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COMPUTER AIDED DESIGN OF THE BEST TR FORGING TECHNOLOGY FOR CRANK SHAFTS

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Abstract

Improvement of the TR crank shaft forging technology is the objective of the paper. New concept of forging of crank shafts is considered. Plastometric tests were performed for steels used for manufacturing of crank shafts and a rheological model for these steels was determined. This model was implemented in the finite element software and simulations of various variants of forging were performed. Results of simulations were used to select the best variant, which gives the lowest loses of the material and proper shape of the final product. Two technological parameters are selected as the optimization variables. Finite element simulations of the forging process for various values of the selected parameters were performed. Optimization of the forging process is performed using the surface response methodology. Optimal forging parameters are given in the paper.

Key words: forging of crank shafts, finite element method, inverse analysis

1. INTRODUCTION

The technology of forging of crank shafts developed at the Metal Forming Institute in Poznan, Poland (TR method – following the name of the inventor, Rut & Walczyk, 2000; 2002) is the subject of this paper. This technology gives very good results when shape of the shoulders of the crank is close to an ellipse. New constructions of crank shafts require large juts at the side of journals of main bearings. In consequence, machining of deep grooves in the stock material is needed. It is technologically inconvenient and it leads to an increase of material waste, what causes an increase of the costs of manufacturing. To avoid this inconvenience, additional forging operation is introduced. This is an unsymmetrical pre-upsetting of the stock material, which involves proper flow of the material needed to obtain required shape of the crank shoulders. There are several possible variants of this process and experimental analysis of all variants would be very costly. Thus, the objective of the project is design of the best forging technology, which gives the shape of the crank shaft closest to the ideal one. The finite element model of forging of crankshafts was developed and applied to simulate various technological variants. Surface response method is used to determine the best variant.

2. FE MODEL

FORGE finite element code is used for simulation of forging of crank shaft. The model applied in this code is based on the Norton-Hoff constitutive law (Norton, 1929; Hoff, 1954) and is described in (Chenot & Bellet, 1992). This law is generally written in the form of relationship between stress tensor ($\underline{\sigma}$) and the strain rate tensor ($\dot{\underline{\varepsilon}}$):

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$$\underline{\boldsymbol{\sigma}} = 2K\left(\sqrt{3}\dot{\varepsilon}_i\right)^{m-1}\underline{\dot{\boldsymbol{\varepsilon}}} \qquad (1)$$

The value of $m = 1$ corresponds to the Newtonian fluid with a viscosity $\eta = K$, $m = 0$ is the plastic flow rule for a rigid-plastic material obeying the Levy-Mises flow rule and the Huber-Mises yield criterion. The value of $m = 0.16204$ is used in the present work and the relation between the yield stress and the constant K is:

$$K\left(T,\varepsilon,\dot{\varepsilon}\right) = \frac{\sigma_p}{\sqrt{3}^{m+1}\dot{\varepsilon}_i^m} \qquad (2)$$

Yield stress σ_p in the Norton-Hoff model is described as a function of temperature, strain rate and strain. The Hansel and Spittel equation (Hansel & Spittel, 1979) is used to describe this relationship:

$$\sigma_p = A\varepsilon^n \exp\left(-B\varepsilon\right)\dot{\varepsilon}^m \exp\left(-CT\right) \qquad (3)$$

The coefficients in equation (3) were determined for the two steels with chemical composition given in table 1. Axisymmetrical compression tests were carried out on the Gleeble 3800 simulator at the Institute for Ferrous Metallurgy in Gliwice, Poland and the coefficients were determined using inverse analysis (Szeliga et al., 2006).

Table 1. *Chemical compositions of the investigated steels, wt %.*

Steel	C	Mn	Si	Cr	Cu	Ni	Mo	V	Co	Nb
30CrMo12	0.40	0.42	0.28	2.9	0.068	0.081	0.37	0.084	0.044	0.027
34CrNiMo6	0.40	0.61	0.19	1.6	0.084	1.6	0.20	0.13	0.066	0.040

Table 2. *Coefficients in equation (3) obtained from the inverse analysis for the investigated steels.*

	A	*n*	*B*	*m*	*C*
30CrMo12	13525	0.28	0.59686	0.16204	4.089×10^{-3}
34CrNiMo6	7136.6	0. 172	0. 3693	0. 1718	3.7455×10^{-3}

Mechanical solution is coupled with the thermal model, which is based on the finite element solution of the Fourier equation.

$$\nabla \bullet k\nabla T + Q = \rho c_p \frac{\partial T}{\partial t} \qquad (4)$$

where: k – heat conductivity, T – temperature, Q – rate of heat generation due to plastic work, ρ – density, c_p – specific heat, t – time.

