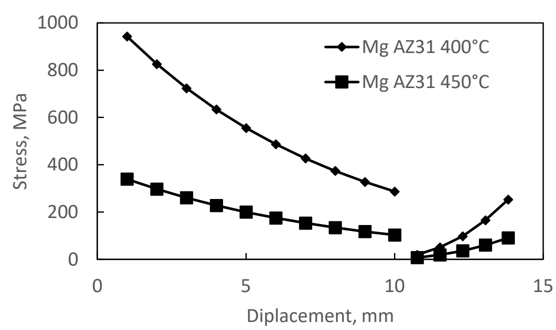


Figure 4 Stress behaviour for AZ31 Mg alloy during extrusion at 400° and 450°C increased to consider at the stem level the stress after the entire deformation.

Materials Research Proceedings 44 (2024) 433-443 https://doi.org/10.21741/9781644903254-47

Under the two temperature conditions also for the ZM21 magnesium alloy a decrease in tension until the beginning of the conical zone and then an increase can be observed as reported in Figs. 5 and 6.

The tensioning at 400°C is higher than the results obtained by the same equations (1) and (2) at 450°C. It means that under the conditions of the present investigation the high values of tension in the cylindrical part of the extruder depend on the friction while those obtained in the conical one are related mainly to the deformation.

The eq. (5) allows the calculation of the highest load that could be of about some tens of kN.

By those values of stress the temperature increase can be analysed in detail. In particular, by equation (6) and (7) the temperature contribution due to deformation and mainly that due to friction can be calculated, respectively. In figs. 7 and 8 the temperature increase in the cylindrical and conical zone for both magnesium alloys at 400° and 450°C is shown previously (condition 1) and after deformation (condition 2).

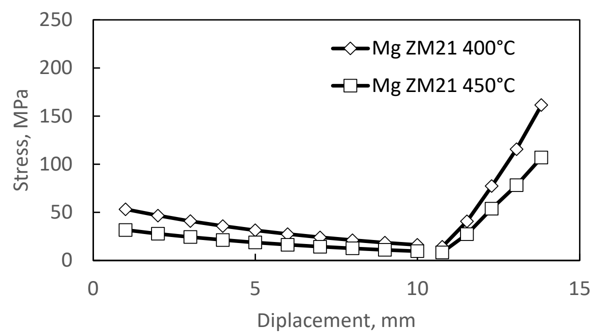


Figure 5 Stress behaviour for ZM21 Mg alloy during extrusion at 400° and 450°C.

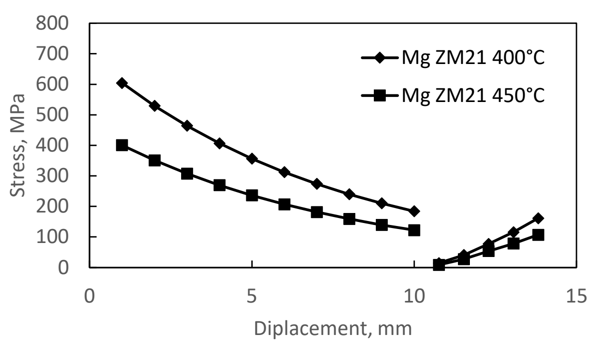
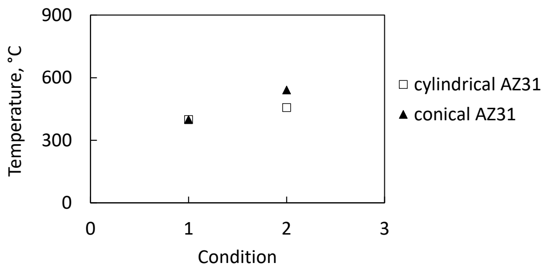
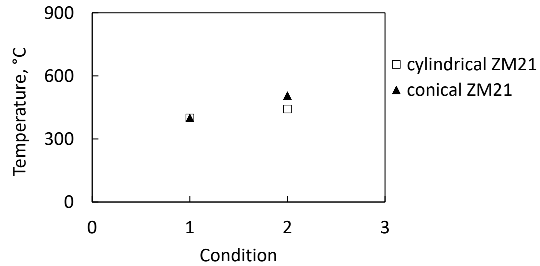


Figure 6 Stress behaviour for ZM21 Mg alloy during extrusion at 400° and 450°C increased to consider at the stem level the stress after the entire deformation.

