Investigation of Lateral Surface Contour at Forging of Billets with Upsetting Ratio Above 2.5

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Abstract. List of the most used functions (circle, parabola, ellipse, hyperbola, cosine, hyperbolic cosine), which are applied to approximate of billets contours at upsetting and pointed to the lack of a universal equation for these purposes, was analyzed. The advantages and disadvantages of each type of equations are pointed. The paper presents the results of upsetting of lead cylindrical specimens with a upsetting ratio 2.0–4.0. The experiment shows the stages of a “double barrel” forming on the lateral surface of a billet and its subsequent transition to a single one. The authors propose to use the “superformula” recently invented by Johan Gielis as a universal equation that allows to approximate the contour of the lateral surface of a billet at all stages of upsetting. The paper presents comparative initial data necessaries to determine upsetting force and pressure, taking into account the barrel-shape calculated by the superformula, and the coefficient of friction determined by Gubkin’s method. The equations coefficients have find, which give approximately the same results comparables to upsetting of specimens from lead, and these equations proposed for the calculation of the forming at upsetting from double-barrel to single-barrel workpiece.

1. Introduction
Upsetting of a billet is a common forging operation, intended primarily for the manufacture of forgings with large cross-sections from billets of smaller cross section, refining the cast structure of the ingot, pre-forming of the billet for further piercing or closed die forging. In addition, upsetting helps to receive a grain flow in the deformable metal to improve the performance properties of the finished parts, to weld hydrogen flakes, to remove scale from the surface and align the mechanical properties along the axis of the forgings [1, 2]. A limitation of the upsetting process is the limiting height $H_0$ to diameter $D_0$ ratio (upsetting ratio or aspect ratio), the excess of which leads to a bulk buckling. In the literature from the beginning of the last century to the present is copied the ratio that ensures the sustainability of the upsetting [1, 2]:

$$
H_0 / D_0 \leq 2.5.
$$

Due to limitation (1), it is often necessary to use coggled forgings as primary billets instead of cheaper rolled stocks product, because the latter with a cross-sectional size of more than 250 mm is produced in a limited amount.

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2. State of the art review

The wide application of upsetting in the forming processes makes it necessary to constantly research and improving. Studies are carried out in the field of choosing the optimal conditions of contact friction between billet and dies, in particular, lubricants for upsetting [3–6], identifying the influence on the process of geometric dimensions, temperature, upsetting reduction ratio (engineering strain) and strain rate [7, 8], chemical composition of billet material [5, 9], stress state of billet [10, 11], predicting the curvature of its lateral surface and choosing the optimal preform for subsequent die forging [7, 9, 12–15]. Primary materials for research are increasingly used billets in shells, powder and bimetallic specimens [5, 16, 17].

Modern technologies, equipment and tools have long allowed to upset billets outside the inequality (1). For example, PSTPÖ1Z-4000 hydraulic press of 40 MN force provides precise centering of the billet and the main hydraulic cylinder axes due to a centering device located between the press columns, similar to the interaction of a piston, engine cylinders, etc. [18–20]. As a result, the probability of buckling for billets with upsetting ratio $H_0/D_0 \leq 3.3$ is eliminated at forging. Upsetting of ingots and pre-rolled stocks with the ratio $H_0/D_0 = 2.0–2.5$ is recommended to be carried out between open dies with a concave spherical face, which centres the axis of the preformed workpiece coaxially with the press axis [1, 2]. Billeted ingots with $H_0/D_0 > 3.0$ are upset with the location of the shank in the hole of the lower die [21].

Increasing the limiting ratio $H_0/D_0$ allows to reduce the pressure and force at upsetting, to reduce the cost of the initial billet (the ingot is cheaper than rolled product), to increase the forging ratio and improve physical and mechanical properties of forgings. But in the literature there are not enough researches about upsetting of billets with the ratio $H_0/D_0 \leq 2.5$ [4, 13, 14]. This is due to the limited technological capabilities of processing and lack of forging theory of such ultrahigh bodies, namely the justification for the appearance and subsequent disappearance of the contour of the “double barrel” on the lateral surface of the upset billets. The evolution of the contour of billets affects the change in pressure and force during their upsetting. To calculate these parameters formulas of two types are used use (Table 1).