Neumann boundary condition is assumed:

$$k\nabla T = \alpha\left(T_a - T\right) \qquad (5)$$

where: k – heat conductivity, T_a – ambient or tool temperature, α – heat transfer coefficient, ρ – density, c_p – specific heat, t – time.

The heat transfer coefficient of 4000 W/m^{2}K at the contact surface between the tool and the sample is assumed. Cooling in air is simulated on the remaining part of the surface. Friction factor 0.8 in Tresca model is used.

3. MODIFIED TR PROCESS

Idea of the conventional TR process is described in publications (Rut & Walczyk, 2000; 2002; Walczyk et al. 2010; Milenien et al. 2009) and is not repeated here. Modification of this process is presented in figure 1 in the form of the FE model (Walczyk et al. 2010; Milenin et al. 2009). The sets of dies for unsymmetrical pre-upsetting, which distinguishes the considered process from the conventional one, is shown in figure 1a. Beyond face die inserts (1_1; 2_1), clamping die inserts (1_2; 2_2), bending tool (3), one more additional tool – foreanvil (4) –, which bends the material to form the crank at this primary stage of the process, is also shown in this figure. The sets of dies for forging of the crank throw are shown in figure 1b. The foreanvil (4) is replaced with anvil (5). The variant presented in figure 1 is the main variant of the modified process (I) and the remaining variants are obtained by removing various tools.

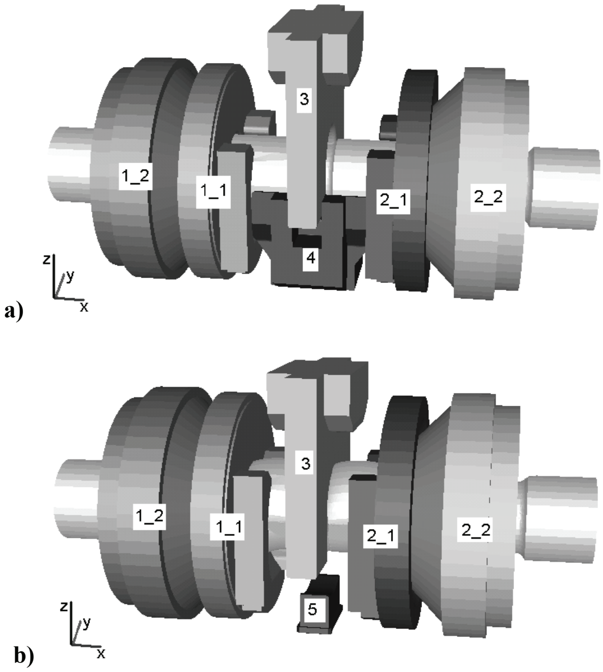

Fig. 1. *The process model (variant I) generated in Forge 3: (a) unsymmetrical pre-upsetting b) forging of the crank throw.*

