Multi-criteria analysis of the coatings quality obtained by cladding with a flexible tool

A V Zotov and D A Rastorguev
Togliatti State University, Belarusian Street, 14, Togliatti City, 445020, Samara Region, Russian Federation

E-mail: A.Zotov@tltsu.ru

Abstract. In the article the technology of surface modification is considered on the basis of thermo-mechanical method by means of cladding with flexible (wire) tool. Here we propose a multi-criteria optimization technique to determine the characteristics of a flexible tool and processing modes by the criterion of the maximum possible adhesion of the coating applied to the workpiece surface. Mathematical dependences are presented for determining the base temperature of the product surface, which is created by friction of the tool pile; temperature in contact when cladding; the energy of mechanical activation; relative strength coefficient of the adhesion of particles as a result of the chemical reaction. The simulated data are obtained from the variation of the input parameters and the resulting output factors of the adhesion process: the ratio of the base temperature of the machined product surface to the contact temperature, the ratio of the mechanical activation energy to the total activation energy of the process and the value of the relative strength coefficient of the adhesion. The data obtained as a result of modeling were used to optimize the output factors of the adhesion process. Optimization technique was used, where grey relational analysis and fuzzy logic theory are combined.

1. Introduction

In modern conditions, one of the main directions of development of the machine-building complex is the introduction of resource-saving technologies into production. About 80% of the conjugated surfaces in the mechanisms are refused due to wear. The performance characteristics of engineering products improve by the use of surface modification technology. Technologies that increase strength, wear resistance and durability have a share of about 50% of the total number of technologies introduced into production in recent years. Also about 20% of surface modification technologies are aimed at obtaining the effect of environmental safety [1].

One of the new technologies that corresponds to modern trends is the technology of cladding products with a flexible tool. Coating is carried out thermo-mechanically by means of a flexible tool (a disk wire brush) entering simultaneously into contact with the element of the coating material and the workpiece surface of the component.

The metal of the coating is pressed against the bristles of the wire brush and heated to high temperatures in the contact region. Particles of the metal coating are then caught on the ends of the bristles and transferred to the surface being treated. The product surface is strengthened as a result of intensive plastic deformation by flexible elastic elements. Metal particles of the coating that are located on the ends of the bristles are simultaneously subjected to plastic deformation and are captured by the surface of the product. Strong bonding of the particles to the surface is assured by removal of the oxide films on the surface and the exposure of clean surface areas during the joint plastic deformation of the particles and the surface layer [2].
2. Relevance
Currently, cladding with a flexible tool is increasingly used in production processes [2–8]. Moreover, this method of surface modification can be used both for corrosion protection and for increasing the wear resistance of friction pairs for various functional purposes. So in the works [3, 4] the problems are considered on the application of cladding to protect weld seams from corrosion and increase the corrosion and antifriction resistance of friction pairs of hydraulic equipment. In [5–7], the problems of increasing wear resistance and bearing capacity of friction pairs of the main units of metal rolling equipment were considered, and in [8, 9] – increasing the wear resistance of metalworking equipment guides.

At the moment, the actual problem is the operational choice of processing parameters that will allow to constantly forming a surface layer of high quality. One of the main performance criterion is the shear resistance on the relative penetration for dry surfaces in tin bronze can withstand much more.

As a coating material used tin bronze CuSn6Zn6Pl3, and as an object of cladding – structural steel AISI 5135. The coating material was chosen for the following reasons:

Almost all works [2–9] are devoted to the study of the parameters of the cladding process to some extent, and as a result, the ranges of the parameters variation are determined. The main parameters have a significant effect on the value of adhesion during cladding.

In this paper, a multi-criteria technique is proposed to assess the adhesion of the applied coating to the base by varying the circumferential velocity of the tool, the diameter of the pile and the length of the bending part of the wire. These parameters have a significant effect on the value of adhesion during cladding.

The remaining parameters were chosen on the basis of experience and equal: the diameter of the wire tool used – 250 mm, the actual fill factor of the working surface of the tool – 0.15, the tightness is 2 mm. As a coating material used tin bronze CuSn6Zn6Pl3-C, and as an object of cladding – structural steel AISI 5135. The coating material was chosen for the following reasons – the dependence of the relative shear resistance on the relative penetration for dry surfaces in tin bronze can withstand much more larger loads that do not lead to scratching or micro-cutting.

