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OPTIMIZATION OF EXTRUSION PROCESS BY GENETIC ALGORITHMS AND CONVENTIONAL TECHNIQUES

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Original scientific paper

The purpose of this research is the determination of the optimal cold forward extrusion parameters with the minimization of tool load as objective. This paper deals with different optimization approaches in order to determine optimal values of logarithmic strain, die angle and friction factor with the purpose to find minimal tool loading obtained by cold forward extrusion process. Two experimental plans based on factorial design of experiment and orthogonal array have been carried out. Classical optimization, according to the response model of extrusion forming force, and the Taguchi approach are presented. The obtained extrusion force model as the fitness function was used to carry out genetic algorithm optimization. Experimental verification of optimal forming parameters with their influences on the forming forces was also performed. The experimental results show an improvement in the minimization of tool loading. The results of optimal forming parameters obtained with different optimization approaches have been compared and based on that the characteristics analysis (features and limitations) of presented techniques.

Keywords: *metal forming, forward extrusion force optimization, design of experiments, Taguchi approach, genetic algorithm*

Optimizacija procesa istiskivanja primjenom genetskog algoritma i konvencionalnih tehnika

Izvorni znanstveni članak

Svrha ovoga rada je određivanje optimalnih parametara procesa hladnog istosmjernog istiskivanja s ciljem minimizacije opterećenja alata. U radu su predstavljeni različite optimizacijski pristupi u cilju definiranja optimalnih vrijednosti logaritamske deformacije, kuta matrice i faktora trenja s ciljem određivanja minimalnog opterećenja alata procesa hladnog istosmjernog istiskivanja. U tomu cilju izvedena su dva eksperimentalna plana temeljena na faktornom ortogonalnom planu i ortogonalnom nizu. Predstavljena je klasična optimizacija dobivenog modela sile istiskivanja kao i Taguchi pristup. Dobiveni model sile istiskivanja korišten je kao funkcija cilja u optimizaciji pomoću genetskog algoritma. Eksperimentalna provjera optimalnih parametara procesa i njihov utjecaj na silu istiskivanja je također prikazan u radu. Eksperimentalni rezultati prikazuju poboljšanja u procesu minimizacije opterećenja alata. Izvršena je usporedba rezultata dobivenih različitim optimizacijskim tehnikama, kao i analiza prezentiranih tehnika s njihovim mogućnostima i ograničenjima u praktičnoj primjeni.

Ključne riječi: *oblikovanje deformiranjem, optimizacija sile istosmjernog istiskivanja, planiranje eksperimenta, Taguchi pristup, genetski algoritam*

1 Introduction
Uvod

The metal forming process is characterized by various process parameters including the shape of the workpiece and product, forming sequence, shapes of tools or dies, friction, forming speed, temperature and material property of the workpiece and those of the tools. Therefore, the determination of the optimal forming parameters by using optimization techniques is a continuous engineering task with the main aim to reduce the production cost and achieve desired product quality [1, 2].

Forming technologies, that have been applied for a number of years in a definite conventional form, can be innovated by applying the knowledge from the area of modelling, simulations, optimizations, theory of processes, computer technique and artificial intelligence. The optimization methods have been improved by development of applied mathematics, statistics, operational researches, design of experiment, simulation and information-computational methods. Today, there are more different optimization methods. The use of the existing methods depends on objects modelling, required degree of model accuracy, type of process and necessity of optimization.

In this research, mathematical modelling of the extrusion force and the different optimization approaches used to determine optimal values of logarithmic strain, die angle and friction factor with the purpose to find optimal tool load obtained by cold forward extrusion process have been carried out [3, 4, 5]. Hence, optimization, i.e., minimization of the cold forward extrusion force has been carried out by two experimental plans based on factorial design of experiment and orthogonal array. By using these plans classical mathematical and genetic algorithm (GA) optimization was performed, according to response model of extrusion forming force, and the Taguchi approach, respectively. Finally, the confirmation experiment was conducted to verify the optimal extrusion parameters with the minimal tool load and to confirm the effectiveness of these approaches. The value of presented techniques and obtained results has a practical implication for the smallest energy consumption, longer tool life, better formability of the work material and the quality of the finished product.