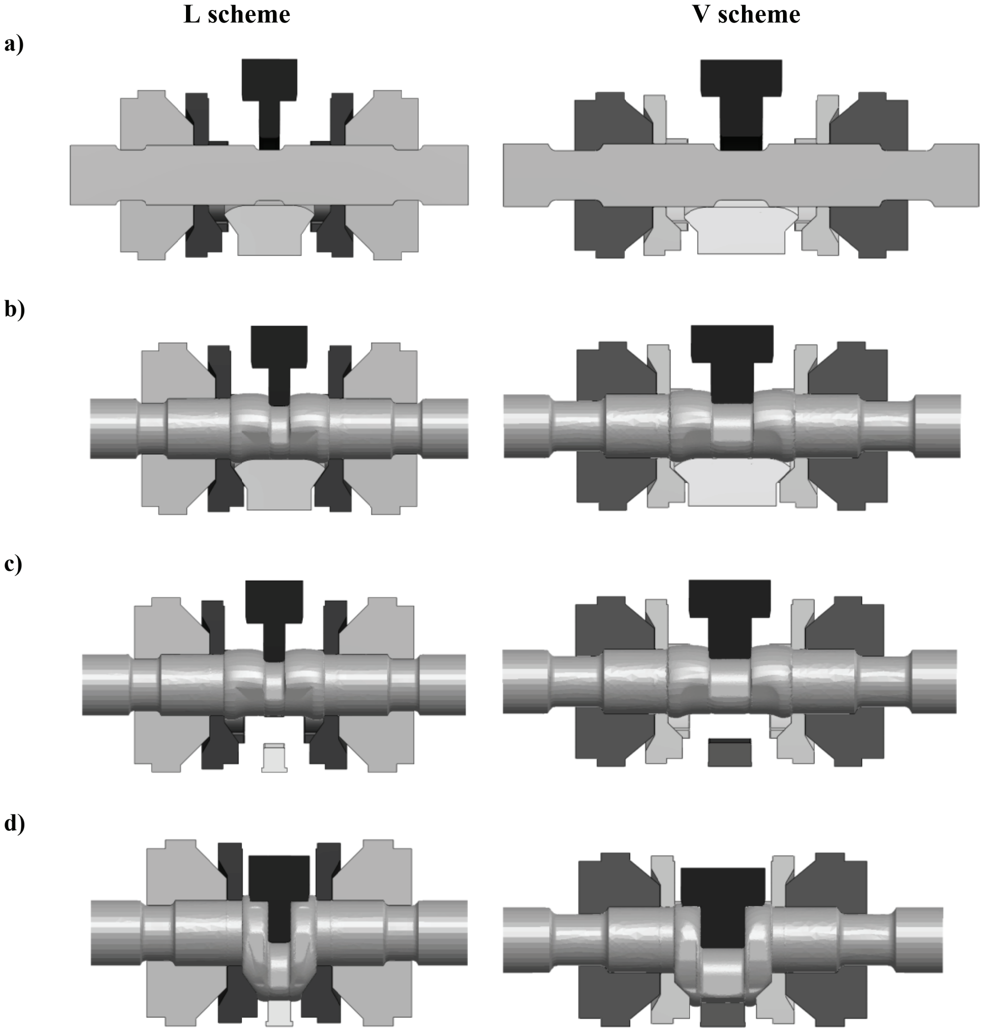

Fig. 3. Schematic illustration of forging: a) beginning of the unsymmetrical pre-upsetting; b) end of the unsymmetrical pre-upsetting; c), beginning of the forging of the crank throw; d) end of the forging of the crank throw.

Beyond variant I, in which all the tools are used, the following variants are considered (see Fig. 1):
II – Without the anvil (5).
III – Without the juts at both sides at the top of the bending tool (3). These juts form the shape of the top part of the crank webs in variants I and II.
IV – Without the anvil (5) and without the juts at both sides at the top of the bending tool (3).

Due to symmetry of the shape and boundary conditions, only half of the workpiece is considered in simulations. The finite element mesh with 60000 elements was generated. The number of elements was changing due to remeshing. The number of nodes was changing, as well, between 12000-15000. Initial temperature was 1180°C. Results for the steel 30CrMo12 only are presented in this work. Similar results were obtained for the steel 34CrNiMo6. Flow stress model for the steel 30CrMo12 is based on equation (3). Results of simulations for all 4 variants (I-IV) are presented in (Walczyk et al., 2010) and these variants are compared and evaluated in that publication. Variant I was selected as the best, as far as accuracy of the final shape of the crank shaft is considered. The analysis in (Walczyk et al., 2010) aimed also at the forces acting on the tools and at the metal flow during forging. It was concluded that the variant I requires the largest forces. In conclusions, variants II-IV, which give lower dimensional accuracy of products, is advised only in the case when capacity of the press is too low and does not allow to perform variant I.

The objective of the present work is application of numerical simulations in selection of optimal technological parameters for the variant I. The set of tools for the first stage (unsymmetrical pre-upsetting) in this variant is shown in figure 3. Two schemes are investigated: L and V. The difference between these schemes lies in the width of bending tool, which is 186 mm for L scheme and 381 mm for V scheme.

4. OPTIMIZATION OF THE FORGING PROCESS

An attempt to optimize the forging process parameters was made. The aim of optimization was to obtain the required shape of the crankshaft. As it is mentioned above, since the variant I appears to give better results than the others, this variant is considered. Two parameters were chosen as decision variables: bending tool displacement during forging of the crank throw (d_1) and initial spacing of face die inserts (d_2). Displacement modification of bending tool during forging of the crank throw caused various displacements at the primary stage (total shift must be constant). Velocity of bending tool is constant in simulations. In the case of spacing of face die inserts, different initial setup causing various velocity of the tool is considered. Nine simulations were made for each scheme. Absolute value of percentage volume difference between obtained and ideal shape of the crankshaft is assumed as the objective function. Values of decision variables and obtained accuracy for L schemes are presented in table 3. The second order response surface (Myers & Montgomery, 1995) was constructed on the basis of simulations (Figure 4).

