Predictions of stress distribution and material flow in coining process for bi-material commemorative coin

Yuchun Peng, Jiangping Xu and Yuan Wang
School of Mechanical Engineering, Jiangsu University, 301 Xuefu Road, Zhenjiang City, Jiangsu, People’s Republic of China
E-mail: wangyuan@ujs.edu.cn

Keywords: Bi-material, coining process, mathematical model, deform 3D

Abstract
Bi-material commemorative coins have the characteristics of weight reduction, beauty and corrosion resistance. However, due to different characteristics of bi-materials, defects such as stress concentration, drop of inner core and micro-cracks often occur at interface of materials in usage. Engineers usually employ multiple mold trials to check the bonding state of two material regions, judge the stress concentration area and modify the process to avoid micro-crack sprout. Based on the professional metal forming software Deform 3D, stress distribution and material flow in coining processes for single and bi-material commemorative coins are studied. Numerical examples demonstrate that there are three typical stages over the whole process whether the coin is single or bi-material. And stress concentrations appear at the corners of upper/lower dies and the material interface in case of bi-material. The former concentration lead to sprout of micro-cracks along the shear bands and the latter triggers cracks at the interface. In addition, two materials with different hardness are adopted in the core and ring, respectively, to investigate the mutual interaction behavior at interface. Numerical findings indicate that large strains occur at the edge and the interface in case of bi-material with soft core. These imply that deep adhesion happens at the interface in case of that soft material is in the core. It suggests that hard material in the inner core and soft one in the outer ring may cause falling of the core.

1. Introduction

The bi-material commemorative coin is made of blank with inner core and outer ring where different materials are assigned. As shown in figure 1, setup and diagram of coining process for producing bi-material coin are illustrated (see panels (a)–(d)). The whole process can be divided into three stages: stage I is the initial forming stage (panel (b)); Stage II is the rough forming period (panel (c)), and stage III is the final coining phase (panel (d)). Stage I covers the duration from initial movement of the upper die to the moment that central area of the upper die contacts the workpiece surface. Stage II is the rough forming process that materials flow to fill the gap among tools and workpiece, and radial deformation is constrained by the collar. Stage III is the final embossing stage that cavities are sufficiently filled and the coin is eventually produced. Compared with single material coin, coin with dual materials has good corrosion resistance, aesthetic value and high collection value with reduced weight. In the early 1990s, China began to study the manufacture of bimetallic coins, especially for precious metal coins. Generally speaking, bi-material coins are usually composed of cylinder inner core and outer ring of different materials. The former can be obtained by blanking process, and the latter can be produced through punching and edging processes. Under the action of mechanical press, the two regions occur plastic deformation and are squeezed together. When the bonding force of the material interface is small, the inner part is easy to drop. If the bonding force is too large, stress concentration and micro-cracks occur at the material interface. As in the actual production of bi-material commemorative coins, there is still lack of corresponding theory to analyze the stress concentration and material flow during the coining process. The micro-cracks and potential failure areas of commemorative coins are often judged by the experience of technicians. Therefore, more and
more scholars adopt upper bound methods [1–4] and numerical methods to study the stamping process of bi-material coins [5–12].

At present, scholars have contributed to forging process of bi-material through analytical methods and experiments. Plancak et al used C15E and C45E steels to study the connection process of two bi-metallic axisymmetric parts in a closed die for upsetting [13]. The forming load, material flow and joint section filling were analyzed. Then, they used two parallel flat plate dies to experimentally study the compression properties of bi-metallic components, and verified the consistency of theoretical prediction and experiment [14]. Essa et al proposed a behavior of bi-metallic upsetting ring billets for mild steel (C45E grade), the results showed that the interface of material can maintain good contact under certain conditions [15]. Politis et al used copper and lead (Pb) to analyze the material flow and thickness distribution of forged bi-metallic gears [16]. Cetintav et al studied cold heading using pure copper, brass and 1020 steel, and analyzed the mechanical properties of cylindrical bi-metallic materials produced by a single part [17]. Graf et al investigated the forging processing of plastic (PA6) and aluminum alloy (EN-AW6060) for lightweight constructions. The results showed that the plastic based hybrid materials had a certain potential in the field of forging technology [18]. Napierala et al proposed a new forming process of multi-material components, and investigated the process mechanics, failures, and process window [19]. Khanawapee et al studied the change law of cylinder shape and radius after cold heading of bi-material Al7075 and S15C, the confirmatory test showed that the friction coefficient effect would lead to different point shapes of inner core [20]. Although material flow, interfacial contact condition and failures in forging process with bi-material were studied and validated in literature [14, 15, 19], the mechanical reasons for micro-crack and dropping of inner core of a coin in coining process are worth exploring.