First of all, it is necessary to determine the temperature of the base of the workpiece surface formed by friction of the tool pile. In work [9] the mathematical model is presented for determination of temperature of a basis taking into account a variable step between spots of contact of flexible elements with the processed surface during sliding along it:

\[
\theta_0 = \frac{Q \cdot (3 + \varphi_S)}{8 \cdot \varphi_S \cdot \pi \cdot \lambda \cdot S \cdot \psi} \cdot \exp \left( -\frac{\zeta^2 \cdot \varepsilon_B \cdot P \varepsilon_S}{4 \cdot \psi} \right) + \theta_2, \tag{1}
\]

\[
\theta_2 = \frac{Q}{2 \cdot \pi \cdot \lambda \cdot S} \cdot \sum_{\nu=1}^{n_N} \left( \frac{1}{\psi} \right) + 2 \cdot \frac{Q}{2 \cdot \pi \cdot \lambda \cdot S} \cdot \sum_{\nu=1}^{n_N} \left( \frac{1}{\psi} \cdot \exp \left( -\frac{\zeta^2 \cdot \varepsilon_B \cdot P \varepsilon_S}{4 \cdot \psi} \right) \right), \tag{2}
\]

where \( Q \) is the power of the source, \( W \); \( \varphi_S \) is the dimensionless coordinate; \( \lambda \) is coefficient of thermal conductivity of the processed material, \( W^{-1} \cdot m^{-1} \cdot (m \cdot ^{\circ}C)^{-1} \); \( S \) is step in the longitudinal direction, m; \( \psi = x \cdot S^{-1} \); \( \zeta = y \cdot S_{p}^{-1} \) are dimensionless coordinates; \( x, y \) are coordinates of the contact spot on the machined surface, m; \( S_{p} \) is step in the transverse direction, m; \( \varepsilon_B \) is the multiplicity factor of the step; \( P \varepsilon_S \) – Peclet criterion; \( \theta_2 \) is total influence of all wires in the contact zone on the local temperature of the point source under
consideration, °C; \( n_v \) is the number of tool wires passing past the point source currently being considered.

Secondly, the temperature in contact during cladding needs to be determined. Using the known expression [10], the contact temperature \( \theta_c \) is determined taking into account the base temperature of the treated surface:

\[
\theta_k = \theta_o + K_e \left( \theta_p - \theta_o \right) \left[ K_e + \text{erf}(\alpha) \right]^{-1},
\]

where \( K_e \) is the criterion of the thermal activity of the coating material with respect to the base material; \( \theta_p \) is temperature of the particle of the coating material upon contact with the surface to be treated, °C; \( \text{erf}(\alpha) \) is the error functional integral; \( \alpha \) is a coefficient that estimates the relationship between the criteria for thermal activity and fusion heat.

The next step is to determine the activation energy of the process \( E_a \). It is found on the assumption that at least 70% of the atoms in contact come into the reaction:

\[
E_a = k_b \theta_k \left( \ln(t_o) + 30 \right),
\]

where \( k_0 \) is the constant Boltzmann; \( t_o \) is the time of physic-chemical interaction of the particle with the base material, s.

When applying coatings with a wire tool, the value of the mechanical activation energy \( E_p \) has a significant effect on the process:

\[
E_p = E_{ka} \cdot \left( n_{a1} + n_{a2} + n_{av} \right)^{-1},
\]

where \( E_{ka} \) is the energy of mechanical activation upon impact, J; \( n_{a1}, n_{a2}, n_{av} \) – the number of atoms excited by impact in the main material, particle and pile, respectively.

The mechanical activation energy at impact is determined from the following dependencies:

\[
E_{ka} = E_K - E_{\sigma}, \quad E_K = 0.5 \left( m_v \cdot V_{n_{uk}}^2 \right), \quad E_{\sigma} = \sigma_{m} \cdot \Delta S,
\]

where \( E_k \) is the kinetic energy of the impact, J; \( E_\sigma \) is the energy expended on the formation of a new surface of the particle during its deformation, J; \( m \) is the mass of the pile, kg; \( \sigma_m \) is the coefficient of surface tension of the coating material, \( J \cdot m^{-2} \); \( \Delta S \) is the change in the particle surface area when it is rolled out of a drop with a nominal diameter in a smeared material.

As can be seen, the selected parameters of variation have a direct effect on the energy of mechanical activation.

