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Optimization of structural parameters for elliptical cross-section spiral equal-channel extrusion dies based on grey theory

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Abstract The elliptical cross-section spiral equal-channel extrusion (ECSEE) process is simulated by using Deform-3D finite element software. The ratio m of major-axis to minor-axis length for ellipse-cross-section, the torsion angle φ, the round-ellipse cross-section transitional channel L_1, the elliptical rotation cross-section transitional channel L_2 and the ellipse-round cross-section transitional channel L_3 are destined for the extrusion process parameters. The average effective strain ε_{ave} on cross-section of blank, the deformation uniformity coefficient α and the value of maximum damage δ_{max} are chosen to be the optimize indexes, and the virtual orthogonal experiment of L_{16} (4^5) is designed. The correlation degree of the process factors affecting ε_{ave}, α and δ_{max} is analyzed by the numerical simulation results using the weights and grey association model. The process parameters are optimized by introducing the grey situation decision theory and the ECSEE optimal combination of process parameters is obtained: φ of 120°, m of 1.55, L_1 of 7 mm, L_2 of 10 mm, and L_3 of 10 mm. Simulation and experimental results show that the material can be refined with the optimized structural parameters of die. Therefore, the optimization results are satisfactory.

1. Introduction

With the rapid development of industrialization, for the need of the ultrafine-grained (UFG) materials used in information, biological, medical and aerospace, spaceflight and other fields, the large-scale production of UFG materials has become one of the core technologies in global metal industry.[1] Severe plastic deformation (SPD) method can fabricate bulk UFG metals and alloys.[1,2] For example, intense rolling or drawing is accompanied with microstructure refinement and formation of cells, subgrains and fragments.[2,3] SPD method has become a highly productive potential technology for preparation of UFG bulk materials. The most common SPD methods include[1–3] equal-channel angle pressing (ECAP), high pressure torsion (HPT), multi-directional forging (MF), sandglass extrusion (SE), accumulated roll-bonding (ARB), repetitive corrugation and straightening (RCS), twist extrusion (TE)[4] and constrained groove pressing (CGP). Northwestern

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Polytechnical University professor Li proposed a new SPD method named elliptical cross-section spiral equal-channel extrusion (ECSEE)[5] based on years of research at home and abroad. The new technology has the good deformation and high efficiency for materials forming due to its advantage of collecting the torsion shear, extrusion and upsetting deformation.

Considering the various process parameters and complexity deformation mechanism of ECSEE, it is necessary to optimize the ECSEE dominant affecting factors of process indexes and parameters. The correlation of process parameters and process indexes is the basis of establishing the optimization model. There are varieties of theoretical approaches currently, such as regression analysis,[6] artificial neural networks,[7] genetic algorithms[8] and some other factors and secondary factors of conventional analysis methods, such as analysis of variance[9] and principal component analysis.[10] These above-mentioned methods try to find the model of statistical regularities from a large number of data samples. So many shortcomings are inconvenient in the practical analysis.[11,12]

The grey theory[11,12] analysis eliminates the defects of mathematical statistical methods in systematic analysis and can provide a solution of system in which the model is unsure or the information is incomplete. Some other researchers have investigated the optimization of process parameters in many fields, for example, the electrical discharge grinding of diamond woodworking cutter,[13] the injection molding,[14] the electrical discharge machining[15,16] and the laser cutting.[17] Xie et al. combined the grey theory with Robust theory in the design of deep drawing[18] and stamping.[19] Some scholars created the innovative theory of grey-Taguchi method to broaden the application of the grey theory.[20,21]

The purpose of this paper is to present an efficient method to find the significant die structural parameters affecting ECSEE process by integrating grey analysis and statistical method. Furthermore, it is feasible to obtain structural parameters for a desired deformation process by the grey analysis. The FEM and experimental results also verify the accuracy of optimal solution.

