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FE simulation and bending speed optimization of N-TR continuous grain flow forging process for solid heavy crankshaft

Symulacja MES i optymalizacja prędkości gięcia w procesie kucia ciężkich, jednolitych wałów korbowych z ciągłym przebiegiem włókien metodą N-TR

Abstract
N-TR (new TR) is a new continuous grain flow forging process for solid heavy crankshafts forming proposed by the authors. In N-TR process, the mechanical coupling of upsetting and bending action via the toggle mechanism in TR process is decoupled by an independent additional cylinder to provide bending action, which provides the feasibility of process optimization. In this paper, a heavy crankshaft modeled 601 was selected as a case study to optimize the N-TR process with FE simulation in DEFORM-3D. Relationship of die filling versus bending speed-stroke parameters was set up from the simulations, which shows that lower bending speed in the beginning stage and higher speed in the ending stage benefit die filling. Optimum die filling and engineering feasible speed-stroke parameters was acquired.

Streszczenie
Autorzy przedstawili metodę N-TR (nowa TR) będącą nowym procesem kucia ciężkich, jednolitych wałów korbowych z ciągłym przebiegiem włókien. W metodzie N-TR mechaniczne sprzężenie spęczania z równoczesnym wyginaniem, spowodowane działaniem mechanizmu kolanowego w metodzie TR, zostało zlikwidowane dzięki zastosowaniu siłownika powodującego niezależne wyginanie, co umożliwia optymalizację procesu kucia. Przeprowadzono optymalizację procesu kucia ciężkiego wału korbowego typu 601 metodą N-TR korzystając z symulacji MES w programie DEFORM-3D. Badano związek stopnia wypełnienia wykrojów narzędzi z prędkością wyginania. Stwierdzono, że niższa prędkość wyginania na początku procesu i wyższa prędkość wyginania na końcu procesu sprzyjają wypełnieniu wykrojów. Uzyskano optymalne wypełnienie wykrojów narzędzi dla technicznie realnych prędkości wyginania.

Key words: heavy crankshaft, continuous grain flow forging, upset forging, N-TR, FE simulation, process optimization

Słowa kluczowe*: ciężkie wały korbowe, kucie z ciągłym przebiegiem włókien, spęczanie, N-TR, symulacja MES, optymalizacja procesu*

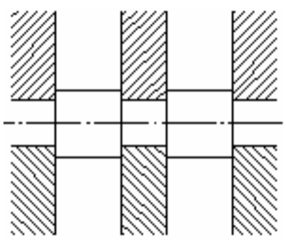
1. INTRODUCTION

Heavy crankshafts are key parts of heavy diesel engines. The crankshafts formed by continuous grain flow forging are superior to that by free forging. The continuous grain flow forging process improves significantly the fatigue strength by beneficial continuous metal grain flow paralleling the profiles of the crankshaft, material usage and machining productivity as compared to the free forging processes, of the crankshafts. N-TR (new TR) process is a new continuous grain flow forging process for solid heavy crankshafts forming proposed by the authors. The N-TR process is an innovation of the TR process, which has an independent additional bending cylinder that provides the feasibility of process optimization.

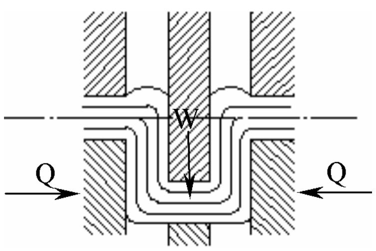
In this paper, a heavy crankshaft modeled 601 was selected as a case study to optimize the N-TR process with FE simulation in DEFORM-3D. Section 2 presents an introduction of the N-TR process, Section 3 presents FE models of N-TR continuous grain flow forging of heavy crankshaft, Section 4 presents the FE simulation results and discussion, and finally Section 5 gives a conclusion remark.

