Sensitivity analysis for thickness uniformity of Al coating layer in extrusion of Mg/Al clad bar

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Abstract

Although Mg alloys possess many attractive properties, the use of Mg alloys has been limited due to their extremely poor corrosion resistance. In the authors' previous study, they have developed a new process for Mg/Al cladding by hot extrusion with a convex die. In the extrusion process, it was found that the thickness uniformity of the Al coating layer can be controlled by changing the die angle. However, the optimal condition of the extrusion and the influences of extrusion parameters on the coating thickness uniformity remain unclear. In this study, therefore, the sensitivity analysis has been performed in order to evaluate the influences of extrusion parameters on the coating thickness uniformity. The sensitivities of the following five parameters were evaluated; (1) initial thickness of the coating material plate, (2) extrusion temperature, (3) ram speed, (4) die angle and (5) ratio of simulated flow stress to the experimental one for pure Al. In order to perform the sensitivity analysis, the process for Mg/Al cladding was modelled. The results from the extrusion model fairly agree with the experimental results. Thus, it can be said that the present model of Mg/Al cladding process is reliable. From the sensitivity analysis, it was found that the initial thickness of the coating material plate and die angle influence on the uniformity most. The extrusion temperature, ram speed and flow stress ratio do not have significant influences.

Keywords: plastic deformation, extrusion, coating, cladding, corrosion resistance

1. Introduction

Mg alloys have the lowest density among all structural metal materials and they have attracted attentions over many years. In recent years, Mg alloys are expected as a material saving weight of automobile components and being of some helps to solve the global environmental issues [5]. However, the practical use of Mg alloys has been limited due to their extremely poor corrosion resistance [1]. Although a number of processes have been proposed to overcome this disadvantage, those processes still possess problems e.g. difficult surface treatment prior to the process, non–uniformity of the coating and negative effect on the environment [4]. Therefore, the present authors have developed a new cladding process of Mg alloys with pure Al, as a more promising process, by a conventional hot extrusion method with a convex die [9]. The Mg/Al cladding extrudate exhibited an excellent corrosion resistance and notably, it was found that the coating thickness uniformity can be controlled by changing the die angle, which is defined as the angle between extrusion direction and the die's working face. Thus, this new cladding process is expected to provide a broader range of application field to Mg alloys. However, detailed information about the influences of other extrusion parameters such as the extrusion temperature and ram speed on the coating thickness uniformity are still unclear, which is necessary for obtaining the uniform thickness coating under given conditions. Therefore, in the present study, sensitivity analysis was performed to evaluate the influences of some extrusion parameters on the coating thickness uniformity. In order to perform the sensitivity analysis, the process for Mg/Al cladding was modelled by using a finite element (FE) code, and validity of the model was investigated.

2. Methodology

2.1 FE model

An FE model of the extrusion process was developed in the commercial Forge 2011 software. The FE code is based on the Norton–Hoff viscoplastic flow rule [2]:

$$\boldsymbol{s} = 2K\left(\sqrt{3}\dot{\bar{\varepsilon}}\right)^{m-1}\dot{\boldsymbol{\varepsilon}} \qquad (1)$$

where $\boldsymbol{s}$ is the deviatoric stress tensor, K is material consistency, m is the strain rate sensitivity and $\dot{\boldsymbol{\varepsilon}}$ is the strain rate tensor. $\dot{\bar{\varepsilon}}$ is the effective strain rate, which is described as

$$\dot{\bar{\varepsilon}} = (\frac{2}{3}\sum_{i,j} \dot{\varepsilon}_{ij}^2)^{\frac{1}{2}} . \quad (2)$$