The upsetting force according to the first type of formulas (2)–(9) depends on the contact area of the billet with the tool $F$ and the upsetting pressure $p$, which, in turn, is determined by the yield strength of the deformed material $\sigma_y$ multiplied by the correction coefficient $C$, that takes into account the diameter to height ratio $H_0/D_0$ and the coefficient of friction $\mu$ between the end face of the billet and the upsetting dies. In this case, for hot upsetting, the coefficient of friction a priori is taken $\mu = 0.5$. The coefficient of friction is not a constant value in the process of deformation. The spread in values of the coefficient of friction, determined by many different methods, is significant for the same material with the same geometric shape. For upsetting operations, most often used values of the friction coefficient are those that are determined by the ring compression test (upsetting of ring specimens), which does not provide a geometric similarity of the method to the considered process of upsetting of cylindrical billets and, therefore, casts doubt on the correspondence of the calculated value of the coefficient to its real value during the upsetting of a cylindrical billet.

Assignment to the coefficient of friction of its maximum value equal to 0.5 is the upper estimate of the upsetting force and is justified in the upsetting of ingots without lubrication. In the technological process of hot forging, in which one of the transitions can be, for example, upsetting of a billet with a layer of glass lubricant [21], the values of the friction coefficient can be much lower than 0.5. In this case, the calculated values of the upsetting force will be significantly higher than the real values. The end surface area of the billets $F$ in the first type of equations (2)–(9) is overestimated, since it is determined by the diameter calculated without taking into account barrel formation, i.e., exceeding the value of the end diameter under conditions of real upsetting. The yield strength $\sigma_y$ is usually selected from reference books in which its value is fixed according to the results of tensile tests, while it would be more correctly to apply the conditional yield stress $\sigma_{0.2}$ determined by compression tests. In addition, hardening of the metal during the upsetting process,
especially in the cold state, is not always taken into account. At the same time, the friction forces arising between the billet and the die at upsetting determine one or another barrelling shape of the upset billet, characterized primarily by the radius of curvature $R$, which is determined by the diameters of the barrel $D_b$ and the ends $D_m$ of the billet. These values are quite accurately measured experimentally.

**Table 1. Equations for calculating the $C$ coefficient [22–26].**

| Equations that take into account the coefficient of friction $\mu$, the friction factor $m$ ($\mu=m$) and the geometric dimensions of the billets |
|---|
| $C = 1 + \frac{\mu D}{3H}$ |
| $C = \frac{1}{2} \left( \frac{\mu D}{H} \right)^2 \left[ \exp \left( \frac{\mu D}{H} \right) - \left( \frac{\mu D}{H} \right) - 1 \right]$ |
| $C = 1 + \frac{\mu D}{H 3\sqrt{3}}$ |
| $C = \frac{H_0}{H} \left( 1 + m \frac{2R_0}{H} \sqrt{\frac{H_0}{H}} \right)$ |
| $C = \left( 1 + \frac{\mu D}{3H} \right)^2$ |
| $C = \left[ 1 + \frac{\mu D_0}{H_0} \exp \left( \frac{3\varepsilon}{2} \right) \right]^{-1}$ |
| $C = \frac{\mu D_0 \sqrt{H_0}}{3H^{\frac{3}{2}}}$ |
| $C = \frac{8bR_{ideal}}{H} \left\{ \left[ \frac{1}{12} + \left( \frac{H}{bR_{ideal}} \right)^2 \right]^{\frac{3}{2}} - \left( \frac{H}{bR_{ideal}} \right)^3 + \frac{m}{24\sqrt{3} \left( e^{\frac{H}{2}} - 1 \right)} \right\}$ |
| $b = \frac{4mH}{R_{ideal} \sqrt{3}} \left( 1 + \frac{2mH}{R_{ideal} \sqrt{3}} \right)$ |