The coefficient of relative strength of particle adhesion is determined as a result of the chemical reaction in contact, using the known expressions [10, 11], taking into account the mechanical activation energy, by the value of which the activation barrier decreases:

\[
K_{em} = 1 - \exp \left[ \nu_o \cdot \left( K_{em} \cdot \exp\left( \frac{E_a}{K_b \theta_k} \right) \right)^{-1} \right],
\]

where \( \nu \) is the frequency of natural vibrations of atoms, \( s^{-1} \); \( K_{em} = 1 - E_p \cdot E_a \) is the coefficient of mechanical activation.

In order to ensure high-quality adhesion of the coating material to the base of the treated surface, the technique of selecting the required cladding modes is presented below. It is based on a multi-criteria analysis that takes into account all the main factors.

It is assumed that the coefficient of the relative strength of adhesion \( K_{em} \), the ratio of the mechanical activation energy to the total activation energy of the process \( E_p \cdot E_a^{-1} \) and the ratio of the base surface temperature to the contact temperature \( \theta_o / \theta_k \) reflect the main factors of adhesion processes.

The required activation level of the chemical interaction of the base with the coating particle occurs when at least 70% of the atoms in contact come into reaction, therefore, based on experience, it is
accepted that the qualitative adhesion of the coating to the base of the treated surface occurs when the following conditions are met:

\[ K_{cm} \geq 0.7, \ E_p \cdot E_{a}^{-1} \geq 0.15, \ \theta_{a} \cdot \theta_{k}^{-1} \geq 0.2 \]  

(8)

Table 1 shows the simulation data.

| Parameters of the cladding process | Adhesion factors |
|-----------------------------------|------------------|
| \( d_0 (mm) \) | \( l (mm) \) | \( V_{ok} (m/s)^{f} \) | \( \theta_{a} \cdot \theta_{k}^{-1} \) | \( E_p \cdot E_{a}^{-1} \) | \( K_{cm} \) |
| 0.2 | 20.0-40.0 | 25.0 | 0.476-0.212 | 0.082-0.174 | 0.639-0.678 |
| 0.2 | 60.0-80.0 | 25.0 | 0.114-0.057 | 0.267-0.360 | 0.721-0.768 |
| 0.25 | 20.0-40.0 | 25.0 | 0.679-0.319 | 0.059-0.133 | 0.630-0.660 |
| 0.25 | 60.0-80.0 | 25.0 | 0.179-0.095 | 0.207-0.282 | 0.693-0.728 |
| 0.3 | 20.0-40.0 | 25.0 | 0.740-0.413 | 0.048-0.108 | 0.626-0.650 |
| 0.3 | 60.0-80.0 | 25.0 | 0.262-0.143 | 0.168-0.230 | 0.675-0.703 |
| 0.2 | 20.0-40.0 | 30.0 | 0.487-0.222 | 0.119-0.253 | 0.654-0.714 |
| 0.2 | 60.0-80.0 | 30.0 | 0.124-0.063 | 0.387-0.523 | 0.783-0.859 |
| 0.25 | 20.0-40.0 | 30.0 | 0.728-0.341 | 0.088-0.194 | 0.641-0.687 |
| 0.25 | 60.0-80.0 | 30.0 | 0.195-0.105 | 0.301-0.409 | 0.738-0.795 |
| 0.3 | 20.0-40.0 | 30.0 | 0.827-0.469 | 0.067-0.155 | 0.633-0.670 |
| 0.3 | 60.0-80.0 | 30.0 | 0.280-0.156 | 0.243-0.333 | 0.710-0.754 |
| 0.2 | 20.0-40.0 | 35.0 | 0.518-0.237 | 0.161-0.345 | 0.672-0.761 |
| 0.2 | 60.0-80.0 | 35.0 | 0.134-0.069 | 0.530-0.716 | 0.863-0.963 |
| 0.25 | 20.0-40.0 | 35.0 | 0.774-0.357 | 0.119-0.265 | 0.654-0.720 |
| 0.25 | 60.0-80.0 | 35.0 | 0.206-0.114 | 0.411-0.559 | 0.796-0.880 |
| 0.3 | 20.0-40.0 | 35.0 | 0.900-0.488 | 0.090-0.211 | 0.642-0.695 |
| 0.3 | 60.0-80.0 | 35.0 | 0.293-0.167 | 0.332-0.456 | 0.754-0.821 |
| 0.2 | 20.0-40.0 | 40.0 | 0.547-0.248 | 0.211-0.453 | 0.694-0.819 |
| 0.2 | 60.0-80.0 | 40.0 | 0.142-0.075 | 0.695-0.940 | 0.954-1.000 |
| 0.25 | 20.0-40.0 | 40.0 | 0.820-0.371 | 0.154-0.347 | 0.669-0.761 |
| 0.25 | 60.0-80.0 | 40.0 | 0.215-0.121 | 0.539-0.734 | 0.869-0.970 |
| 0.3 | 20.0-40.0 | 40.0 | 0.960-0.477 | 0.121-0.279 | 0.655-0.727 |
| 0.3 | 60.0-80.0 | 40.0 | 0.291-0.171 | 0.437-0.599 | 0.810-0.903 |