The flow stress model for AZ80 Mg alloy (Mg–8.2mass%Al–0.56mass%Zn–0.44mass%Mn) was developed from the inverse analysis in our previous study [10]. The derived flow stress model is:

$$\sigma_{Mg} = \sqrt{3}\left[\exp(-5.304 \cdot \varepsilon) \cdot 5.923\varepsilon^{0.538}\exp\left(\frac{-2313.4}{T}\right) + \{1 - \exp(-5.304 \cdot \varepsilon)\} \cdot 0.444\exp\left(\frac{2820.7}{T}\right)\right]\left(\sqrt{3}\dot{\varepsilon}\right)^{0.1592} \quad (3)$$

where ε is strain, T is temperature and $\dot{\varepsilon}$ is strain rate. The flow stress model of a commercial pure Al (99.6%: Al–0.125Si–0.175Fe–0.025Zn–0.025Cu–0.015Mn–0.015Mg–0.015Ti), which corresponds to a coating material, was taken from the database of Forge and expressed by using a Hansel–Spittel law [6] as follows:

$$\sigma_{Al} = 268.88875\exp(-0.00539T)\varepsilon^{0.17012}\dot{\varepsilon}^{0.15041}\exp\left(\frac{-0.00018}{\varepsilon}\right). \quad (4)$$

The temperature range to which this model can be applied is 523–823 K, which covers the extrusion temperature range of our focus.

The initial geometries of the extrusion process were identical to the ones used in our previous experiment [9]. Fig. 1 shows the initial meshes of the billet, coating material plate and the extrusion tools of the container and die. Considering the symmetry of the geometries, a 2D axisymmetric hot extrusion module was adopted. The meshes in the container and die were set uniformly. On the other hand, those in the billet and coating material plate were not uniform, being finer in the vicinity of the die aperture, where severe deformation occurs. The bearing of this die is slightly tilted and the corner radius of the die aperture is set to 0.5 mm. The mesh was refined also at the corner of the die and container wall.

In this study, friction at all interfaces was controlled by a Coulomb limited Tresca law which is expressed by the following relations:

$$\tau = \mu\sigma_n \frac{\Delta v}{\Delta v} \text{ if } \mu\sigma_n < \bar{m}\frac{\sigma_0}{\sqrt{3}} \quad (5)$$

and

$$\tau = \bar{m}\frac{\sigma_0}{\sqrt{3}}\frac{\Delta \boldsymbol{v}}{\Delta v} \text{ if } \mu\sigma_n > \bar{m}\frac{\sigma_0}{\sqrt{3}} \tag{6}$$

where τ is the shear stress, μ is the Coulomb's friction coefficient, σ_n is the normal stress vector, $\bar{m}$ is the shear friction coefficient and $\Delta\boldsymbol{v}$ and Δv are differences of velocities between two solids in vector and scalar representation, respectively. In the experimental extrusion process, boron nitride (BN) powder was sprayed on the container and die surfaces as a lubricant [9]. It is known that the friction parameter of the BN powder, μ, is 0.17 [3] and it is empirically known that the friction coefficient, μ, is approximately half of the coefficient $\bar{m}$ [11]. Therefore, in the present simulation, the friction coefficients μ and $\bar{m}$ were set at 0.17 and 0.34, respectively, at the interfaces of container/billet, container/coating material and die/coating material. Since the billet and coating materials are bonded together after flowing out through the die bearing, the friction parameter for the interface between the billet and coating material was taken as the "bilateral sticking" which means that nodes at the interface cannot leave the contact.

The ambient temperature was set at 298 K and the initial temperature of the container, die, billet and coating material was set at 583 K, which is the same temperature as that in the experiment [9]. All the tools were assumed to be perfectly rigid, and for simplicity the friction coefficient at the tool/deformed materials interfaces and the thermal coefficient were assumed to be constant through the whole process.