Equations that take into account the diameters of the ends, “barrels” and the radius of curvature of the contour of billets lateral surface

| Equations |
|---|
| $C = \left[ 1 - \frac{2R}{R_b} \right] \ln \left( 1 - \frac{R_b}{2R} \right)$ |
| $C = \left[ 1 - \frac{2R}{D_b} \right] \ln \left( 1 - \frac{D_b}{2R} \right)$ |
| $C = \left[ 1 - \frac{4R}{D_b} \right] \ln \left( 1 - \frac{D_b}{4R} \right)$ |
| $C = \frac{\left( D_b^2 - 4RD_m \right) \ln \left( 1 - \frac{D_b}{4R} \right)}{D_b^2}$ |

In the equations of the second type (10)–(13) the use of parameters $D_b$ and $D_m$ obtained by direct measurements, instead of the value of friction coefficient calculated from the results of indirect measurements without full compliance with scale and geometric similarity, will increase the
Although upsetting force and pressure. However, when calculating the radius of curvature \( R \) according to the equation:

\[
R = \frac{\left[ 1 + \left( \frac{y'}{y''} \right)^2 \right]^{\frac{3}{2}}}{y''}
\]  

(14)

where \( y' \), \( y'' \) – the first and second derivative functions approximating the contour of the meridional generating lateral surface of the upset billet, it is necessary to know the type of function that approximates the contour of the lateral surface of the “barrel”. Small inaccuracies in the choice of function can lead to large spread in value of \( R \), since the first and second derivatives of the approximating function are part of the equations (10)–(13).

Today, researchers intuitively assume in advance one or another type of contour of the lateral surface of the upset billet, and hence the type of approximating function (Table 2), and then select the appropriate values of the coefficients included in this function. That is, for the upsetting of billets there is no universal function, which is able to describe any of the possible contours of the lateral surface of the deformed billets (in particular, contour of the “double barrel”).

**Table 2.** Some equations for approximating the barrel-shaped lateral surface of the billet after upsetting.

| Equation | Designation |
|----------|-------------|
| Parabola: \( y = \frac{2(D_m - D_b)}{H^2} x^2 + \frac{D_b}{2} \) | \( D_{b}, D_{m}, H \) – diameters of a barrel, an end face and height of the billet |
| Ellipse: \( \frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \) | \( a = \frac{H}{2\sqrt{1 - \left( \frac{D_m}{D_b} \right)^2}}, b = \frac{D_b}{2} \) |
| Circle: \( x^2 + (y - b)^2 = R_{circle}^2 \) | \( b = \frac{D_b^2 - D_m^2 - H^2}{4(D_b - D_m)} \), \( R_{circle} = \frac{(D_b - D_m)^2 + H^2}{4(D_b - D_m)} \) |
| Cosine: \( y = a \cos(bx) \) | \( a = \frac{D_b}{2}, b = \frac{2}{H} \arccos \left( \frac{D_m}{D_b} \right) \) |
| Hyperbolic cosine: \( y = a \cosh(bx) \) | \( a = \frac{D_m}{2}, b = \frac{2}{H} \arg \cosh \left( \frac{D_b}{D_m} \right) \) |
| Hyperbola: \( -\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 \) | \( a = \frac{H}{2\sqrt{\left( \frac{D_b}{D_m} \right)^2 - 1}}, b = \frac{D_b}{2} \) |

Purpose of the research is the process of “barrelling” during upsetting of billets with upsetting ratio \( H_0/D_0 = 2.0–4.0 \), identification of a universal equation for approximating the barrel-shaped contours of upset billets, and the most acceptable formulas for calculating the upsetting force and pressure.
3. Materials and methodology of research

The research was performed on lead billets with a diameter of $D_0 = 30$ mm with upsetting ratio $H_0/D_0 = 2.0–4.0$. The upsetting was carried out without lubrication between flat dies with a stroke rate of 2 mm/s. The coefficient of friction between the billet and dies (by the Gubkin method) was $\mu = 0.41$. The upsetting reduction ratio determined by the equation:

$$
\varepsilon = \left( H_0 - H \right) / H_0.
$$

(15)

On the lateral surface of the billets at a distance along the height equal to 0.1 from the original height $H_0$, performed circular lines. The curvature of the contour of the lateral surface at upsetting was studied by the results of changing the diameter of these lines during the gradual upsetting of billets with upsetting reduction ratio of 0.1 to 0.5 with a step of 0.1.