Instantaneusly the local temperature can rise up to about 550°C for both AZ31 and ZM21 magnesium alloys due to friction and deformation at the conical zone and up to a temperature lower than the former in the cylindrical. If the cooling effect is not considered the temperature rise is able to produce the beginning of semisolid behaviour of the material under investigation notwithstanding the nominal temperature imposed. The material behaviour under similar conditions in terms of temperature is also reported in [8,9].

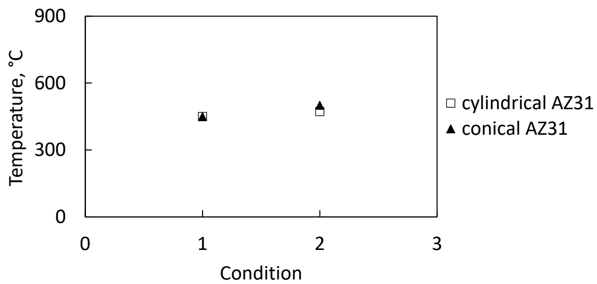


a)

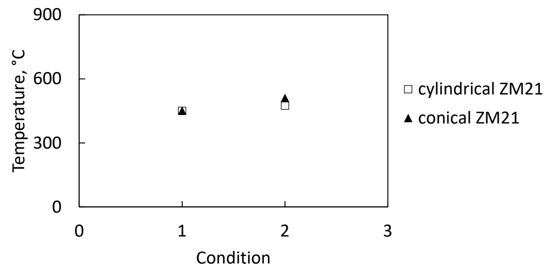


b)

Figure 7 Temperature increase for AZ31 Mg (a) and ZM21 Mg (b) alloy during extrusion 400°C increased for deformation and friction heating.



a)



b)

Figure 8 Temperature increase for AZ31 Mg (a) and ZM21 Mg (b) alloy during extrusion 450°C increased for deformation and friction heating.

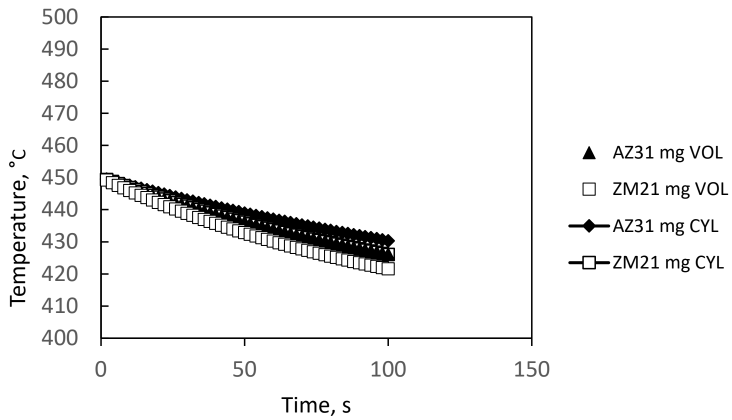
The temperature of AZ31 and of ZM21 mg alloys obtained by equation (8) related to the nominal at 450°C is reported in Fig. 9a) for the entire volume and the cylindrical part. The vacuum cooling condition that is 0 m/s air velocity is considered. The decrease is due mainly in the extruding system at the tool-material contact interface.