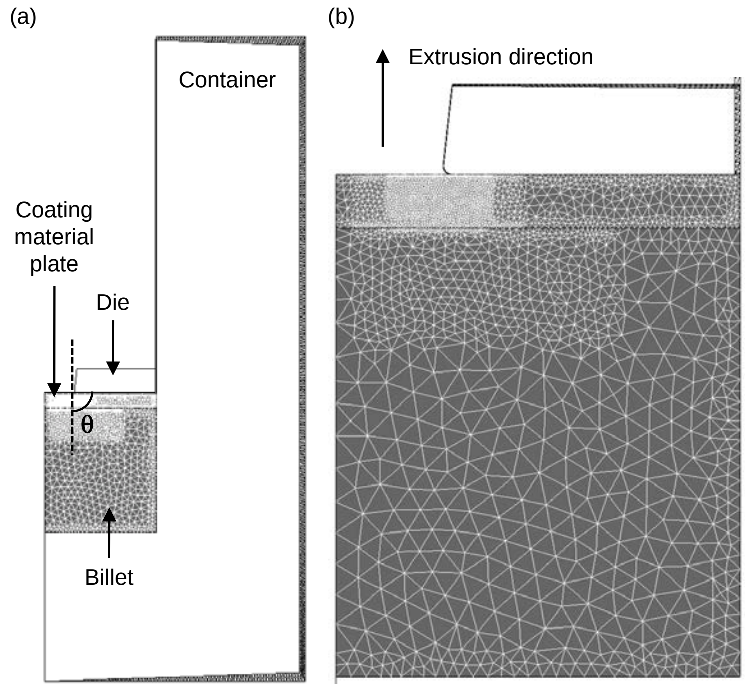

Fig. 1 Initial meshes of (a) the billet, coating material plate, container and the die having an angle of 90 ^{o} and (b) the enlargement of the metal part of (a).

2.2 Model validation

The validity of the model was investigated by comparing the coating thicknesses obtained in the simulation with the experimental results. The coating thickness was evaluated with an automated thickness measurement option in Forge software. The measured coating thickness was smoothed by using the moving–average method per 20 points and compared with the experimental results for the various die angles.

2.3 Sensitivity analysis

The sensitivity analysis can be used to assess the relative importance of input parameter values to the observed output [7]. In the present study, the sensitivity analysis was performed to find which extrusion parameters contribute most to the coating thickness uniformity.

It is empirically known that there are anomalous parts at the beginning and ending stages of the extrusion process. Therefore, the coating thickness was measured in the middle part of the extrudate with a range from 50 to 90 mm from the tip of the simulated extrudate in the extrusion direction as shown in Fig. 1 (b) with the automated thickness measurement option in Forge. The obtained coating thickness with respect to the distance in the measured range was linearly approximated by the least square method and the coating thickness was output every 5 mm in the longitudinal direction of the extrudate. The response, y, for the sensitivity analysis was taken as the level of non–uniformity of the coating thickness and defined as:

$$y = \frac{\sum_{i=1}^{n}(d_i - d_{ave})^2}{d_{ave}^2} \tag{7}$$

where d_i is the coating thickness at the i^{th} position numerated in the measured range, n is the number of the measurement points and d_{ave} is the average coating thickness. For the sensitivity analysis, full two–level Factorial Design (FD) was adopted owing to the low computational costs [8]. The sensitivities of the following five parameters were evaluated: (1) initial thickness of the coating material plate, $l_{initial}$, (2) extrusion temperature, T, (3) ram speed, V_{ram}, (4) die angle, θ and (5) ratio of simulated flow stress to the experimental one for pure Al, a. The parameter a was defined as follows:

$$a = \frac{\sigma_{FD}}{\sigma_{Al}} \tag{8}$$

The parameter levels were empirically chosen and are presented in Table 1. In FD, the average response from high–level runs was compared with the average response from the low–level runs and the influences of the parameter were determined as follows:

$$E = \frac{\sum y^+}{m^+} - \frac{\sum y^-}{m^-} \tag{9}$$

where y is the model output, "+" and "–" indicate the upper and lower limits of the parameter range, respectively and m is the number of model simulations at each level. Furthermore, in order to investigate the influence of each extrusion parameter on the average coating thickness, the sensitivity analysis for the average coating thickness was also performed. The average coating thickness was used as an output, y, and E was calculated by using equation (9).

As explained in this section, the sensitivity analysis is performed with the help of the numerical simulation of the extrusion process as an effective way of data collection. In the following sections, firstly, the developed model is verified and then the sensitivity analysis results are shown.

Table 1. Factors and levels used in the factorial design.