Specifically in the field of bi-material coin production, Kiran and Shaw regarded the embossing of commemorative coins as a net shape precision forming process and developed a simple sawtooth profile analysis model to analyze the interaction between adjacent asperities of commemorative coins using upper bound method [1]. Delamare et al applied the upper bound method to develop an analytical model for calculating the strain energy and shape of a blank to form a metal coin with a central circular design and an outer annular legend [21]. Later, Brekelmans et al established an analytical model by using the upper bound method to analyze the pressure of the central conical axisymmetric relief of metal commemorative coins [2]. As we know, theoretical methods for analyzing coin process can not meet the requirements of coins with complex patterns.

Meanwhile, numerical methods has been employed in coining process to assist engineers to get a better understanding of the upper bound methods and their experiences, especially in bi-material coining [5, 6, 8, 10–12, 22]. Marques and Martins used the rigid plastic formula to simulate the joint of bi-metallic coins [23]. Chandra et al studied the axisymmetric upsetting by using boundary element, and evaluated the ring compression [24]. Wifi et al used updated Lagrangian based elasto-plastic large strain finite element code to simulate the process of upsetting of discs and rings [25]. Yeh et al used a variation upper-bound (VUB) model to

Figure 1. Setup and schematic draw of coining process for bi-material coin. (a) Setup of minting; (b) Initial stage; (c) Rough forming stage; (d) Final coining stage.
predict the barrelling profile of the ring and total forming energy rate, and compared with FEM results to show its capability in upsetting of rings [26]. Xu et al developed a special-purpose 3D dynamic explicit finite element program based on elastic-plastic constitutive equations to simulate the mining process and obtained results that coincide with experimental observations [6]. Altinbalik et al used the modified upper bound solution containing dimensionless optimization parameters to evaluate the forming load of cylindrical profile [27]. Overcoming the extreme small time step in explicit finite element method, Xu et al proposed an improved material point method to predict the filling shortage in the coining process, and its performance was verified by the experimental results [12]. Although many researches have been done in the field of coining process to produce bi-material coins, the origins of sprout of micro-crack and dropping of inner core are still in exploring.

In the work of literature [28], Afonso et al designed a new type of bi-material commemorative coin with polymer inner core and metal ring and built an analysis model of plastic instability of circular plate under uniform radial edge pressure based on plastic theory. The correctness of the model was supported and verified by finite element modeling and experiments. However, there are many coins, especially commemorative coins, are made of dual metals. In this paper, the forming process of single and bi-material commemorative coins systematically studied by using Deform 3D software, the material flow and stress distribution are clarified by interchanging materials of inner core and outer ring. Then, we explore the triggers of micro-crack and dropping of inner core through the observed results by comparing the outputs of single and bi-material cases.

This paper is organized as follows. The theory foundation of coining process in Deform 3D and remeshing situation during simulation is briefly presented in section 2. Section 3 describes the setups of numerical examples in four cases of single and bi-material. Stress distributions and material flow in three typical stages in the four cases are discussed in section 4 while strain characteristics during the pre-coining process are analyzed in section 5. Finally, we conclude with a summary in section 6.