Due to the effect of the very low deforming volume considered that is of about some hundreds of cubic millimetres the real temperature rising is affected by a factor of 10^3 respect to conventional extruding problems. The cooling effect could reduce the temperature increase to maintain the above values. Such results are similar to those found for aluminium alloys under similar conditions [16, 23-25]. Fig. 9b) reports the temperature behaviour given by the equation (9) representing the whole temperature of the alloy considering all of the effects represented by the deformation and friction heating for the nominal temperature of 400°C, included the effect of cooling at the tool-material contact interface at the same temperature without such effects.

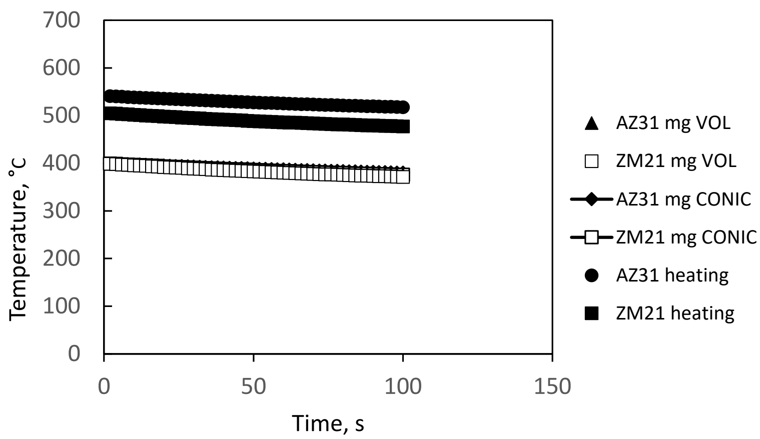
The temperatures determine an increase in the volume that produces deformations, displacements and tensions in the container with a given thermal flow at the specimen tool contact interface as can be observed in Figs. 10, 11 and 12. They report the real temperatures in the whole volume and in the conical zone approximated to 600°C in order to overestimate the effect of pressure on the tool, the elastic deformation amount at the extruder and on the material with related displacements.

The Fig. 13 reports the extruder behaviour under thermal load when the volume of material inside the container is less than that effectively available. At the deformation zone the pressure is equal to 50-65 MPa with a load not higher than 3.5-4.5 kN. Under such condition the analytical modeling is largerly able to describe the behaviour of the magnesium alloys under investigation.

Materials Research Proceedings 44 (2024) 433-443 https://doi.org/10.21741/9781644903254-47



a)



b)

Figure 9 Whole temperature behaviour for AZ31 Mg and ZM21 Mg alloys during extrusion at 450°C in the cylindrical and conical region: a) nominal temperature and b) temperature after deformation and friction heating.

a) b)

Figure 10 Extruding system (a) and temperature of magnesium alloy during extrusion at 450°C with the contribution of deformation and friction heating (b).

a) b)

Figure 11 Deformation of the extruder (a) and of the material magnesium alloy (b) during extrusion at 450°C with the contribution of deformation and friction heating.

Figure 12 Displacements in mm of the extruder wall at 450°C plus the contribution of deformation and friction heating.

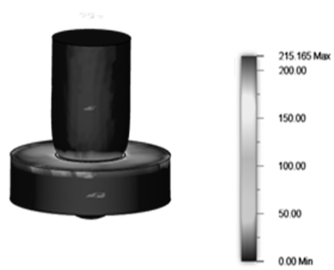


Figure 13 Pressure contact at the conical zone for temperature increase.

Summary

The study of the extrusion of magnesium AZ31 and ZM21 alloys in order to obtain semisolid condition useful for ribs deposition is performed.

The analytical modeling allows to determine the stress values of the materials under investigation knowing the behaviour for given conditions of temperature and strain rate. In detail, the flow stress distribution along the container represented by the cylindrical and the conical zone in which effectively takes place the deformation. Two different conditions were considered in terms of initial nominal working temperature that are 400° and 450°C. For both the conditions the effect of deformation and friction heating produces an increase in temperature up to a value not higher than 600°C. Such temperature is the most useful for determining the semisolid status for rib applications under the additive manufacturing philosophy. In particular when higher conicity angles than 15° do not allow to neglect distortion effects in the conical zone.