	Parameters	Low–level	High–level
($l_{initial}$)	Initial thickness of the coating material plate (mm)	2	5
(T)	Extrusion temperature (K)	523	623
(V_{ram})	Ram speed (mm/sec)	0.033	1
(θ)	Die angle (deg)	90	110
(a)	Ratio of simulated flow stress to the experimental one for pure Al	0.9	1.2

3. Results and discussion

3.1 Model validation

Fig. 2 illustrates the comparison between the experimental and simulation results which shows the changes of coating thickness with respect to the distance from the tip of extrudate for various die angles. The results from the extrusion model fairly agree with the experimental results with respect to the tendency of the increase and decrease in the coating thickness depending on the die angle, and also the thickness values obtained from the extrusion model are very close to those obtained from the experiments. However, even though the simulation successfully reproduces the experimental results in the early stage of the extrusion, the errors between the experimental and simulation results gradually increase as the extrusion proceeds. One of the possible reasons for this should be related to uncertainty in the accuracy of friction coefficient at the die/coating interface. As mentioned above, the friction coefficient at the interface was set at the value of the BN lubricant. However, in the real process, the lubricant may gradually flow off from the die surface as the extrusion proceeds and eventually it can cause errors. In the present study, as was mentioned in the earlier section, the focused coating thickness is in the range from 50 to 90 mm from the tip of the simulated extrudate, and the error is not significant in this range. Therefore, the accuracy of the developed 2D FE model is considered to be reasonable for the present study.

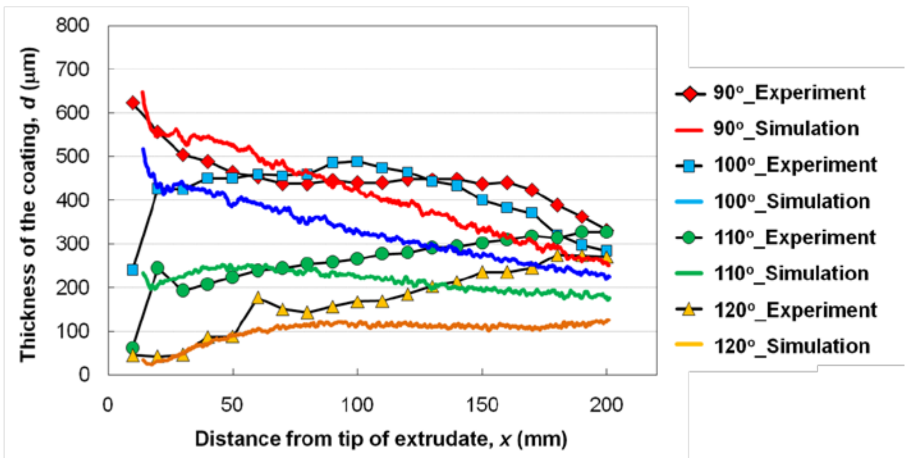

Fig. 2. Comparison between the experimental and simulation results for the changes of coating thickness with respect to the distance from the tip of extrudates with various die angles.

3.2 Sensitivity Analysis

3.2.1 Sensitivity analysis for the coating thickness uniformity

The uniformity obtained for all conditions simulated in the present sensitivity analysis are presented in Fig. 3. From this figure, it can be seen that the higher uniformity is obtained when the die angle is larger and the initial thickness of the coating material plate is thinner.

Fig. 4 exhibits the results of sensitivity analysis with respect to the coating thickness uniformity. It is clear from this figure that the die angle, θ, has the highest influence on the coating thickness uniformity and the initial thickness of the coating material plate, $l_{initial}$, also has a great influence. The extrusion temperature, T, the ram speed, V_{ram}, and the ratio of the flow stress, a, do not have significant influences.