2. Mathematical modeling of coining process

2.1. Theory of deform 3D rigid viscoplastic finite element

Finite element method in Deform 3D is based on rigid viscoplastic variational principle. Generally, the governing equation of rigid viscoplastic mechanics does not consider the volume force and ignores the elastic deformation of the material. The geometric conditions, incompressibility and velocity boundary conditions within the allowable velocity filed are required. In this study, Deform 3D based on updated Lagrangian description is adopted for simulating the coining process of commemorative coins. The governing equations that must be satisfied during the forging process are expressed as follows [29].

\[
3\sigma_{ij,i} = 0
\]

\[
\dot{\varepsilon}_{ij} = \frac{1}{2}(v_{ij,i} + \nu_{ij,i})
\]

\[
\dot{\varepsilon}_{ij} = (3\varepsilon/2\dot{\varepsilon})\sigma'_{ij,i},
\]

\[
\dot{\varepsilon}_{kk} = 0
\]

\[
\sigma_{ij}n_{ij} = F_{i} \text{ on } S_{r}, \nu_{i} = \bar{v}_{i} \text{ on } S_{v}
\]

where \(\sigma_{ij}\) is the Cauchy stress and \(\dot{\varepsilon}\) is the strain rate. \(v\) is the velocity of a point in the physical domain. \(\dot{\varepsilon}\) and \(\sigma\) are the effective strain rate, the effective stress and expressed as 

\[
\dot{\varepsilon} = \sqrt{2(\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij})/3}
\]

and 

\[
\sigma = \sqrt{3(\sigma'_{ij}\sigma'_{ij})/2}
\]

respectively. \(\sigma'_{ij}\) is the deviation stress component. \(S_{t}\) is the traction surface and \(F_{t}\) is traction stress applied on the surface \(S_{t}\). \(n\) is the outward normal to the surface. \(S_{v}\) is the velocity surface and \(\bar{v}_{i}\) is velocity allowed on the surface \(S_{v}\). eqmot is the equilibrium equation for arbitrary point of the coin. eqcompa, eqconst, eqincompr, eqbound are the compatibility conditions, constitutive relation, incompressible and boundary conditions, respectively.

Applying the principle of minimum potential energy, the final equilibrium equation eqmot is written as.

\[
\int_{\Omega} \partial \sigma \delta \varepsilon d\Omega + k \int_{\Omega} \varepsilon_{v} \delta \varepsilon_{v} d\Omega - \int_{S_{t}} F_{t} \delta v_{i} dS = 0
\]

where \(\Omega\) is the workpiece domain, and \(k\) is the positive parameter for volume changes. \(\varepsilon_{v}\) is the volumetric strain rate. The rigid plastic material model is applied in all the following examples.

2.2. Remeshing conditions in simulation process

Under the action of punch, tetrahedral elements in Deform 3D, especially in the regions of workpiece that contact with patterns of the tools, undergo large deformation and become distorted. Thus, the Newton-Raphson based solver takes longer time to get the correct solution and does not converge sometimes due to deteriorated
mesh quality. Remeshing is a convenient way to deal with mesh distortion which is embedded in Deform 3D to
deal with complex nonlinear problems in engineering. The remeshing strategy in the Deform 3D software
includes overall and local divisions. There are four parameters that relate with mesh regeneration during the
running of the solver, namely interference depth, maximum stroke increment, maximum time increment and
maximum step increment. For example, as long as a node of the slave body crosses the surface of a master body
to the depth specified under interference depth, the remeshing process is triggered, and the physical information
of solutions in the previous step is then mapped into the new mesh.

3. Setups of numerical examples

In order to study the natural material flow of workpiece during coining process (see figure 1(a)), patterns on the
inner surfaces of tools are removed. Usually, this kind of process is called pre-embossing which is very useful for
engineers to analyze the flow behaviors of materials due to the deletion of local fillings of cavities.

This section describes the configurations of coining process in four situations in Deform 3D, namely single
material of aluminum/copper, aluminum in inner core and copper in outer region, copper in inner core and
aluminum in outer ring. Due to the symmetrical geometry of the workpiece, only a quarter of the physical model is adopted for reducing
computational efforts. In all the cases, geometries of the tools and related process parameters, such as velocity of the top die
(also call punch sometimes) and friction constant between tools and workpiece, keep the same. The upper die moves downward with a velocity of 0.4 mm s$^{-1}$ and the other two tools are fixed. The upper and lower
dies as well as the collar squeeze the workpiece to flow and fill the gaps among the three tools, thus to form the
final coin.