2 Experimental procedure and setup
Eksperimentalni postupak i plan

The processes of cold and hot extrusion are classified depending upon the direction of material flow in relation to the tool movement direction. Another method of classifying these processes is by their geometry, namely, solid and hollow components [6].

In the solid forward extrusion process, analyzed in this paper, the flow of metal is in the same direction as the direction of action of the machine (punch), where the final product is a solid workpiece with a profile determined by the shape of the die opening, shown in Fig. 1. Forward extrusion force value can be obtained both experimentally using definite measurement equipment and analytically according to well know expression for the total extrusion force [3, 4, 6]. Consequently, it can be concluded that forward extrusion force basically depends on material properties, logarithmic strain, die angle, friction factor and initial geometry of workpiece (billet).

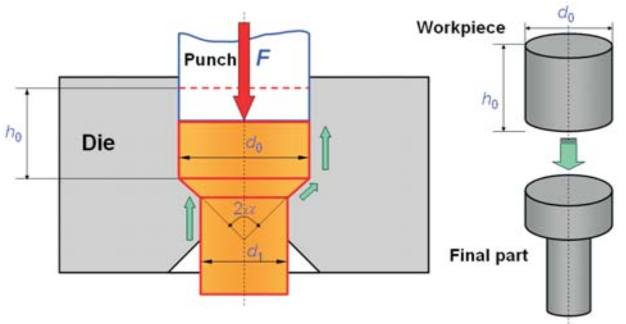

***Figure 1** Extrusion die geometry with initial and formed part*
***Slika 1.** Geometrija matrice za istiskivanje s početnim i oblikovnim izratkom*

From that point of view, the experiment has been carried out by using central composition design with five levels of the three main independent parameters, namely, logarithmic strain (φ), die angle (α) and friction factor (μ) (Table 1) [3, 4, 5]. The overall number of experiments conducted for this central composition design is N = 2^3 + 6 + 6 =20 trials. There are eight (2^3) factorial designs with added six star points and center point repeated six times to calculate pure error.

The forward extrusion operations were performed on hydraulic press with alloyed carbon steel, according to DIN 16MnCr5, (workpiece material) as rod billet (Table 2). Experiments were run with different friction conditions using the following lubricants: MoS_2, phosphate surface & oil, grease, oil, moist oil with five coefficient of frictions according to level parameters, respectively. Initial diameter of workpiece (d_0 = 30 mm) and height (h_0 = 37 mm) for all the experiments were constant.

***Table 1** Levels of independent extrusion parameters*
***Tablica 1.** Razine neovisnih parametara istiskivanja*

Symbol	Parameters / Levels	Lowest	Low	Centre	High	Highest
	Coding	-1,6817	-1	0	+1	+1,6817
A	Logarithmic strain φ	0,112	0,308	0,596	0,884	1,080
B	Half-die angle α (°)	10	18	30	42	50
C	Fricition factor μ	0,066	0,08	0,10	0,12	0,134

***Table 2** Mechanical properties and chemical composition of steel 16MnCr5 (DIN)*
***Tablica 2.** Mehanička svojstva i kemijski sastav čelika 16MnCr5 (DIN)*

Mechanical properties of steel 16MnCr5				
Tensile strength MPa	Yield strength MPa	Brinell hardness HB	Elongation %	Reduction %
570	400	160	26	65
Chemical composition, %				
C	Si	Mn	Cr	S
0,16	0,30	1,15	0,95	0,030

Based on compression test the obtained data for flow stress curve according to Hollomon [6] has the following form:

$$\sigma_f = C \cdot \varphi^n = 960 \cdot \varphi^{0,18}$$

where: σ_f is flow stress, C is constant and n is strain-hardening coefficient.

3 Extrusion force model prediction
Predviđanje modela sile istiskivanja

Design of experiment is a powerful tool for modelling and analysing the influence of process parameters. On the basic of performed experiment can be represented the functional relationship between response of extrusion process, in this case the extrusion force, and the investigated independent parameters by the following polynomial form of mathematical model [3, 4, 5, 7, 8]:

$$Y = b_0 + \sum_{i=0}^{k} b_i \cdot X_i + \sum_{1 \le i \le m}^{k} b_{im} \cdot X_i \cdot X_m + \sum_{i=0}^{k} b_{ii} \cdot X_i^2 + \sum_{1 \le i \le m \le k} b_i \cdot X_i \cdot X_m \cdot X_k + \varepsilon . \quad (1)$$