In the paper [27] there is information that a huge number of different contours are quite accurately described by the superformula of J. Gielis. In the polar coordinates for the radius vector $r$ and the angle $\phi$ the Gielis superformula has the form:

$$
r = \frac{1}{\sqrt{\left[\left(\frac{1}{a} \cos\left(\frac{k}{4} \phi\right)\right)^{n_1} + \left(\frac{1}{b} \sin\left(\frac{k}{4} \phi\right)\right)^{n_2}\right]^{\frac{1}{n}}}}
$$

(16)

where $n_1, n_2, n_3$ – parameters that determine the shape of the curve; $a, b$ – dimensions (values of semi-axes); $k$ – coefficient that characterizes the number of repeating fragments.

In forming processes, superformula (16), as well as its simplified variant – superellipse Lame – has already been successfully used as universal equations to approximate the contours of deformable sheet billets and further analysis of their stress-strain state [28–30]. Regarding the process of billet upsetting, previous attempts to approximate the superformula have shown that the selection of coordinate system is important for the possibility and accuracy of the approximation.

Figure 1 shows a diagram of the selection of the coordinate system of the approximating function relative to the geometric dimensions of the deformed barrel-shaped billet. According to this scheme, the approximation of experimental data can be performed in a system of dimensional and dimensionless coordinates. If the contour of the lateral surface of the upset billets is a “single barrel”, then a system of dimensionless coordinates $x_0 y_0$ with measurement limits on both axes from zero to one is chosen. The $x$-axis is parallel to the axis of the billet and coincides with the generatrix, which forms a cylinder with a diameter equal to the diameter of the end face $D_{eq}$. The $y$-axis intersects the $x$-axis in the plane of the maximum barrel diameter of billet $D_b$. The dimensionlessness of the coordinates $X_i$ and $Y_i$ was ensured by dividing according to the measured real size $h_i$ (mm) by the maximum possible size, which is equal to half the height of the upset billet $H/2$, i.e. $X_i = h_i / (H/2)$, as well as the measured real size:

$$
d_i = \left( D_{ib} - D_{im} \right) / 2
$$

(17)

when $x = h_i$ at the maximum possible size equal to the half-difference between the diameters of the “barrel” and the end face of the billet, i.e.

$$
Y_i = \left( D_{ib} - D_{im} \right) / 2
$$

(18)

In this coordinate system ($y \neq x$) the contour of the “single barrel” is circumscribed by the radius vector $r$ of the superformula when the angle $\phi$ changes within $[0; 90^\circ]$. If the contour of the lateral surface of billets at upsetting evolves from “double” to “single barrel”, the coordinate system $y \neq x_1$ is chosen, in which the $x_1$ axis coincides with the central axis of the billet, and the dimensionlessness of the $Y_i$
coordinate is provided by dividing the measured real radius of the barrel along the axis of the billet by the maximum possible one, i.e.:

\[ Y_i = \frac{D_i'}{2} = \frac{D_{b_{\text{max}}}}{2} = \frac{D_b'}{D_{b_{\text{max}}}}. \]  

(19)

4. Analysis of results

Figure 2 shows the billets with a “double barrel” on the lateral surface after upsetting, and in Figure 3 shows the results of increasing the diameter of the circular lines \( D \) relative to the original diameter \( D_0 \) depending on the height of the billets \( H \), which decreases at upsetting. The location of the circular lines was measured by the parameter \( f \) – the distance from the lower end to the circular line, in particular, ratio \( f/H = 0.5 \) for the line bisecting the specimen height \( H \).

Figure 1. Diagram for selecting the coordinate system of the approximating function.  

Figure 2. Appearance of deformed semi-finished products with a double-barrel on the lateral surface upsetted from the billet with initial dimensions ratio: \( H_0/D_0 = 2.5 \) (a); \( H_0/D_0 = 3.5 \) (b).