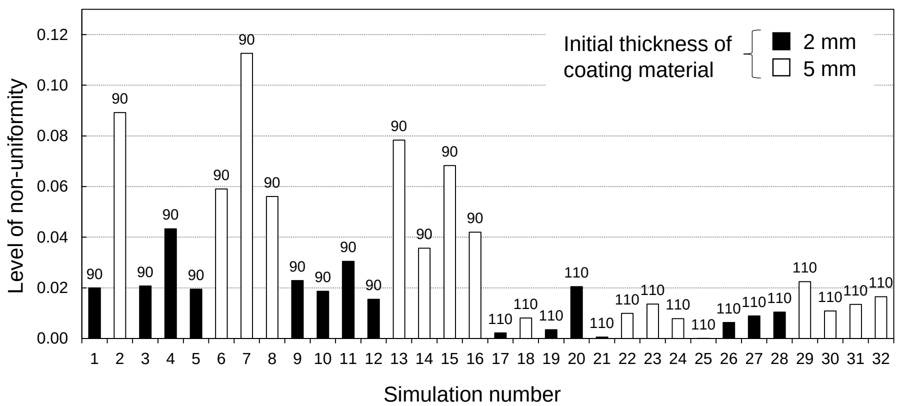

Fig. 3. The level of non–uniformities obtained from the simulations performed for sensitivity analysis. The numbers on the horizontal axis correspond to the simulation numbers shown in Table 2. The black and white bars show the results with the initial thickness of the coating material plate of 2 and 5 mm, respectively. The numbers shown on the data label express the die angle. The smaller value of the level of non–uniformity, y, means the higher uniformity.

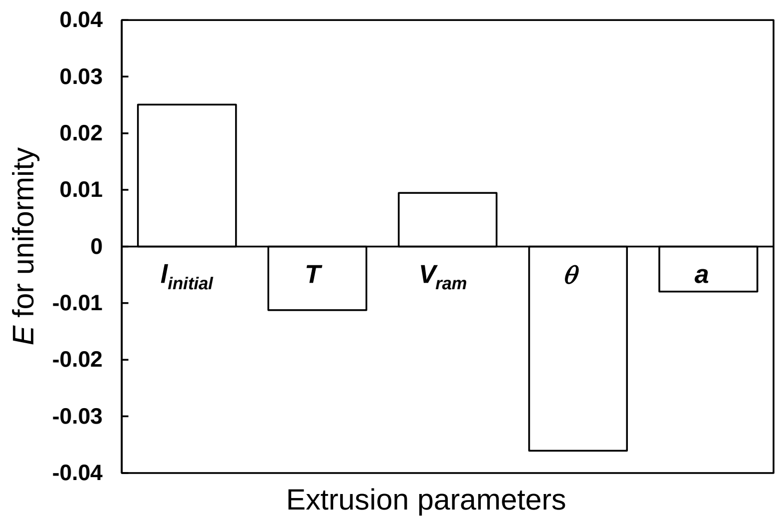

Fig. 4. Effects of the parameters on the coating thickness uniformity. The symbols on the horizontal axis correspond to the factors shown in Table 1. The higher absolute value of the *E* indicates the higher influence on the coating thickness uniformity.

3.2.2 Sensitivity analysis for the average coating thickness

Fig. 5 exhibits the average coating thickness obtained from all the simulations performed for the sensitivity analysis. From the figure, it is clear that the average coating thickness is much thicker when the initial thickness of the coating material plate is thicker.

Fig. 6 exhibits the results of sensitivity analysis with respect to the average coating thickness. The higher absolute value of the sensitivity indicates the higher influence on the average coating thickness. From the figure, it can be seen that the average coating thickness is influenced most by the initial thickness of the coating material plate, $l_{initial}$, and the die angle, θ, also has a great influence. The extrusion temperature, T, the ram speed, V_{ram}, and the flow stress ratio, a, do not have significant influences. These results show the same tendency as the results of sensitivity analysis for the coating thickness uniformity. Thus, it can be said that the important parameters for the present Mg/Al cladding process are the initial thickness of the coating material plate and the die angle.

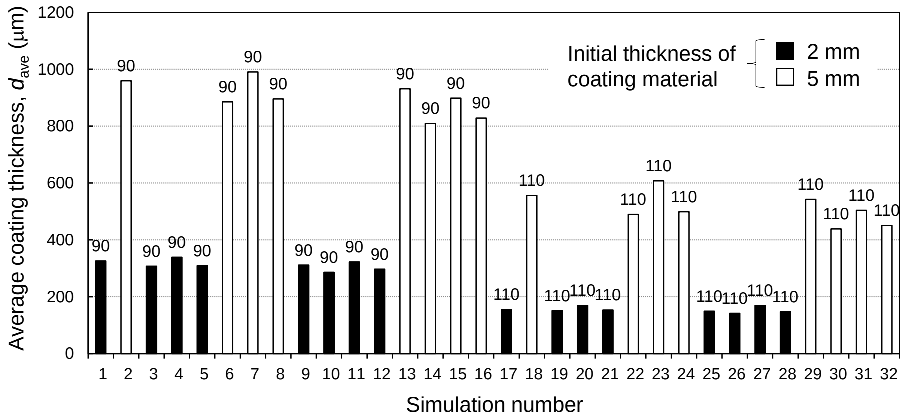

Fig. 5. The average coating thicknesses obtained from the simulations performed for the sensitivity analysis. The numbers on the horizontal axis correspond to the simulation numbers shown in Table 2. The black and white bars show the results with the initial thickness of the coating material plate of 2 and 5 mm, respectively. The numbers shown on the data label express the die angle.