4. Gray relational analysis
The data obtained as a result of modeling were used to optimize the output factors of the adhesion process. The optimization technique is used, where grey relational analysis and fuzzy logic theory are combined.

Gray relational analysis (GRA) is a new technique of quantitative analysis for the multi-response optimization based on obtaining a grey reasoning grade. This optimization method can be applied to variety of technologies, such as laser cutting and welding [12, 13], laser cladding [14, 15], optimization of cutting processing [16].

GRA shows the degree of relationship between objective sequence and target sequence. The grey-fuzzy methodology is a more advanced version of optimization method, which combines GRA and fuzzy
logic theory. In the theory of gray systems, objects are considered with uncertain, incomplete information. In this case, the uncertainties are related to the degree of influence of each output factor on the overall assessment of the process. The traditional GRA uses the average of all criteria or determines the weight of each property. Weighting approach with the definition of weight coefficients is subjective.

5. Calculation of gray relational coefficient
For applying GRA, the normalization of the original output set is performed (grey relational generating). These parameters can be expressed in different units in different ranges. After normalization, all parameters change in the range from 0 to 1 and data set become comparable. Taking into account this property of each criterion, how does it reach the optimum? At the maximum, minimum or some intermediate level, there are three approaches for normalization: “larger-the-better”, “smaller-the-better” and “nominal-the-best”. With the qualitative assessment of all three criteria, a method suitable for all of them is adopted “larger-the-better”. The normalized data of all factors are calculated according to the equation:

\[ x_i(k) = \left[ \max y_i(k)-y_i(k) \right] \cdot \left[ \max y_i(k)-\min y_i(k) \right]^{-1}, \] (9)

where \( i \) is the experiment number; \( y_i(k) \) is the value of the \( k \)-th parameter in the \( i \)-th experiment; \( \max y_i(k) \) is the maximum value of the \( k \)-th parameter; \( \min y_i(k) \) is the minimum value of the \( k \)-th parameter.

The gray relational coefficient (\( \xi_i(k) \)) (GRC) is calculated by the following equation:

\[ \xi_i(k) = (A_{\min} + \psi A_{\max}) \cdot (A_{0i(k)} + \psi A_{\max})^{-1}, \] (10)

where \( A_{0i(k)} = \| x_0(k)-x_i(k) \| \); \( x_0(k) \) is the optimal value of the parameter \( x \); \( \psi \) – coefficient differences (from a range \( 0 \leq \psi \leq 1 \) is usually taken as \( \psi = 0.5 \)) (distinguishing coefficient); \( A_{\min} = \bigwedge \exists k \in \Theta \end{array} | x_0(k)-x_i(k) | \) is the smallest value of \( A_{0i(k)} \); \( A_{\max} = \bigvee \exists k \in \Theta \end{array} | x_0(k)-x_i(k) | \) is the largest value of \( A_{0i(k)} \).

The GRC is used to express the optimum ratio (best is 1) and the actual normalized output. The larger the value of the GRC, the closer the corresponding dataset to the optimal level.

6. Gray-fuzzy relational grade
The theory of fuzzy logic is used for systems with uncertain or incomplete information. In this case, the uncertainty is not directly related to the experiment, but concerns the evaluation of the influence of each output factor on the overall integral estimate. In this paper, gray-fuzzy relational grade (GFRG) is defined using grey-fuzzy method. Using the theory of fuzzy logic, the cladding process is evaluated to derive a general evaluation of the adhesion process. The conclusion is made using a fuzzifier, a database of linguistic rules, an interface engine and a defuzzifier. The base of linguistic rules is compiled according to a certain algorithm.

GRC’s for individual quality factors are used as input process parameters in fuzzy modeling. After the fuzzification of each GRC with the use of membership functions, performing inference engine, defuzzification of output into the evaluation of GFRG is performed.