Figure 3(b-d) indicates that “double barrelling” occurs when billets with a ratio \( H_0/D_0 > 2 \) are upset. In addition, the “double barrel” is fixed at upsetting reduction ratio of the specimens not more than 0.3. When \( H_0/D_0 = 2 \) upsetting of billets increase the ratio \( D/D_0 \) (at \( f/H = 0.5 \)) in 1.05–1.47 times with increasing \( \varepsilon \) within 0.1…0.5. Increasing the upsetting ratio to \( H_0/D_0 = 2.5 \) also increases the maximum diameter of the “barrel” \( D/D_0 = 1.49 \). In addition, in the upsetting reduction ratio \( \varepsilon = 0.1–0.3 \), a “double barrel” appears on the lateral surface of the billets. With increasing \( \varepsilon \) from 0.1 to 0.4, the maximum diameter ratio of the “barrel” is shifted in the area from the ends to the center of the billet and is fixed at ratio \( f/H = 0.78, 0.77, 0.73 \) and 0.68, respectively, for billets with upsetting ratio \( H_0/D_0 = 2; 2.5; 3; 3.5 \). The difference between the maximum diameters ratio of the “double barrel” and the diameter in the central part of the specimen (at ratio \( f/H = 0.5 \)) is insignificant and equal to \( \Delta(D/D_0) = 0.01–0.04 \). The “double barrel” for upset billets with \( H_0/D_0 = 3 \) is already almost indistinguishable at \( \varepsilon \geq 0.3 \). The maximum diameters ratio of the “barrel” is fixed in the range \( f/H = 0.76–0.74 \), and the maximum difference \( \Delta(D/D_0) = 0.02 \) at \( \varepsilon = 0.2 \). It is noticeable that the circular zones, which stand from the end at a distance of 0.1N with increasing \( \varepsilon \) become the end surface of billets. Thus, if lines 1-4 have five experimental measurements of diameters \( D \), then line 5 has only four measurements. The increase in the upsetting ratio of the billets to \( H_0/D_0 = 3.5 \) (Figure 3(d)) with values \( D/D_0 \) at upsetting almost does not differ from the graphs (Figure 2(c)) for upsetting of billets with \( H_0/D_0 = 3 \). In particular, “double barrel” is fixed in the range of upsetting reduction ratio \( \varepsilon = 0.1–0.3 \) and by the parameter \( \Delta(D/D_0) \) is also quite
insignificant. As for upsetting of billets with $H_0/D_0 = 4.0$, then at $\varepsilon = 0.08$ they lost resistance and buckled so that their further deformation was impossible.

The superformula that approximates the contour with a “double barrel” in the coordinates $y_0,x_1$, reproduces the same contour instead of a straight line on the end surface of the billet. Since the end is flat, the approximate values of the superformula coefficients when changing the angle $\phi$ from 0 to $\arctg[(D_\text{min}/2)/(H/2)]$ are not valid, and the calculation of the contour of the “double barrel” should be performed when changing the angle $\phi$ within $\{\arctg[(D_\text{min}/2)/(H/2)]; \pi/2\}$.

Figure 3. Distribution of diameters ratio of the barrel along the height of the upset billets: 1…5 – $\varepsilon = 0.1…0.5$ with a step of 0.1; $H_0/D_0 = 2.0$ (a), 2.5 (b); 3.0 (c), 3.5 (d).

Figure 4 shows lines of the approximating superformula for upsetting of billets with upsetting ratio $H_0/D_0 = 3.5$. The graphs show the maximum of the barrelling at $\varepsilon_2 = 0.2$, after which the diameter of the central part of the billet begins to increase more intensively, and the “double barrel” gradually turns into a single one. For other values of the upsetting ratio of billets and the upsetting reduction ratio the graphs are approximately the same, i.e. superimposed on each other, that is why they are not shown. Table 3 shows the values of the superformula coefficients, which were obtained by approximating the generating lateral surfaces of the upset billets, including “single” and “double barrel”. The calculations followed the recommendations of Johan Gielis [27] to assign (for cases similar to ours) the value of the coefficient $k = 4$. However, later our calculations showed that the change in the values of $k$ in the range from 3 to 5, which already determined other values of the
coefficients $n_1...n_3$, can provide an approximation of experimental data with less error. But such a result can be guaranteed only in the first quadrant of the Cartesian coordinate system.