2. Basic principle of grey theory

2.1. Weighted grey correlation theory

The grey relational coefficient can be calculated as follows:

$$\xi_i(k) = \frac{\xi \max_{i\in m}\max_{k\in n}|x_0(k), x_i(k)|}{\lambda_1\left|\underset{i\in m}{x_0(k)}, \underset{k\in n}{x_i(k)}\right| + \lambda_2\left|\underset{i\in m}{x'_0(k)}, \underset{k\in n}{x'_i(k)}\right| + \xi\max_{i\in m}\max_{k\in n}|x_0(k), x_i(k)|} \tag{1}$$

$$r_i = r(x_0, x_i) = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k) \tag{2}$$

where r_i is the grey relational grade of x_i corresponding to x_0, λ_1 the displacement weighted coefficient, λ_2 the change rate weighted coefficient, $0 < \xi < 1$, $\lambda_1 \geqslant 0$, $\lambda_2 \geqslant 0$, $\lambda_1 + \lambda_2 = 1$; i, k, m, n are the serial numbers.

The sum of the property factors in the series and the entropy of factors are respectively calculated as follows:

$$D_k = \sum_{i=1}^{n} x_k(i) \tag{3}$$

$$e_k = \frac{1}{n}\sum_{i=1}^{n} f\left(\frac{x_i(k)}{D_k}\right) \tag{4}$$

where $f(x) = xe^{1-x} + (1-x)e^x - 1$ is whitening weight function, and the sum of entropy is obtained as

$$E = \sum_{k=1}^{m} e_k \tag{5}$$

The relative weight of factors is described as

$$r_k = \frac{1}{m-E}(1-e_k) \tag{6}$$

Then, the weight of factors is processed by the normalization method:

$$\beta_k = r_k \Big/ \sum_{k=1}^{m} r_k \tag{7}$$

2.2. Grey situation decision theory

Let u_{ij} be the effect of sample for situation s_{ij}[11] under objective function p, where $p \in P = \{1, 2, \ldots, l\}$, $\boldsymbol{U}$ the matrix of the effect of sample objective function p.

$$\boldsymbol{U} = \begin{bmatrix} u_{11}^p & u_{12}^p & \cdots & u_{1m}^p \\ u_{21}^p & u_{22}^p & \cdots & u_{2m}^p \\ \vdots & \vdots & & \vdots \\ u_{n1}^p & u_{n2}^p & \cdots & u_{nm}^p \end{bmatrix}$$

Let r_{ij}^p be the image of u_{ij}^p, denoted as $M_{\text{eff}} : u_{ij}^p \to r_{ij}^p$; M_{eff} is called the interchanging of effect measure or interchanging of effect,[12] and r_{ij}^p is described as the effect measure for the situation s_{ij} under objective function p.

When u_{ij}^p is positive polarity

$$\begin{cases} M_{\text{eff}}(u_{ij}^p) = \dfrac{u_{ij}^p}{\max_i \max_j u_{ij}^p} \\ r_{ij}^p = \dfrac{u_{ij}^p}{\max_i \max_j u_{ij}^p} \end{cases} \tag{8}$$

When u_{ij}^p is negative polarity

$$\begin{cases} M_{\text{eff}}(u_{ij}^p) = \dfrac{\min_i \min_j u_{ij}^p}{u_{ij}^p} \\ r_{ij}^p = \dfrac{\min_i \min_j u_{ij}^p}{u_{ij}^p} \end{cases} \tag{9}$$

When u_{ij}^p is moderately polar

$$\begin{cases} M_{\text{eff}}(u_{ij}^p) = \dfrac{\min(u_0, u_{ij}^p)}{\max(u_0, u_{ij}^p)} \\ r_{ij}^p = \dfrac{\min(u_0, u_{ij}^p)}{\max(u_0, u_{ij}^p)} \end{cases} \tag{10}$$

where u_0 is moderate value.

One function of interchanging of effect is transforming the different polarities of effect sample u_{ij}^p into r_{ij}^p with the uniform polarity, so the whole r_{ij}^p is called the polarity unified space.[11,12]

When $p = 1, 2, \ldots, l$, r_{ij}^{Σ} is called the unified effect measure or the unified measure (Σ means the sum of the functions).

$$r_{ij}^{\Sigma} = \frac{1}{l}\sum_{p=1}^{l} r_{ij}^p \tag{11}$$