Fuzzification is carried out for the GRC \( \xi_i(k) \). The triangular fuzzy membership functions are selected for the input parameters and the output criterion and are shown in Figure 1. For each input parameter triangular membership functions are used: small (S), middle (M) and big (B). For the GFRG seven linguistic variables are chosen: very small (VS), small (S), smaller middle (SM), middle (M), larger middle (LM), big (B), very big (VB).

After the input parameters are fuzzified, the fuzzy output is generated by max-min inference based on the fuzzy rule base. The rules are drawn up on the principle:

- rule 1: if \( \xi_1 \) is A_1 and \( \xi_2 \) is B_1 and \( \xi_3 \) is C_1 then output \( \eta \) is D_1 else,
- rule 2: if \( \xi_1 \) is A_2 and \( \xi_2 \) is B_2 and \( \xi_3 \) is C_2 then output \( \eta \) is D_2 else,
- rule n: if \( \xi_1 \) is A_n and \( \xi_2 \) is B_n and \( \xi_3 \) is C_n then output \( \eta \) is D_n,
where \( A_i, B_i, C_i, D_i \) are fuzzy subsets defined by the corresponding membership functions (\( \mu_{A_i}, \mu_{B_i}, \mu_{C_i}, \mu_{D_i} \)). Fuzzy logic rule viewer are shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** Membership functions for: \( a \) – inputs (GRC); \( b \) – output (GFRG).

This rule base includes fuzzy rules with three inputs as follows: \( A \) (the value of the coefficient of relative strength of adhesion), \( B \) (the ratio of the base temperature of the workpiece surface to the contact temperature) and \( C \) (the ratio of mechanical activation energy to the total activation energy of the process).

Fuzzy inference generates a fuzzy parameter that can be expressed as the following:

\[
\mu_{D_i}(\eta) = (\mu_{A_i}(\xi_1) \land \mu_{B_i}(\xi_2) \land \mu_{C_i}(\xi_3) \land \mu_{D_i}(\eta)) \lor (\mu_{A_i}(\xi_1) \land \mu_{B_i}(\xi_2) \land \mu_{C_i}(\xi_3) \land \mu_{D_i}(\eta)) \lor \ldots
\]

where \( \land, \lor \) are the maximum and minimum operation, respectively.

Finally, multi-responce output \( \mu_{D_i}(D) \) must be transformed into crisp value of GFRG:

\[
D_0 = \sum D \mu_{D_i}(D) \cdot \left[ \sum \mu_{D_i}(D) \right]^{-1}.
\]

7. Results and discussion

In a series of experiments the input parameters had three levels. In accordance with the experiment-design matrix plan, 48 computational experiments were conducted. After normalizing the data, the GFRG was calculated for each experiment. The goal is to define such a set of parameters that the GFRG has the maximum value, which will correspond to the optimal level of control factors.

The GFRG values corresponding to different experimental data are given in table 2. To determine the optimal level of input technological factors, the average values of GFRG for each technological input must be determined. Average GFRGs values are given in table 3. The maximum value of GFRG corresponds to the optimal values of the input parameters. Thus, the optimal level of input factors A1B4C4. Values GFRGs all the experimental data range. As the value of GFRG increases, the optimality of the process according to the selected criteria increases.
The calculated GRC and GFRG are given in table 2 for best 10 experiments.

Table 2. Gray relational coefficient and gray-fuzzy relational grade.

| Experiment № | Grey relational coefficients | Gray-fuzzy relational grade | Rating |
|---------------|-----------------------------|-----------------------------|--------|
|               | $\xi_1(k)$                  | $\xi_2(k)$                  | $\xi_3(k)$ | $GRG$ |
| 27            | 0.577                       | 0.521                       | 0.353     | 0.496  | 10   |
| 28            | 0.835                       | 0.666                       | 0.336     | 0.599  | 3    |
| 32            | 0.609                       | 0.539                       | 0.348     | 0.508  | 9    |
| 33            | 0.343                       | 0.344                       | 0.883     | 0.545  | 6    |
| 39            | 0.803                       | 0.645                       | 0.356     | 0.595  | 4    |
| 40            | 1.000                       | 1.000                       | 0.338     | 0.795  | 1    |
| 43            | 0.588                       | 0.527                       | 0.377     | 0.513  | 8    |
| 44            | 0.862                       | 0.684                       | 0.350     | 0.619  | 2    |
| 45            | 0.352                       | 0.353                       | 1.000     | 0.565  | 5    |
| 48            | 0.658                       | 0.567                       | 0.364     | 0.533  | 7    |