Table 3. Values of the superformula coefficients.

| Upsetting ratio of billets, $H_0/D_0$ | Upsetting reduction ratio, $\varepsilon$ | Value of the superformula coefficients $n_1$ | $n_2$ | $n_3$ |
|-------------------------------------|----------------------------------------|-------------------------------------------|------|-------|
| 2.0                                 | 0.1                                    | 1.4 (0.7)                                | 13.5 (2.1) | 1.3 (1.6) |
|                                     | 0.2                                    | 33 (2.1)                                 | 34 (2.1) | 25.4 (1.4) |
|                                     | 0.3                                    | 2.1 (8.9)                                | 12.3 (0.5) | 1.6 (0.7) |
|                                     | 0.4                                    | 1.6 (2.2)                                | 15.4 (1.2) | 1.1 (1.0) |
|                                     | 0.5                                    | 6.1 (1.2)                                | 66.2 (1.4) | 3.7 (1.2) |
| 2.5                                 | 0.1                                    | 2.7                                      | 10 | 2.6 |
|                                     | 0.2                                    | 2.2                                      | 13.8 | 2 |
| 3.0                                 | 0.1                                    | 7.9                                      | 11.9 | 7.8 |
|                                     | 0.2                                    | 8                                        | 10.5 | 7.9 |
|                                     | 0.3                                    | 3.1                                      | 7.5 | 3 |
|                                     | 0.4                                    | 7.6                                      | 11.4 | 5.8 |
|                                     | 0.5                                    | 3.4                                      | 15.9 | 2.2 |
| 3.5                                 | 0.1                                    | 3.7                                      | 19.9 | 3.5 |
|                                     | 0.2                                    | 1.5                                      | 10.7 | 1.4 |
|                                     | 0.3                                    | 3.4                                      | 7.3 | 3.4 |
|                                     | 0.4                                    | 2.4                                      | 7.6 | 2.2 |
|                                     | 0.5                                    | 3.3                                      | 11.5 | 2.3 |

Figure 4. Approximation of the contour of the double barrel on the lateral surface of the upset billet with $H_0/D_0 = 3.5$; $\varepsilon_1 = 0.1$; $\varepsilon_2 = 0.2$, $\varepsilon_3 = 0.3$.

The coefficients $n_1...n_3$ of the superformula were used to determine the parameters $C$ according to equations (10)–(13), as well as their comparison with the same parameters in equations (2), (3). As a result, it was found that equation (2) coincides with formulas (12), (13), if $\mu = 0.25$ and 0.43, and equation (3) – if $\mu = 0.20$ and 0.34. Therefore, equation (13) is not suitable to determine $C$, because the
values of $\mu = 0.34$, 0.43, as well as $\mu = 0.41$, are overrated. Probably the most suitable for the calculation of upsetting pressure and force are formulas (2) and (12). The values of the approximating coefficients $n_1…n_3$ in quotation marks shown in table 3 for billets with a upsetting ratio $H_0/D_0=2$, i.e. upset without a “double barrel”, obtained for the case when the coordinates $y=0$ were selected, and the ordinate $Y$, was calculated by equation (18).

5. Conclusions
Upsetting of cylindrical billets with the ratio $H_0/D_0 > 2$, at the initial stage creates the contour of the “double barrel” on their lateral surface, which at a upsetting reduction ratio $\varepsilon > 0.3$ turns into a “single barrel”. The difference between the maximum diameters ratio of the “double barrel” and the diameter in the central part of the specimen is quite insignificant and equal to 0.01–0.04. To approximate all possible contours of the lateral surfaces of upset billets, in particular, “single” and “double barrel”, it is advisable to use the universal superformula of J. Gielis. The most acceptable equation for calculating the correction parameter $C$ in the equation to determine upsetting pressure and force, which uses the radius of curvature of the lateral surface of a billet.