3.1. Setups of the four cases

In cases of single material, aluminum or copper is assigned for the workpiece, as shown in figure 2. The main
dimensions of the workpiece are given in panel (a). The outer radius of workpiece takes value of $R_0 = 11.9$ mm.
The thickness in the flat region is $h_1 = 1.6$ mm and maximum thicknesses in the edge is $h_2 = 2.0$ mm. The inner
radius of the collar is $R = 12.15$ mm. The outer radii of punch and the die are both $R_d = 12.1$ mm. The gap
between the upper and lower dies is $h_3 = 2.2$ mm. In panel (b), only the workpiece is meshed with 100000 tetrahedral elements. The upper die, the lower die and the collar are considered as rigid bodies that there is no need to mesh them.

In the rest two cases, the initial blank is modeled as two regions whose materials are assigned by aluminum and copper. The dimensions of three tools keep the same as those in case of single material. The radius of the inner part of the workpiece is $R = 7$ mm and the maximum radial width of the outer ring is $w = 4.9$ mm. Rest dimensions of the workpiece remain unchanged, as shown in figure 3(a). As illustrated in panel (b), the two separated parts of the workpiece, the inner core and the outer ring, are meshed with 80000 and 100000 tetrahedral elements, respectively. We notice that the number of total elements in bi-material cases are much more than that in one material case. This is because that dense elements are meshed in the interfacial regions of the two parts to capture the stress distribution. In what follows, Al-Cu means the case that the inner core is aluminum and the outer ring is copper while Cu-Al is opposite.

3.2. Deform 3D based simulation

The simulation step increment is set to be 0.01 mm for all cases. In case of bi-material simulation, there are six contact pairs: the inner core and the outer ring, the upper die and the inner core, the upper die and the outer ring, the lower die and the inner core, the lower die and outer ring, the outer ring and the collar. The friction coefficient between the inner core and the outer ring is set to be 0.12, and the rest coefficients are set to be 0.4 [20].

Firstly, the upsetting processes of commemorative coin blanks with single material aluminum or copper and bi-material are simulated by Deform 3D software. Due to different material behaviors in the middle region and edge, it would be worth of studying two cases of bi-material, namely aluminum or copper in the inner core and copper or aluminum in the outer ring. Then, the stress and material flow in the forming process are analyzed in the following sections.

4. Analysis of stress distribution and material flow

4.1. Analysis of stress and material flow of single material

Taking the case of aluminum for example (see figure 4), with the movement of the upper die, the mold first contacts the edge area of the blank, then, the pressure and flow rate of materials in the contacted area gradually increase. The materials at the edge of the blank begin to flow to the gap among tools. The panel (a) of figure 4
demonstrates the effective stress distribution at the end of the stage I where the stroke of the upper die is $S = 0.40$ mm. Obviously, material at the point A in panel (a) always contacts with the punch that its stress is maximum. Due to the free space at the edge, all materials tend to flow into this region, as shown in panel (b). Since the materials at the edge contact with the upper die earlier than those at the flat middle region of the workpiece, their velocity magnitudes are larger than others.
During the stage II, all materials in the flat regions undergo large compression of the punch. Their pressures and flow rates increase (see panels (c) and (d)). We also notice that the materials flow along the radial direction and constrained by the collar to form the edge shape of the coin. At the end of the this stage, the stroke of the upper die is $S = 0.45$ mm.

As illustrated in panel (e), all stresses continue increasing and maximum values occur at the four corners of the punch. Due to the sufficient filling of material in the gap, partial materials start to splash (see panels (e) and (f)). The total stroke of the upper die at the last stage is $S = 0.47$ mm.

In case of single material copper, the stress distributions and material flow are plotted in figure 5. Similar conclusions to the case of material aluminum are also drawn in the three stages. The only significant difference is that the effective stresses in this case are much larger due to the higher yield stress of copper.

From the panels (b), (d) and (f) of figures 4 and 5, we observe that the materials in the central of coin are compressed and flow along the thickness direction due to the farthest distance to the free space at the edge. With the decreasing of distances to the edge, the flow directions of materials change from vertical to horizon. Suppressed by the collar, materials are separated into two parts when they contact with the collar initially. Then, one of the them flows up and one flows down along the inner surface of the collar, as shown in panels (d) of figures 4 and 5. The adjacent materials then also change their flow directions and fill the rest free space among the three tools. Finally, materials at the edge begin to splash along the clearances of the collar and the upper/ lower dies (see panels (f) of figures 4 and 5).