Table 3. Response table - the optimal level of parameters.

|          | Level 1 | Level 2 | Level 3 | Level 4 |
|----------|---------|---------|---------|---------|
| A        | 0.477   | 0.453   | 0.456   |         |
| B        | 0.450   | 0.431   | 0.461   | 0.506   |
| C        | 0.406   | 0.434   | 0.474   | 0.533   |

8. Conclusions
In this paper, the method of application of gray-fuzzy optimization is considered in relation to the modeling of the cladding process. For multi-criteria assessment of the effectiveness of technological and design parameters in cladding for adhesion processes, an integral parameter in the form of a GFRG was used. It is determined by the input data-simulation results: the ratio of the base temperature of the machined product surface to the contact temperature, the ratio of the mechanical activation energy to the total activation energy of the process and the value of the relative strength coefficient of the adhesion.
The final evaluation of each experiment is integrated to a complex parameter in the form of GFRG, which determines the rating of the experiment or the degree of proximity to the optimal level. The technique of combined gray-fuzzy optimization can be used to evaluate the effectiveness of different processing methods, more objectively change the parameters of the processing modes to achieve a given goal.

References

[1] Borisov V N and Pochukaeva O V 2013 Studies on Russian Economic Development 24 pp 26–34 https://doi.org/10.1134/S1075700713010048
[2] Belevskii L S, Tulupov S A, Smirnov O M, Gordon J and Belevskii I L 2006 Metallurgist 50 pp 497–505 https://doi.org/10.1007/s11015-006-0112-8
[3] Levantsevich M A, Maksimchenko N N, Belyi A N, Dema R R, Kadoshnikov V I, Nefed’ev S P, Kharchenko M V, Amirov R N, Razumov M S and Serebrovskii V I 2017 Chem. Petrol. Eng. 52 pp 779–84 https://doi.org/10.1007/s10556-017-0270-5
[4] Sheleg V K, Levantsevich M A, Pilipchuk E V and Dema R R 2018 J. Fric. Wear 39 pp 6-11 https://doi.org/10.1007/s10303-016-0110-7
[5] Antsupov Jr A V, Antsupov A V, Antsupov V P, Slobodianskii M G and Rusanov V A 2016 J. Fric. Wear 37 pp 494–99 https://doi.org/10.3103/S1068366616050032
[6] Belevskii L S, Kadoshnikov V I, Ismagilov R R, Aksenova M V, Belevskaya I V and Yulchubaev N B 2011 Steel 41 pp 175–78 https://doi.org/10.3103/S0967091211020021
[7] Belevskii L S, Belevskaya I V, Belov V K, Gubarev E V and Efimova Yu Yu 2016 Metallurgist 60 pp 434-39 https://doi.org/10.1007/s11015-016-0310-y
[8] Maksimchenko N N 2013 Russian Engineering Research 33 pp 692–96 https://doi.org/10.1007/S1068366618010117
[9] Zotov A V, Rastorguev D A and Dema R R 2017 Procedia Engineering 206 pp 1432–37 https://doi.org/10.1016/j.proeng.2017.10.657
[10] Litvin R V and Koval’enko M S 2008 Powder Metallurgy and Metal Ceramics 47 pp 102-11 https://doi.org/10.1007/s11106-008-0014-3
[11] Alkhimov A P, Kosarev V F and Papyrin A N 1998 J. Appl. Mech. Tech. Phys. 39 pp 318–23. https://doi.org/10.1007/BF02468100
[12] Pandey A K and Dubey A K 2013 Int. J. Adv. Manuf. Technol. 65 pp 421–31 https://doi.org/10.1007/s00170-012-4181-5
[13] Sathiya P, Abdul Jaleel M Y, Katherasan D and Shanmugarajan B 2011 Struct. Multidisc. Optim. 44 pp 499–515 https://doi.org/10.1007/s00158-010-0615-6
[14] Mondal S, Paul C P, Kukreja L M, Bandyopadhyay A and Pal P K 2013 Int. J. Adv. Manuf. Technol. 66 pp 91–96 https://doi.org/10.1007/s00170-012-4308-8
[15] Mondal S, Bandyopadhyay A and Pal P K 2014 Int. J. Adv. Manuf. Technol. 70 pp 2151–58 https://doi.org/10.1007/s00170-013-5393-z
[16] Shi K, Zhang D and Ren J 2015 Int. J. Adv. Manuf. Technol. 81 pp 645–51 https://doi.org/10.1007/s00170-015-7218-8