***Table 3** Values of coefficients obtained by MS Excel*
***Tablica 3.** Vrijednosti koeficijenata dobivenih pomoću MS Excel*

	Coefficients	Standard Error	t Stat	P-value	Lower 95 %	Upper 95 %
Intercept	607,642112	8,486322	71,60253	1,021E-13	588,4447	626,8395
b_1	170,391547	5,630156	30,26409	2,296E-10	157,6552	183,1279
b_2	13,7988415	5,630156	2,450881	0,036703	1,062534	26,53515
b_3	48,9601595	5,630156	8,696057	1,129E-05	36,22385	61,69647
b_{11}	12,2010429	5,480255	2,226364	0,053010	-0,196165	24,59825
b_{22}	51,6142631	5,480255	9,418222	5,879E-06	39,21705	64,01147
b_{33}	6,19185237	5,480255	1,129847	0,287752	-6,205356	18,58906
b_{12}	-1,75	7,356529	-0,237884	0,817298	-18,39164	14,89164
b_{13}	0,25	7,356529	0,033983	0,973632	-16,39164	16,89164
b_{23}	4,75	7,356529	0,645685	0,534597	-11,89164	21,39164
b_{123}	11,5	7,356529	1,563237	0,152433	-5,141637	28,14164

Today, different kinds of software tools for design of experiment have been developed. In this paper, the MS Excel package was used to calculate all the coefficients values including interactions (Table 3). After taking into consideration only significance coefficients (highlight) the obtained mathematical model in coding form is:

$$Y = 607,64 + 170,39 \cdot X_1 + 13,79 \cdot X_2 + 48,96 \cdot X_3 + 12,2 \cdot X_1^2 + 51,61 \cdot X_2^2 + 11,5 \cdot X_1 \cdot X_2 \cdot X_3 \quad (2)$$

or after transformation Eq. (2) extrusion force model as function of the logarithmic strain (φ), die angle (α) and friction factor (μ) has the following physical form (Fig. 2):

$$F = 52,93 + 915,33 \cdot \varphi + 147 \cdot \varphi^2 - 10,45 \cdot \alpha + 0,355 \cdot \alpha^2 + 5423,62 \cdot \mu - 16,56 \cdot \varphi \cdot \alpha - 4991 \cdot \varphi \cdot \mu - 98,325 \cdot \alpha \cdot \mu + 165,6 \cdot \varphi \cdot \alpha \cdot \mu . \quad (3)$$

For the 95 % confidence level the R^2 = 0,99 what shows a good interdependency of the input parameters (φ, α, μ) and response (F). In Table 4 are presented the results obtained by predicted model (3) and analytical model (6) and compared with experimental results. It is evident that forming force prediction model given in (3) decribes accurately enough (model explains 99 % of the variability in force F) the

Table 4 *Design of experiments with experimental and model results*
Tablica 4. *Plan eksperimenta s eksperimentalnim i modelskim rezultatima*

№ trial	Parameters						Extrusion force F (kN)		
	$\varphi \leftrightarrow X_1$		$\alpha \leftrightarrow X_2$		$\mu \leftrightarrow X_3$		Experiment (average F)	Predicted model (3)	Analytical model (6)
	logarithmic strain	coding	half-die angle °	coding	friction coefficient	coding			
1	0,308	-1	18	-1	0,08	-1	445	426,81	332,05
2	0,884	+1	18	-1	0,08	-1	790	790,59	677,40
3	0,308	-1	42	+1	0,08	-1	478	477,40	433,92
4	0,884	+1	42	+1	0,08	-1	770	795,19	762,98
5	0,308	-1	18	-1	0,12	+1	560	547,73	390,48
6	0,884	+1	18	-1	0,12	+1	860	865,51	757,39
7	0,308	-1	42	+1	0,12	+1	566	552,32	485,22
8	0,884	+1	42	+1	0,12	+1	905	916,11	819,68
9	0,596	0	30	0	0,10	0	610	607,64	564,60
10	0,596	0	30	0	0,10	0	614	607,64	564,60
11	0,596	0	30	0	0,10	0	605	607,64	564,60
12	0,596	0	30	0	0,10	0	611	607,64	564,60
13	0,596	0	30	0	0,10	0	606	607,64	564,60
14	0,596	0	30	0	0,10	0	597	607,64	564,60
15	0,112	-1,6817	30	0	0,10	0	338	355,56	304,95
16	1,080	1,6817	30	0	0,10	0	963	928,76	862,10
17	0,596	0	10	-1,6817	0,10	0	725	730,45	554,76
18	0,596	0	50	1,6817	0,10	0	799	776,87	661,95
19	0,596	0	30	0	0,066	-1,6817	556	525,29	517,39
20	0,596	0	30	0	0,134	1,6817	711	689,99	611,81

experimental results within experiment domain.