References
[1] Dineshbabu C, Arivazhagan R, Venkatesh R, Balasubramani K and Periyasamy R 2020 Materials Today: Proceedings 21 601–611
[2] Petrov M, Kalpin Y and Petrov P 2020 Procedia Manufacturing 47 1504–1511
[3] Ragab A R 2002 Materials Science and Engineering A334 114–119
[4] Kulkarni K M and Kalpakjian S 1969 Journal of Engineering for Industry 743–754
[5] Kumar P, Ranjan R K, Singh D and Singh V 2019 AIP Conference Proceedings 2142 170023
[6] Egea A J S, Martynenko V, Abate G, Deferrari N, Krahmer D M and López de Lacalle L N 2019 The International Journal of Advanced Manufacturing Technology 102 1623–1633
[7] Wang X, Li H and Sandrashekhar K 2017 Journal of Materials Processing Technology 1–24
[8] Anishchenko A, Kukhar V, Artiukh V and Arkhipova O 2018 MATEC Web of Conferences 239 06006
[9] Mahesh E S, Jyothi K, Rao K V and Murty M S 2015 International Journal of Scientific and Research Publications 5(10) 1–9
[10] Sahu M K, Valarmathi A, Baskaran S, Anandakrishnan V and Pandey R K 2014 Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 228(11) 1501–1507
[11] Krallics G, Ree A, Bobor K and Szombathelyi V 2013 Materials Science Forum 752 85–94
[12] Ashtiiani H R R and Shahsavari P 2018 Prediction Journal of Advanced Materials and Processings 6(1) 29–45
[13] Kukhar V, Balalayeva E, Prysiazhnyi A, Vasylevskyi O and Marchenko I 2018 MATEC Web of Conferences 178 02003
[14] Markov O E, Gerasimenko O V, Shapoval A A, Abdulov O R and Zhytnikov R U 2019 International Journal of Advanced Manufacturing Technology 103(5-8) 3057-3065.
[15] Usami M and Oya T 2014 Procedia Engineering 81 371–376
[16] Essa K, Kacmarcik I, Hartley P, Plancak M and Vilotic D 2012 Journal of Materials Processing Technology 212 (4) 817–824
[17] Egorova R V, Egorov M S and Skorikov A V 2013 Metallurgist 57(5-6) 442–448
[18] Korol S, Moroz M, Yelistratov V and Moroz O 2019 IEEE International Conference on Modern Electrical and Energy Systems (MEES) 30–33
[19] Korol S O, Moroz M M, Korol S S and Serhiienko S A 2017 Scientific Bulletin of the National University 5 56–61
[20] Chernenko S, Klimov E, Chernish A, Pavlenko O and Kukhar V 2018 International Journal of Engineering and Technology(UAE) 7(4) 120–124
[21] Anishchenko A S, Feofanov Yu V and Bogun A B 1992 Chemical and Oil and Gas Engineering 11 33–35
[22] Altan T, Ngaile G and Shen G 2005 Cold and hot forging: Fundamentals and Applications (Ohio: Materials Park, ASM International) p 333
[23] Torrente G 2018 Materials Research 21(4) 1–7
[24] Zhou X and Li Z 2006 Journal of Engineering Mechanics 132(2) 149–157
[25] Aluko O and Adeyemi M B 1998 Journal of Materials Engineering and Performance 7(4) 474–478
[26] Christiansen P, Martins P A F and Bay N 2019 Manufacturing Engineering Education 4 85–104
[27] Gielis J A 2003 American Journal of Botany 90(3) 333–338
[28] Anishchenko A, Kukhar V, Artiukh V and Arkhipova O 2018 MATEC Web of Conferences 239 06007
[29] Anishchenko O S, Kukhar V V, Grushko A V, Vishtak I V, Prysiazhnyi A H and Balalayeva E Yu 2019 Materials Science Forum 945 531–537
[30] Anishchenko O, Kukhar V, Artiukh V, Trebukhin A and Zotkina N 2020 Advances in Intelligent Systems and Computing 982 809–817