Table 3. *Values of the objective function for L scheme, %.*

d_1, mm / d_2, mm	275	285	295
1082	1.23	1.06	0.96
1094	0.01	1.06	0.89
1106	0.64	0.81	0.99

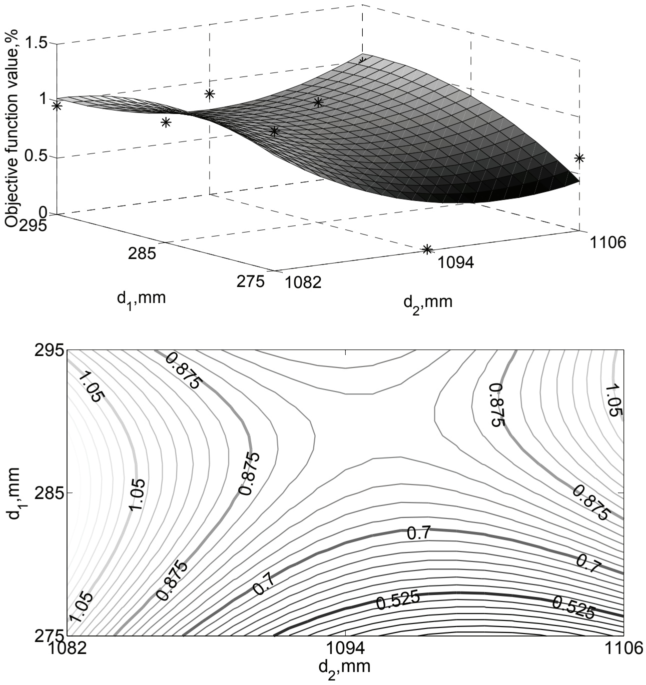

Fig. 4. *The second order response surface constructed on the basis of simulations for the L scheme.*

Since the obtained surface is concave, its minimum is located on a boundary. In this case, optimal values of decision parameters were assumed d_1 = 275 mm and d_2 = 1094 mm for bending tool displacement during forging of the crank throw and initial spacing of face die inserts, respectively.

Values of decision variables and obtained objective function for the scheme V are shown in table 4. The second order response surface was constructed similarly to the previous case and it is shown in figure 5.

Table 4. *Values of the objective function for V scheme, %.*

d_1, mm / d_2, mm	275	285	295
1354	1.07	0.99	0.98
1368	0.07	0.14	0.26
1382	0.93	1.05	1.22

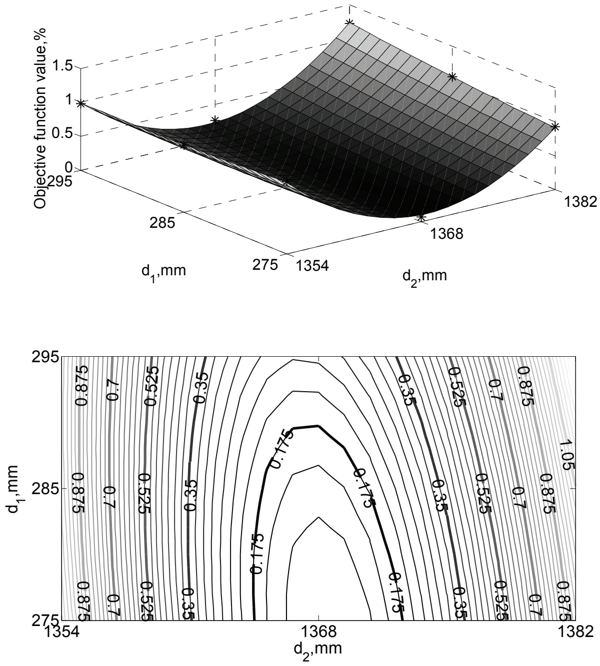

Fig. 5. *The second order response surface constructed on the basis of simulations for the V scheme.*

Unlike the previous case, surface is convex what allows determination of the minimum. Optimal values of decision parameters are d_1 = 272.7 mm for bending tool displacement during forging of the crank throw and d_2 = 1368.7 mm for the initial spacing of the face die inserts. Results obtained in both cases suggest purposefulness of making additional simulations for bending tool displacement less then 275 mm.