The increase in temperature determines a thermal load on the extruder evaluated by means of the numerical simulation getting an acceptable elastic deformation on the tools with a reacting force at least one order of magnitude less than the extruding force.

References

[1] S. Singh, G. Singh, C. Prakash and S. Ramakrishna, Current status and future directions of fused filament fabrication, Journal of Manufact. Proc. 55, 2020, 288. https://doi.org/10.1016/j.jmapro.2020.04.049

[2] M. Mousapour, M. Salmi, L. Klemettinen and J. Partanen, Feasibility study of producing multi-metal parts by Fused Filament Fabrication (FFF) technique, Journal of Manufact. Proc. 67 (2021) 438. https://doi.org/10.1016/j.jmapro.2021.05.021

[3] N. Kumar, V. Gupta, P. Saxena, A. Bajpai, C. Lahoda, J. Polte, Filament fabrication and subsequent additive manufacturing, debinding, and sintering for extrusion-based metal additive manufacturing and their applications: A review, Composites Part B 264 (2023) 110915. https://doi.org/10.1016/j.compositesb.2023.110915

[4] M. B. Jabłońska, Effect of the conversion of the plastic deformation work to heat on the behaviour of TWIP steels: a review, Archives of Civil and Mechanical Engineering 23 (2023) 136 https://doi.org/10.1007/s43452-023-00656-0

[5] S. Roshchupkin, A. Kolesov, A. Tarakhovskiy, I. Tishchenko, A brief review of main ideas of metal fused filament fabrication, Materials Today: Proceedings 38 (2021) 2063-2067. https://doi.org/10.1016/j.matpr.2020.10.142

[6] F. W. C. Farias, V. R. Duarte, I. Oliveira, J. da Cruz P. Filho, N. Schell, E. Maawad, J.A. Avila, J.Y. Li , Y. Zhang, G. Santos, J.P. Oliveira, In situ interlayer hot forging arc based directed energy deposition of Inconel® 625: process development and microstructure effects, Additive Manufacturing 66 (2023) 103476. https://doi.org/10.1016/j.matpr.2020.10.142

[7] A. I. Nurhudan, S. Supriadi, Y. Whulanza A. S. Saragih, Additive manufacturing of metallic based on extrusion process: A review. Journal of Manufacturing Processes 66 (2021) 228–237. https://doi.org/10.1016/j.jmapro.2021.04.018

[8] Y. Qi Li, F. Li, F. Wei Kang, H. Q. Du, Z. Y. Chen, Recent research and advances in extrusion forming of magnesium alloys: A review, Journal of Alloys and Compounds, 953 (2023) 170080. https://doi.org/10.1016/j.jallcom.2023.170080

[9] J. Feng, D. Zhang, H. Hu, Y. Zhao, X. Chen, B. Jiang, F. Pan, Improved microstructures of AZ31 magnesium alloy by semi-solid extrusion, Materials Science & Engineering A 800 (2021) 140204. https://doi.org/10.1016/j.msea.2020.14020

[10] S. A. Parasız , B. L. Kinsey, N. Mahayatsanun, J. Cao, Effect of specimen size and grain size on deformation in microextrusion, Journal of Manufacturing Processes 13 (2011) 153–159. https://doi.org/10.1016/j.jmapro.2011.05.002

[11] B. Meng, M. Wan, R. Zhao, Z. Zou, H. LIU, Micromanufacturing technologies of compact heat exchangers for hypersonic precooled airbreathing propulsion: A review. Chinese Journal of Aeronautics (2021) 34 79-103. https://doi.org/10.1016/j.cja.2020.03.028