4.2. Analysis of stress and material flow of bi-material Al-Cu

As demonstrated in figure 6(a), materials of copper in the edge initially are compressed by the punch and enter into plastic state firstly while aluminum materials in the inner core starts to contact with the punch and most of them are in elastic state. Then, the maximum effective stress reaches a higher value due to the contribution of copper in the outer ring. Still the material flow obeys the same rule in case of single material that those in the center flow down and those near the edge flow horizontally, as shown in figure 6(b). One difference is that the materials adjacent to the interface of two regions exhibit small flow. This can be explained that the two parts are physically separated with few mutual compression at the interface in the first stage I. In the stage II, more materials of the aluminum and copper are compressed by the tools with the upper die move downward (see figure 6(c)). So effective stresses increase further and the two separated parts squeeze each other to make a whole object. The materials at interface flow towards the free space and those at the edge flow following the same rule in cases of the single material (see figure 6(d)). As the aluminum materials in the core squeeze the outer ring.
continuously, there forms an arc curve at the interface (see the intersection of the two regions in panel (e)). This drum-like shape can be commonly seen in cylinder upsetting process. We notice that stress concentration occurs at the interface. This may help engineers to understand the sprout of micro-crack in bi-material coining process. At the end of stage III, only few materials splash out and sufficient material fillings finish shaping the edge of final product (see figure 5(f)).

4.3. Analysis of stress and material flow of bi-material Cu-Al

In order to optimize the material combination of aluminum and copper in the two regions for getting less opportunity of micro-crack at interface and avoiding drop of the inner core, coining process with inner copper and outer aluminum is simulated that corresponding results are plotted in figure 7. Since the hardness and yield stress of copper is much different from those of aluminum, the material behaviors are much different from the above case. In the stage I, the mold first contacts the edge material of aluminum when the upper die moves downward. Then, the compressed stress and flow velocity of materials in the contacted area gradually increase. The panel (a) of figure 7 demonstrates the effective stress distribution at the end of this stage. Apparently, effective stresses in both regions are at same level, even the materials at the edge contact with the upper die earlier than those at the flat inner core. All materials tend to flow into the free space, including these at the interface, as shown in panel (b). As the punch continues moving down, the stresses increase significantly in the inner core during the stage II while the behaviors of material flow keep the same as above two cases, as demonstrated in panel (c). At the end of stage III, the final coin seems to be sufficient filling and material flows stop (see panels (e) and (f)).

As shown in figure 8, the effective stresses over the center line of the coin section (see line in panel (a) of figure 7) at three stages are plotted. As we can see from the panels (a) and (b), the materials in flat regions are all in plastic state at the end of stage I and their stresses increase from stage I to stage III. The position of maximum stress shifts from a point B whose $X-$ coordinate is the same as point A to the point C as shown in see panels (a)-(d) (see points A, B and C in panel (a) of figure 7). Recall that point A is in which material first contacts with the punch during stage I. Therefore, the stress of point B is always maximum under the actions of the punch and the lower die until the end of stage I. After the materials reach the inner surface of the collar and are blocked by the collar, the point with maximum stress eventually moves to point C which is near the intersection point of the shear bands (see similar bands in panels (c) and (e) of figures 4 to 7). Comparing the stress distributions in the flat region of coin in the cases of bi-material, both significant changes appear at the interface of two regions (see see panels (c) and (d)). Due to higher hardness and yield stress of copper in the core, the same punch stroke causes higher stress and internal force (see panel (d)). Thus, larger stresses achieve in the whole inner core by comparing those in panel (a). In a sense, harder material in the core would increase the possibility of micro-cracks. Of course, it also increases the press force.
Figure 9. The stress distribution of the whole coin. Panels in first row plot the stress for case of aluminum, the second row for the case of copper, the third row for the case of Al-Cu and the last row for the case of Cu-Al. The first column indicates stress in the first stage I, the second column for the stage II and the last column for the stage III.