Results of calculations of the strains distribution for the L scheme of the best technology (d_1 = 275 mm, d_2 = 1094 mm) and for the non-optimal technology (d_1 = 275 mm, d_2 = 1082 mm) are shown in the Figure 6.

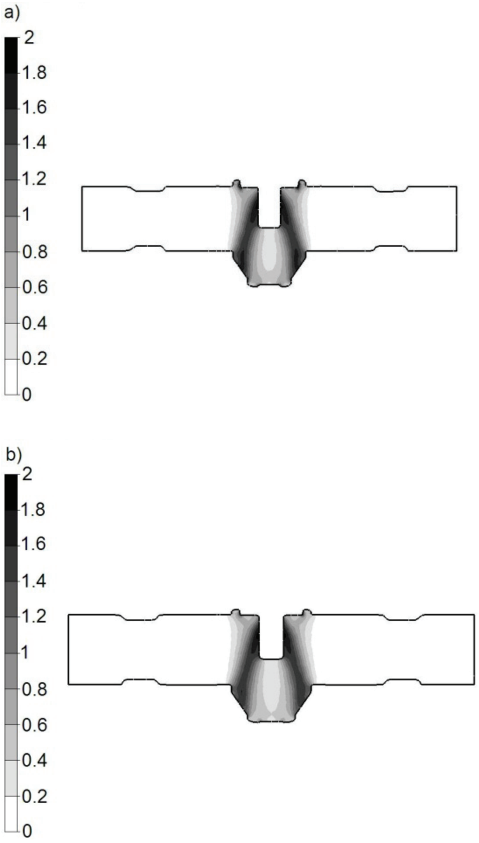

Fig. 6. *Calculated distribution for L scheme of strains for the best technology d_1 = 275 mm, d_2 = 1094 mm (a) and for the decision parameters d_1 = 275 mm, d_2 = 1082 mm (b).*

5. CONCLUSIONS

A concept of design of the best forging technology for crankshafts is presented in the paper. By introduction of additional tools efficient forging of crankshafts with more complicated shapes of the crank webs is possible. The analysis performed in (Walczyk et al., 2010) has shown that resistance to forming connected with shaping of crank throws depends mainly on the degree of the constraint of the deformation zone. The largest resistance to deformation and, in consequence, the largest forces, are observed in variant I, in which all tools are used. On the other hand, this variant gives the best accuracy of the shape of the products. Optimization of the technological parameters for the variant I was performed in the present work and the following conclusions are drawn:

- Two optimization variables are selected in the considered process, bending tool displacement during forging of the crank throw and initial spacing of face die inserts.
- Finite element simulations allow generation of the data for the construction of the response surface. The method based on this surface can be efficiently used for searching for the best forging technology.
- Performer analysis has shown that the optimum for the L scheme is for d_1 = 275 mm and d_2 = 1094 mm for bending tool displacement during forging of the crank throw and initial spacing of face die inserts. This minimum is located at the boundary of the searching domain.
- The optimum for the V scheme is for d_1 = 272.7 mm and d_2 = 1368.7 mm for bending tool displacement during forging of the crank throw and initial spacing of face die inserts.

The general conclusion is that in the considered process of forging of crank shafts the sensitivity of the objective function with respect to the optimization variables is low, see tables 3 and 4. Therefore, this paper should be considered more a presentation of the optimization methodology based on RSM then solving of the technological problem of forging. The robustness of the presented optimization approach will be examined in the near future.

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WSPOMAGANE KOMPUTEROWO PROJEKTOWANIE NAJLEPSZEJ TECHNOLOGII KUCIA WAŁÓW KORBOWYCH METODĄ TR

Streszczenie

Celem pracy jest ulepszenie metody TR wykorzystywanej podczas kucia wałów korbowych. Wykonano próby plastometryczne, dla wykorzystywanych do produkcji stali, w celu wyznaczenia parametrów modelu reologicznego. Zbudowany model został wykorzystany w symulacjach MES. Otrzymane rezultaty posłużyły do określenia najlepszych parametrów procesu kucia zapewniających najmniejszą stratę materiału oraz odpowiedni kształt wału. Za zmienne decyzyjne przyjęto dwa parametry. W ustalonych granicach zmienności parametrów optymalizacyjnych wykonano symulacje MES. Przedstawiono wyniki otrzymane metodą RSM.

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