In this particular case a second-order model was proposed with interactions from the two main reasons:

(i) it is not possible to use classical (mathematical) optimization at the first-order model,
(ii) better explain the behaviour of the process parameters.

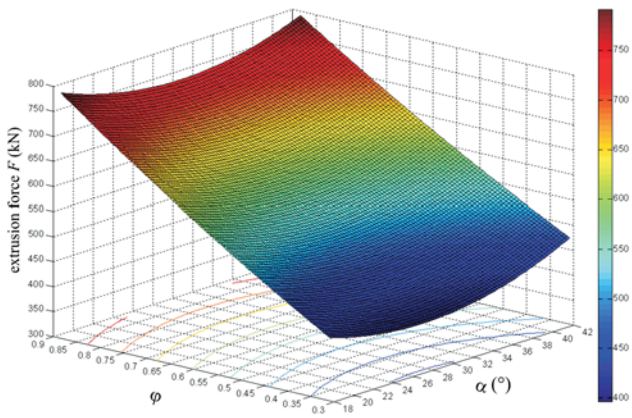

Figure 2 *Response surface for μ = 0,08*
Slika 2. *Odzivna površina za μ = 0,08*

4
Optimization of extrusion force
Optimizacija sile istiskivanja

Determination of optimal forming parameters by using optimization techniques is a continuous engineering task with main aim to reduce the production cost and achieve the desired product quality. For the forming process such as forward extrusion, the forming conditions, play an important role in the efficient use of a machine tool. Since the cost of extrusion process is sensitive to the forming conditions optimum values have to be determined before a part is put into production. To select the forming parameters properly, there are considerable number of optimization techiques and some of them are shown in Fig. 3 [4, 9]. The

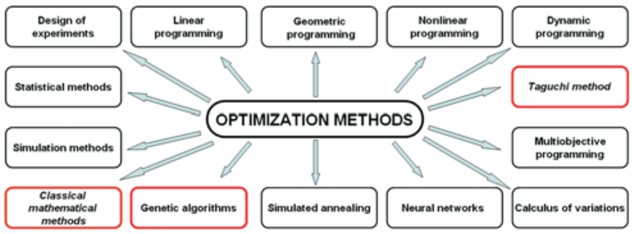

Figure 3 *Optimization methods*
Slika 3. *Optimizacijske metode*

optimum forming parameters in this case will be determined by the different optimization approaches, classical mathematical and genetic algorithm based on experimental obtained model, analytical based on literature known equation and the Taguchi, with the objective to minimize forward extrusion force. It is already known that minimal extrusion force can be achieved with low strain and coefficient of friction as technological and tribological parameters, respectively. In this case study emphasis is on geometrical aspect of the extrusion force minimization, that is, it will be a function of die angle only.

4.1
Classical mathematical optimization
Klasična matematička optimizacija

In classical mathematical analysis the optimization of extrusion process parameters was carried out by derivation of the obtained mathematical model (3). In this particular case derivation of predicted mathematical model will be performed with the aim to find optimal half-die angle (α):

$$\frac{\mathrm{d}F}{\mathrm{d}X_i}=0 \quad i=1,2,3, \text{ that is for die angle } \frac{\mathrm{d}F}{\mathrm{d}\alpha}=0 \tag{4}$$

in this case study:

$$\frac{\mathrm{d}F}{\mathrm{d}\alpha}=0 \Rightarrow -10{,}45+0{,}71\alpha-16{,}56\varphi-98{,}325\mu+165{,}6\varphi\mu$$

or optimal half-die angle (α_{opt}) (Table 5) is:

$$\alpha_{\text{opt}} = \frac{10{,}45 + 16{,}56\varphi + 98{,}325\mu - 165{,}6\varphi\mu}{0{,}71}. \quad (5)$$