Figure 10. Strain distribution in cases of single material. Panels in left and right columns plot strain distributions in cases of aluminum and copper in the three stages, respectively. Panels in the first, second and third rows show results in the stage I, II and III, respectively.
Figure 11. Strain distribution in cases of bi-material. Panels in left and right columns plot strain distributions in cases of Al-Cu and Cu-Al in the three stages, respectively. Panels in the first, second and third rows show results in the stage I, II and III, respectively.

Figure 12. The stress distribution of the whole coin. Panels in first row plot the stress for case of aluminum, the second row for the case of copper, the third row for the case of Al-Cu and the last row for the case of Cu-Al. The first column indicates stress in the first stage I, the second column for the stage II and the last column for the stage III.
Herein, we plot the stress distribution of the whole coin in the three typical stages for the four cases, as shown in figure 9. Just as discussed above, all coins are with sufficient filling according to the panels in the last column and stress concentrations are found at the interface in cases of Al-Cu and Cu-Al.

5. Analysis of strain distribution

As demonstrated in figures 10 and 11, the strain concentrations in the three stages are plotted in the four cases. There are two typical deformations that one is at the edge in all cases and the other is at the interface in cases of bi-material. Looking at the strain distributions at the edge in the four cases, large strain initially occurs at point A where maximum stress appears (see figure 7(a)). Eventually, large deformations happen in the edge and a shear-like bands are formed due to the compression of three tools in all cases. As the punch moves downward and contacts the flat upper surface of the coin, materials in flat regions are compressed and flow into the gap among tools. Therefore, the strains there are almost uniform in the cases of Al/Cu. In cases of bi-material, there are interactions at the interfaces where strain mutations are found. By comparing the strains at interfaces in figure 11, the strains at interfaces in case of Al-Cu are much larger than those in Cu-Al. This indicates that soft materials in the core lead to large deformation and better adhesion at interface. As well, we plot the strain distribution of the whole coin in the three typical stages for the four cases, as shown in figure 12. Panels in four rows plot the stresses for cases of aluminum, copper, Al-Cu and Cu-Al, respectively and each row demonstrates the strain evolution at the three stages. These plots support the conclusions obtained above that large strains occur at the edge and deep adhesion happens at the interface in case of soft material in the core.

6. Conclusion

As a special forming industry, the simulation analysis technology of imprint forming develops slowly because of confidentiality. According to experience, most of the embossing technicians use the method of multiple mold trials to optimize the design of the initial blank edge and mold, and avoid drop of the inner core in the production of bi-material coins. This has greatly hindered the research and development of bi-material based commemorative coins. The present study conducts simulations of coining process with single/two materials to analyze the material flow and stress distribution, aiming at assisting engineers to figure out the reason for falling of the inner core in coin. In order to get a better understanding of material flow during the coining, patterns of the tools are removed and pre-forming of commemorative coin is implemented in Deform 3D software. Some typical characteristics of material behaviors are concluded as follows.

- Whether the coin is single or bi-material, three stages exists over the whole process. Large stress/strain happens at the position that the punch and coin initially contact in the first stage. All materials flow towards the free space of the coin edge until some of them are hindered by the inner surface of the collar during the second stage. Then, materials undergo compression of the three tools and form the shear-like band in the last stage. Finally, materials fill the gap sufficiently and few of them splash through the clearances of the collar and the upper/lower dies.

- Stress concentrations occur at the edge of the coin and the interface of two materials. In the former situation, the four corners of upper and lower dies trigger the concentrations and might lead to micro-cracks sprouting along the shear bands. In the latter situation, large stress is located in the region of harder material that also promotes the sprout of cracks.

- Large strains occur at the edge in cases of single or bi-material as well as at the interface of dual materials. Deep adhesion happens at the interface in case that softer materials are in the core. Thus, possibility of drop of the core should be reduced.