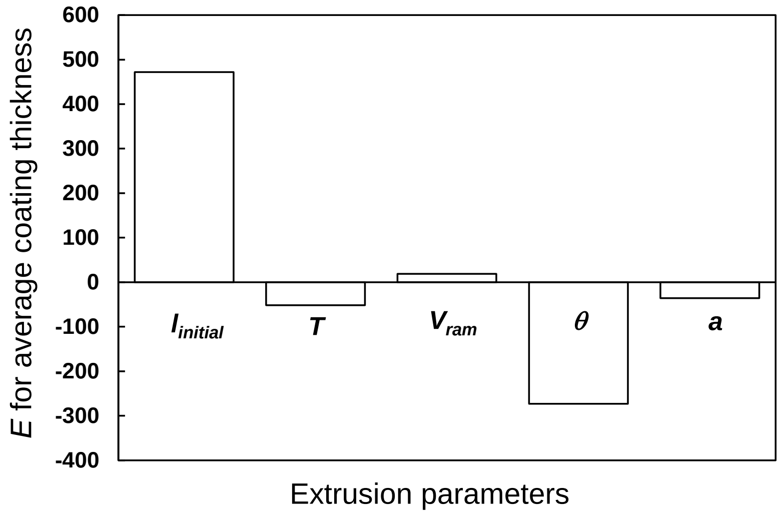

Fig. 6. Effects of the parameters on the average coating thickness. The symbols on the horizontal axis correspond to the factors shown in Table 1. The higher absolute value of the *E* indicates the higher influence on the average coating thickness.

As a summary of the sensitivity analysis, the uniformity of the coating thickness and the average coating thickness are summarized in Table 2. The level of non-uniformity and the average coating thickness are ranked and are presented in ascending order of the uniformity and thickness. The first place for the uniformity is the results which showed the least value of the level of non-uniformity, and the first place for the average coating thickness is the results which showed the thinnest average coating thickness. From the table, it is clear that the most uniform thickness coating was obtained in Simulation #25 because it exhibits the least value of the level of non-uniformity. Therefore, the optimal condition to obtain the uniform thickness coating is given by the die angle of 110 ^{o}, the initial thickness of the coating material plate of 2 mm, the extrusion temperature of 623 K, the ram speed of 1 mm/s and the ratio of the flow stress of 0.9.

Table 2. Summary of the sensitivity analysis.

Simulation number	Initial thickness of the coating material plate, $l_{initial}$ (mm)	Extrusion temperature, T (K)	Extrusion velocity, V_{ram} (mm/sec)	Die angle, θ (deg)	Flow stress of the coating material, a	Level of non-uniformity	Uniformity (Rank)	Average coating thickness (μm)	Average thickness (Rank)
1	2	523	0.033	90	0.9	0.01997	18	325.85	15
2	5	523	0.033	90	0.9	0.08922	31	959.45	31
3	2	623	0.033	90	0.9	0.02073	20	307.18	11
4	2	523	1	90	0.9	0.04331	26	339.38	16
5	2	523	0.033	90	1.2	0.01946	17	308.91	12
6	5	623	0.033	90	0.9	0.05905	28	885.14	27
7	5	523	1	90	0.9	0.11257	32	990.37	32
8	5	523	0.033	90	1.2	0.05608	27	895.60	28
9	2	623	1	90	0.9	0.02287	22	311.29	13
10	2	623	0.033	90	1.2	0.01862	16	286.48	9
11	2	523	1	90	1.2	0.03046	23	322.35	14
12	2	623	1	90	1.2	0.01550	14	297.33	10
13	5	523	1	90	1.2	0.07832	30	931.24	30
14	5	623	0.033	90	1.2	0.03565	24	809.14	25
15	5	623	1	90	0.9	0.06825	29	898.25	29
16	5	623	1	90	1.2	0.04196	25	828.42	26
17	2	523	0.033	110	0.9	0.00219	3	155.02	6
18	5	523	0.033	110	0.9	0.00810	7	556.24	23
19	2	623	0.033	110	0.9	0.00347	4	150.96	4
20	2	523	1	110	0.9	0.02051	19	169.76	8
21	2	523	0.033	110	1.2	0.00054	2	153.44	5
22	5	623	0.033	110	0.9	0.00991	9	489.73	19
23	5	523	1	110	0.9	0.01359	13	607.53	24
24	5	523	0.033	110	1.2	0.00783	6	498.94	20
25	2	623	1	110	0.9	0.00003	1	149.11	3
26	2	623	0.033	110	1.2	0.00629	5	142.08	1
27	2	523	1	110	1.2	0.00891	8	169.41	7
28	2	623	1	110	1.2	0.01040	10	147.87	2
29	5	523	1	110	1.2	0.02247	21	542.89	22
30	5	623	0.033	110	1.2	0.01089	11	438.35	17
31	5	623	1	110	0.9	0.01343	12	504.24	21
32	5	623	1	110	1.2	0.01649	15	450.88	18