Furthermore, based on literature known mathematical model for total solid forward extrusion force [6]:

$$F_{\text{tot}} = A_0 \cdot \sigma_{f,m} \left[\frac{2}{3}\hat{\alpha} + \left(1 + \frac{2\mu}{\sin 2\alpha}\right)\varphi_{\max} \right] + \pi \cdot d_0 \cdot l \cdot \mu \cdot \sigma_{f,0} \quad (6)$$

or for minimum force requirements optimal die angle is calculated by the following equation:

$$\frac{\mathrm{d}F_{\text{tot}}}{\mathrm{d}\alpha} = 0 \;\Rightarrow\; \cos 2\alpha_{\text{opt}} = -3\mu\,\varphi_{\max} \pm \sqrt{9\mu^2\varphi_{\max}^2 + 1}. \quad (7)$$

It can further be seen from (7) that the optimum die opening angle is dependent on the friction factor (μ) and the logarithmic strain (φ) but independent of the material properties [6].

***Table 5** Optimal half-die angle results*
***Tablica 5.** Optimalne vrijednosti pola-kuta matrice*

φ	0,308	0,596	0,884
μ	0,08	0,10	0,12
α_{opt}	27,23°	28,57°	29,92°

4.2 Taguchi approach
Taguchi pristup

In this paper the optimization based on the Taguchi approach [5, 10, 11, 12, 13] is used to achieve the more efficiency extrusion parameters, especially for die angle, and to compare the results obtained with other optimization techniques. Parameter design is the key step in the Taguchi approach to achieve high quality without increasing cost. To solve this problem the Taguchi approach uses a special design of orthogonal arrays where the experimental results are transformed into the *S/N* ratio as the measure of the quality characteristic deviating from the desired value. Table 6 shows that the experimental plan has three levels and an appropriate Taguchi orthogonal array with notation L_9 (3^4) was chosen (Table 7). The last column of parameters notation with D (Table 7) was used to estimate the experiment error. The right side of the table includes the average results (each trial has 3 samples) of the measured force and the calculated signal-to-noise (*S/N*) ratio with associated trial number according to the classical plan. The *S/N* ratio, as the yardstick for analysis of experimental results, is calculated according to the following equation:

$$\frac{S}{N} = \eta = -10 \cdot \lg_{10} \cdot \left(\frac{1}{n} \cdot \sum_{i=1}^{n} y_i^2 \right) \quad (8)$$

where is: η – signal-to-noise ratio (*S/N*), n – number of repetitions of the experiment, y_i – measured value of quality characteristic.

The above equation, which is used to calculate the *S/N* ratio, is in relation to the *smaller-is-better* quality characteristics, what in the particular case means minimization of extrusion force.

No matter the applications, the method of

***Table 6** Levels of independent extrusion parameters according to the Taguchi approach*
***Tablica 6.** Razine neovisnih parametara istiskivanja prema Taguchi pristupu*

Symbol	Parameters	Level 1	Level 2	Level 3	Degrees of freedom (DOF)
A	logarithmic strain φ	0,308	0,596	0,884	2
B	half - die angle α, °	18	30	42	2
C	friction factor μ	0,08	0,10	0,12	2
Central composition plan (Table 4)		-1	0	+1	

***Table 7** Three-level orthogonal array, L_9 (3^4), with experimenatal results (average) and calculated signal-to-noise (S/N) ratios*
***Tablica 7.** Tri razine ortogonalnog niza, L_9 (3^4), s eksperimentalnim rezultatima (srednja vrijednost) i izračunatim odnosima signal-buka (S/N)*

Trial №	A logarithmic strain	B half - die angle	C friction factor	D experimental error	Experimental results, average *F*, kN	*S/N* ratio	Trial № (Table 4)
1	1	1	1	1	445	-52,968	1
2	1	2	2	2	450	-53,065	new exp.
3	1	3	3	3	566	-55,061	7
4	2	1	2	3	658	-56,365	new exp.
5	2	2	3	1	664	-56,445	new exp.
6	2	3	1	2	645	-56,192	new exp.
7	3	1	3	2	860	-58,691	6
8	3	2	1	3	740	-57,386	new exp.
9	3	3	2	1	835	-58,434	new exp.