[12] N. Krishnan, J. Cao, K. Doh, Study of the Size Effect on Friction Conditions in Microextrusion—Part I: Microextrusion Experiments and Analysis, J. Manuf. Sci. Eng. 2007, 129(4): 669-676. https://doi.org/10.1115/1.2386207

[13] Yu Y. , Hisanao K., Tsuyoshi, F, Effect of forming conditions on microstructure and room-temperature mechanical characterization of Zn–22Al superplastic microtubes fabricated by direct extrusion, Materials Science & Engineering A 844 (2022) 143160. https://doi.org/10.1016/j.msea.2022.143160

[14] M. Schewe, H. Wilbuer, A. Menze, Simulation of wear and effective friction properties of microstructured surfaces, Wear 464–465 (2021) 203-491. https://doi.org/10.1016/j.wear.2020.203491

[15] S. Li, X. Yang, J. Hou, W. Du, A review on thermal conductivity of magnesium and its alloys,

Journal of Magnesium and Alloys, 8 (2020) 78–90. https://doi.org/10.1016/j.jma.2019.08.002

[16] B. Liu, Y. Wang , Z. Lin, T. Zhang, Creating metal parts by Fused Deposition Modeling and Sintering, Materials letter 263 (2020) 127252. https://doi.org/10.1016/j.matlet.2019.127252

[17] N. Bontcheva , G. Petzov , L. Parashkevova, Thermomechanical modelling of hot extrusion of Al-alloys,followed by cooling on the press, Computational Materials Science 38 (2006) 83–89. https://doi.org/10.1016/j.commatsci.2006.01.009

[18] M. S. Kesler, M. L. Neveau, W. G. Carter, H. B. Henderson, Z. C. Sims, D. Weiss, T. T. Li, K. McCall, M. Glicksman, O. Rios, Liquid direct reactive interface printing of structural aluminum alloys, Applied Materials Today 13 (2018) 339–343. https://doi.org/10.1016/j.apmt.2018.10.005

[19] Huang, W., Chen, S., Xiao, J., Jiang, X., Jia, Y. Laser wire-feed metal additive manufacturing of the Al alloy. Opt. Laser Technol. (2021) 134, 10662. https://doi.org/10.1016/j.optlastec.2020.106627

[20] L. E. S. Paes, H. Santos Ferreira, M. Pereira, F. A. Xavier, W. L. Weingaertner, L.O. Vilarinho, Modeling layer geometry in directed energy deposition with laser for additive manufacturing, Surface & Coatings Technology 409 (2021) 126-897. https://doi.org/10.1016/j.surfcoat.2021.126897

[21] C. Bruni, M. El Mehtedi, and F. Gabrielli, Flow curve modelling of a ZM21 magnesium alloy and finite element simulation in hot deformation, Key Engineering Materials Vols. 622-623 (2014) 588-595. https://doi:10.4028/www.scientific.net/KEM.622-623.588

[22] C. Bruni et al., Constitutive models for AZ31 Magnesium alloys, Key Engineering Materials, 367 (2008) 87-94. https://doi.org/10.4028/www.scientific.net/KEM.367.87

[23] R. R. Yadav, Y. Dewang, J. Raghuwanshi,V. Sharma, Finite element analysis of extrusion process using aluminum alloy, Materials Today: Proceedings 24 (2020) 500–509. https://doi.org/10.1016/j.matpr.2020.04.302

[24] N. Fietier, Y. Krahenbuhl, M. Vialard, New methods for the fast simulations of the extrusion

process of hot metals, Journal of Mat. Proc. Technology 209 (2009) 2244–2259. https://doi.org/10.1016/j.jmatprotec.2008.05.022

[25] A. García-Domínguez, J. Claver, A.M. Camacho, M. Sebastián. Comparative Analysis of Extrusion Processes by Finite Element Analysis, Procedia Engineering 100 (2015) 74. https://doi.org/10.1016/j.proeng.2015.01.344