4. Conclusions

The process for Mg/Al cladding by hot extrusion with convex dies was modeled and validity of the model was assessed. A sensitivity analysis was performed to evaluate the influences of some extrusion parameters on the coating thickness uniformity and the average coating thickness. The following conclusions were obtained.

- The developed 2D FE model of the process for AZ80 Mg alloy/Al cladding is considered to be reliable.

- The die angle and the initial thickness of the coating material plate have the highest influence on the coating thickness uniformity and the average coating thickness, respectively. These two parameters showed much more significant influences on both the coating thickness uniformity and average coating thickness than the other parameters such as extrusion temperature, ram speed and the ratio of simulated flow stress to the experimental one for pure Al.

Acknowledgements

The financial support by JSPS KAKENHI Grant Numbers 25·1024 is gratefully acknowledged.

References

[1] Ambat R, Aung N N, Zhou W (2000) Evaluation of microstructural effects on corrosion behaviour of AZ91D magnesium alloy. Corrosion Sci 42:1433-1455.

[2] Chenot J L, Bellet M (1992) The viscoplastic approach for the finite-element modelling of metal forming processes. In: P. Hartley, I. Pillinger, C.E.N. Sturgess (Eds) Numerical Modelling of Material Deformation Processes, Springer–Verlag, London, Berlin, pp. 179–224.

[3] Funahashi T, Koitabashi T, Uchimura R, Koshida T, Yoshida A, Ogasawara T (1992) Development and Application of High-Purity Hexagonal Boron Nitride (h-BN) Powder. Kawasaki Steel Giho. 24: 135–141.

[4] Gray J E, Luan B (2002) Protective coatings on magnesium and its alloys – a critical review. J Alloy Compd 336:88–113.

[5] Kulekci M K (2008) Magnesium and its alloys applications in automotive industry. Int J Adv Manuf Technol 39:851–865.

[6] Mehtedi M El, Musharavati F, Spigarelli S (2014) Modelling of the flow behaviour of wrought aluminium alloys at elevated temperatures by a new constitutive equation. Mater Des 54: 869–873.

[7] Saltelli A, Homma T (1992) Sensitivity analysis for model output, performance of black box techniques on three internatinoal benchmark exercises. Comput Stat Data Anal 13:73–94.

[8] Saltelli A, Chan K, Scott E M (2000) Sensitivity analysis. Wiley, New York.

[9] Tokunaga T, Matsuura K, Ohno M (2012) Aluminum coating on magnesium-based alloy by hot extrusion and its characteristics. Mater Trans 53:1034–1041.

[10] Tokunaga T, Kuziak R, Matsuura K (2014) Determination of the flow stress model of AZ80 Mg alloy, Computer Methods in materials Science 14:147–154.

[11] Zhang Q, Feldera E, Bruschib S (2009) Evaluation of friction condition in cold forging by using T-shape compression test. J Mater Process Technol 209:5720–5729.