$$A1 = \frac{1}{3}(\eta_1 + \eta_2 + \eta_3) = \frac{1}{3}(-52{,}968 - 53{,}065 - 55{,}061) = -53{,}698$$

$$A2 = \frac{1}{3}(\eta_4 + \eta_5 + \eta_6) = \frac{1}{3}(-56{,}365 - 56{,}445 - 56{,}192) = -56{,}334$$

$$A3 = \frac{1}{3}(\eta_7 + \eta_8 + \eta_9) = \frac{1}{3}(-58{,}691 - 57{,}386 - 58{,}434) = -58{,}17$$

According to the above equations, in the same manner, are calculated *S/N* ratios for parameter B(B1, B2, B3) & C(C1, C2, C3). The influence of each control parameter can be more clearly presented with response graphs (Fig. 4), whereas the influence of interactions between control parameters is analysed but without significant contribution to the optimal results and for that reason it is not presented here. A response graph shows the change of the *S/N* ratio when control parameter is changed from one level to the other. The slope of the line determines the power of the control parameters' influence, presented in statistical analysis of variance (Table 8) as contribution. Error factor includes the influence of all factors not included in the experiments and effects of experimenatal error, in this case that effects have no significant influence (0,55 %).

The settings of control parameters for achievement of the best value of the quality characteristic can be determined by response graphs presented. Best value is at the higher value of the *S/N* ratio, or according to Fig. 4, it can be concluded that the minimal extrusion force (F = 432,11 kN)

***Table 8** Analysis of variance (ANOVA)*
***Tablica 8.** Analiza varijance (ANOVA)*

Symbol	Extrusion parameters	Degrees of freedom	Sum of squares (*SS*)	Mean square (*MS*)	*F* - ratio	Contribution, %
A	logarithmic strain φ	2	30,32	15,16	160,539	88,91
B	half-die angle α, °	2	1,314	0,657	6,962	3,85
C	friction factor μ	2	2,279	1,139	12,066	6,69
Error		2	0,188	0,094		0,55
Total		8	34,101			100

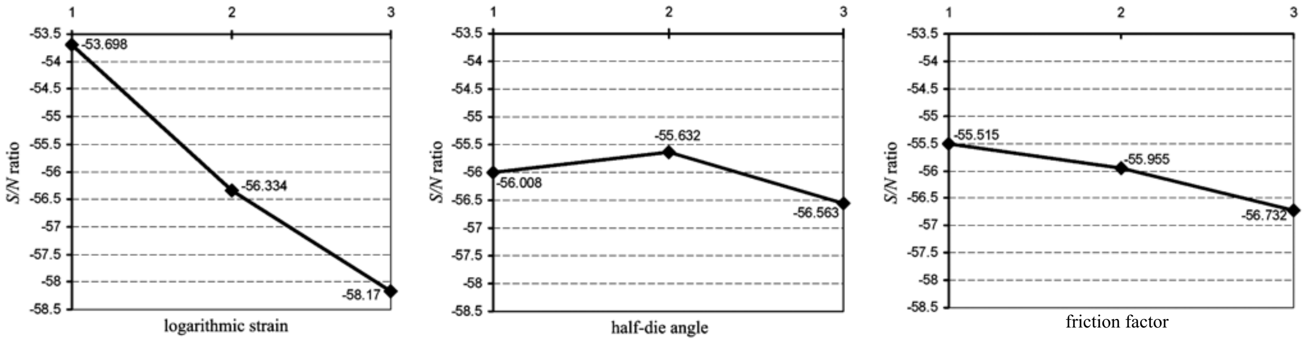

***Figure 4** S/N graphs for control parameters*
***Slika 4.** S/N grafovi za kontrole parametre*

***Table 9** The results comparison of the different models with experiment*
***Tablica 9.** Rezultati usporedbe različitih modela i eksperimenta*

№ trial	Experimental values *F*, kN	Prediction model (3)	Analytical model (6)	Relative error of models comparing to experimental results	
				Prediction, %	Analytical, %
1	445	426,81	332,05	4,08	25,38
2	790	790,59	677,40	0,75	14,25
4	770	795,19	762,98	3,27	0,91
5	560	547,73	390,48	2,19	30,27
9 ÷ 14	597÷614	607,64	564,60	0,27÷1,78	5,42÷8,04
15	338	355,56	304,95	5,19	9,77
17	725	730,45	554,76	0,75	23,48
19	556	525,29	517,39	5,52	6,94
			Average (1÷20)	0,60	12