Although several numerical examples have been implemented to study the material behaviors during coining process in cases of single/bi-material and critical conclusions have been drawn, there is still much work to explore by cooperating with the engineers of mint company. In this paper, the formation mechanisms of micro-cracks and core falling off in the production of single and double material coins are studied by simulation. However, the effect of the gap between the inner core and the outer ring on stress concentration and interfacial adhesion has not been further studied and explored by the combination of simulation and experiment. Furthermore, the height of inner core also has a great influence on the filling of surface patterns and forming force. Moreover, the design of grooves in the inner core or outer ring is also of great engineering significance to prevent the inner core from falling off.
Acknowledgments

This work was supported by Senior Talent Foundation of Jiangsu University (No. 19JDG022) and the fund from Shenyang Mint Company Limited (No. 20220056).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Yuan Wang  https://orcid.org/0000-0001-7391-9382

References

[1] Kiran C and Shaw M C 1983 CIRP Ann. 32 151–4
[2] Brekelmans W, Mulders L, Ramaekers J and Kals J 1988 CIRP Ann-Manu. Techn. 37 235–8
[3] Haghighat H and Asgari G 2011 Int. J. Mech. Sci. 53 248–53
[4] Martin F, Sevilla L, Camacho A and Sebastian M 2013 Procedia Engineering 63 413–20
[5] Choi H H, Lee J H, Bijun S K and Kang B S 1997 J. Mater. Process. Tec. 72 396–402
[6] Xu J, Liu Y, Li S and Wu S 2008 CMES-Comp. Model. Eng. 38 201–16
[7] Zhong W, Liu Y, Hu Y, Li S and Lai M 2012 Int. J. Adv. Manuf. Tech. 63 939–53
[8] Zheng W, Wang G C, Wu T and Song L B 2012 Mater. Sci. Forum 704 (Switzerland: Trans Tech Publ) 129–34
[9] Xu J, Khan K A and El Sayed T 2013 Precis. Eng. 37 389–98
[10] Alexandrino P, Leitão P J, Alves L M and Martins P A 2018 Manuf. Rev. 5 3
[11] Ghassemi E, Tan M J, Jarfors A E and Lim S 2013 Int. J. Mech. Sci. 71 56–67
[12] Xu J, Chen X, Zhong W, Wang F and Zhang X 2021 Int. J. Mech. Sci. 196 106258
[13] Plancak M, Car Z, Viloti ć D, Movrin D and Kršulja M 2012 Ann. Fac. Eng. Hunedoara 10 157
[14] Essa K, Kacmarcik I, Hartlic P, Plancak M and Vilotic D 2012 J. Mater. Process. Tech. 212 817–24
[15] Politis D, Lin J, Dean T and Balint D 2014 J. Mater. Process. Tech. 214 2248–60
[16] Çetinsav I 2014 Farklı malzeme kullanılarak üretilmiş bimetalik malzemelerin mekanik özelliklerinin incelenmesi Master’s thesis Trakya Üniversitesi Fen Bilimleri Enstitüsü
[17] Graf M, Hartel S, Binotsch C and Awiszus B 2017 Procedia Eng. 184 497–505
[18] Napierala O, Dahneh C and Tekkaya A E 2019 CIRP Ann-Manu. Techn. 68 269–72
[19] Khanawapee U and Butdee S 2020 Mater. Today 26 1262–70
[20] Delamare F and Montmitonnet P 1984 J. Mech. Work. Technol. 10 253–71
[21] Alexandrino P, Leitão P J, Alves L M and Martins P A 2019 P. I. Mech. Eng. L-J. Mat. 233 842–9
[22] Marques M B and Martins P 1991 J. Mater. Process. Tech. 26 337–48
[23] Chandra A and Srivastava R 1991 Math. Comput. Model. 15 81–92
[24] Wu T, Abdel Hamid A, El Monayri H and El Abbasi N 1996 J. Mater. Process. Tech. 56 918–32
[25] Yeh W C and Wu M C 2005 J. Mater. Process. Tech. 170 392–402
[26] Altinbalik T and Can Y 2011 Indian. J. Eng. Mater. S. 18 416–24
[27] Afonso R M, Alexandrino P, Silva F M, Leitão P J, Alves L M and Martins P A 2019 P. I. Mech. Eng. B-J. Eng. 233 2358–67
[28] Lv C, Zhang L, Mu Z, Tai Q and Zheng Q 2008 J. Mater. Process. Tech. 198 463–70
[29] Lv C, Zhang L, Mu Z, Tai Q and Zheng Q 2008 J. Mater. Process. Tech. 198 463–70