***Table 10** The comparison of the optimal results obtained with different methods and confirmation test*
***Tablica 10** Usporedba optimalnih rezultata dobivenih različitim metodama i test provjere*

	Initial parameters	Optimal forming parameters				*Confirmation test*
		Prediction model (5)	Analytical model (7)	Taguchi approach	Genetic algorithm	
Level	A1B1C1	A1C1	A1C1	A1C1	A1C1	A1C1
Force *F*, kN	445	396,41	318,01	432,11	398,03	402
Optimal half-die angle α, °		B = α =27,23°	B = α =10,88°	B2 = α =30°	B = α =27,28°	α_{opt} =27,23°

will be achieved at the following level combination of parameters (A1B2C1) (Table 10):

- logarithmic strain, $\varphi = 0{,}308$,
- half – die angle, $\alpha = 30°$ and
- friction factor, $\mu = 0{,}08$.

Finally, three objectives can be achieved through the parameter design of the Taguchi method: (i) determination of the optimal design parameters for a process, (ii) estimation of each design parameter to the contribution of the quality characteristics, and (iii) prediction of the quality characteristics based on the optimal design parameters [11].

4.3 Genetic algorithm
Genetski algoritam

Evolutionary algorithms have been successfully applied to optimization problems in several areas [3, 14, 15, 16, 17, 18]: engineering design, process planning, assembly and transportation problems, image processing, scheduling, and so on.

In this particular case the genetic algorithm will be used for the optimization of the cold forming process parameters. Genetic algorithms are based on the principles of natural genetics and natural selection or Darwin´s theory of survival of the fittest. The basic elements of natural genetics: reproduction, crossover and mutation are used in the genetic search procedure. GAs are well suited heuristic (stochastic) techniques that can find the global optimum solution by searching the space with a high probability.

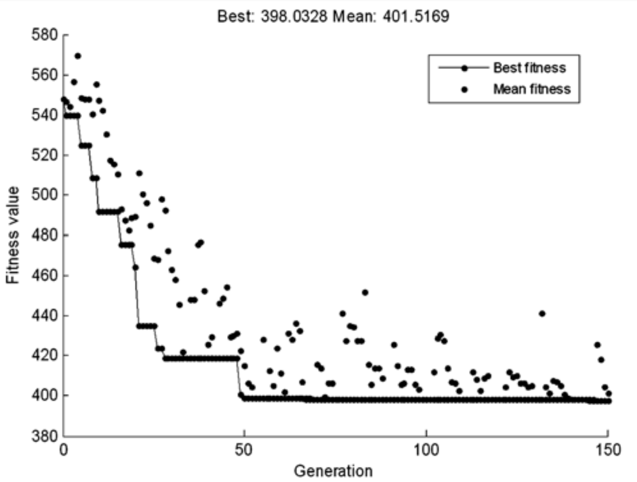

Figure 5 *Fitness function values through generations*
Slika 5. *Vrijednosti funkcije cilja-dobrote kroz generacije*

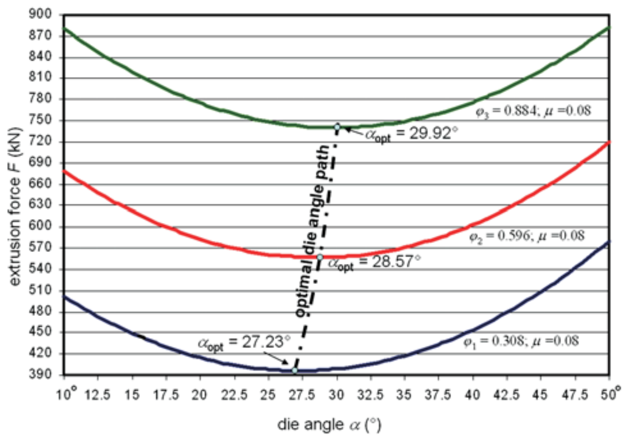

Figure 6 *Optimal die angle path*
Slika 6. *Optimalna staza vrijednosti kuta matrice*

Although GA is a robust method more widely used for discrete problems in this paper it was used to solve continuous optimization problem.

Genetic operators (reproduction, crossover and mutation) provide ways of defining new populations from existing ones. First step in GA optimization is to set up an initial population as defined number of initial individuals (chromosomes) which was created randomly.

Evaluation process has a task to evaluate each solution that can be used for creating new individuals (children) and in that way can become part of the next generation. Fitness attributes can serve well for this purpose. The population can be ranked according to the objective function (fitness function) value. After that, by the selection procedure from that population the best individuals (parents) can be chosen for reproduction and promotion to the next population. Children are produced either by making random changes to a single parent (mutation) or by combining the pair of parents (crossover). The current population has been replaced with the children to form the next generation. At each iteration, the genetic algorithm performs a series of computations on the current population to produce a new one. Genetic algorithm runs while one of the stopping criteria is met.

Optimization (minimization) of the extrusion force and determination of the process parameters were performed by Matlab genetic algorithm toolbox. The obtained mathematical model (3) is used as the fitness function. The boundary values for process parameters are the following: logarithmic strain (φ) between 0,308 and 0,884, die angle (α) from 18° to 42° and friction factor (μ) from 0,08 to 0,12.

Optimal forming conditions for a minimal extrusion force were achieved for the following evolutionary parameters: G = 150 generations and population size M = 10. The genetic operators crossover and mutation were used and probability was p_c = 0,6 and p_m = 0,2, respectively. The presented evolutionary algorithm provides the following optimal condition values:

- logarithmic strain, φ = 0,308,
- half – die angle, α = 27,28° and
- friction factor, μ = 0,08.

Obtained fitness value decreasing through generations and for the final generation the extrusion force F = 398,03 kN is shown in Fig. 5.

5 Results analysis
Analiza rezultata

Some of presented optimization approaches need mathematical model or fitness function to obtain optimal parameters of process. Those models are compared with experimental results (Table 9) and in the presented case show very small deviation of foreseen values of predicted model (3) (average 0,60 %) within domain of experiment. That obtained prediction model (3) is a very good base for finding the optimal parameters with the purpose of process efficiency increasing, what was verified with confirmation test (Table 10).

The optimal parameter values for the different approaches are presented in Table 10. The presented optimization techniques give accurate results (confirmation test) with small deviation between each other, except for the analytical method. Final step is to verify the improvement using optimal level of parameters (about 10 %). Since the model (3) has the interaction parts the optimal die angle depends on strain and friction, i.e. optimal die angle path (Fig. 6) for the different input conditions has been established.

6 Conclusions
Zaključci

In this paper an application is shown of different optimization approaches to find optimal cold forward extrusion parameters with emphasis on geometrical aspect of the process, that is, die angle. The presented optimization techniques, the classical Taguchi and genetic algorithm, have their features, merits and limitations that are demonstrated on a study case with the following conclusions:

(i) Classical experimental design methods are too complex and not easy to use. A large number of experiments have to be carried out especially when the number of process parameters increases. To solve this problem, the Taguchi approach uses a special design of orthogonal arrays to study the entire parameter space with a small number of experiments, what is obvious if we compare Table 4 and Table 7. Furthermore, to obtain optimal value of process parameters the classical method needs the prediction model which was used for optimization procedure, which is not necessary for orthogonal arrays design. Also, the parameters value needs to be defined as strictly numerical, not as a description of state.

(i) On the other hand, by the clasical experimental design methods it is possible to obtain mathematical model which is a powerful tool to predict response for any of input parameters' values within the experiment domain, and optimal values can be any of the parameters' points i.e. parameters are continuous and can take any real value. This is impossible in the Taguchi approach, because optimal value has to be one of the parameter levels, see Table 10, and the solution may give the value of the objective functions that is very far from the original optimum value. In addition, the Taguchi approach is better for parameters can only have discrete values in contrast to classical optimization technique and continuous values.

(ii) The third optimization techniques, genetic algorithm, present a very good possibility (fast, simple and accurate) to find optimal input parameters for fitness function in the cold forming process.

Finally, all the optimization techniques presented here have some potentiality (more or less) to improve initial process parameters or in the study case the minimization of extrusion force by means of an optimal die angle with high accuracy that is also verified by the confirmation experiment.

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