2. N-TR CONTINUOUS GRAIN FLOW FORGING PROCESS OF HEAVY CRANKSHAFT

The continuous grain flow forging is also called *upset forging*. The principle of continuous grain flow forging of heavy crankshaft is shown in Fig. 1. This kind of forging can keep the continuity of fibred microstructure in the billet and makes the fibred structure parallel the profiles of the crankshaft.



(a) Pre-upset forging
(a) odkuwka przed spęczaniem



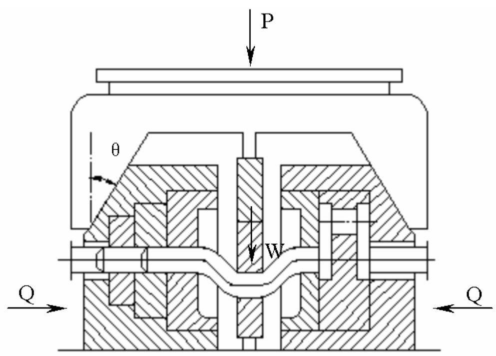
(b) Post-upset forging
(b) odkuwka po spęczaniu

Fig. 1. Principle of continuous grain flow forging of heavy crankshaft

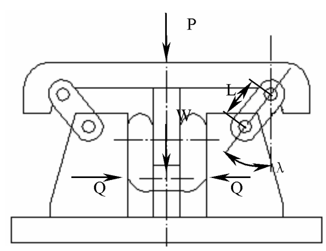
Rys. 1. Zasada kucia ciężkiego wału korbowego z zachowaniem ciągłości włókien

Conventional continuous grain flow forging processes of heavy crankshaft includes RR process by R. Roedrer and TR process by T. Rut [1], as are shown in Fig. 2. In RR process, working load *P* of hydraulic press is decomposed into bending load *W* and upsetting load *Q* by inclined matching planes of angle $\theta \approx 40^\circ$ [2] with perpendicular. While in TR process, the upsetting load *Q* is acquired by the toggle mechanism of toggle angle $\lambda = 20^\circ \sim 68^\circ$ from the working load *P* of hydraulic press [3].

The advantage of the TR process is that it can provide greater clamping load at the beginning and greater upsetting load at the ending in the upsetting process than the RR process, which may amplify the capability of the press. The disadvantage of the TR process is the mechanical coupling of upsetting and bending action via the toggle mechanism, which limits the optimization of forming quality and process parameters.



(a) RR process



(b) TR process

Fig. 2. Setup of RR process (a) and TR process (b) of continuous grain flow forging of heavy crankshaft

Rys. 2. Schemat procesu RR (a) i procesu TR (b) kucia ciężkiego wału korbowego z zachowaniem ciągłości włókien

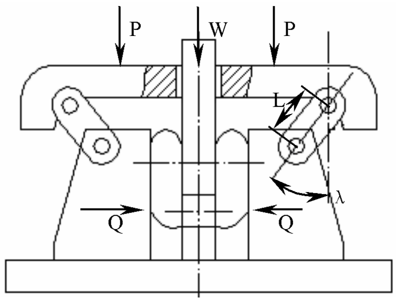


Fig. 3. Setup of N-TR process of continuous grain flow forging of heavy crankshaft

Rys. 3. Schemat procesu N-TR kucia ciężkiego wału korbowego z zachowaniem ciągłości włókien

To overcome the disadvantage of the TR process, a new TR (N-TR) process was proposed by the authors [4]. As is shown in Fig. 3, an independent additional bending cylinder to provide bending action decouples the mechanical coupling of upsetting and bending action via the toggle mechanism in TR. In N-TR process, the upsetting load *Q* is acquired by the toggle mechanism from the working load *P* of hydraulic press, while bending load *W* is provided by the independent additional bending cylinder. The speed of the independent additional bending cylinder can be accurately controlled. Thus, the N-TR has the advantages of the TR process of continuous grain flow, greater clamping load at the beginning and greater upsetting load at the ending in the upsetting process, and the independent additional bending cylinder provides the feasibility of process optimization to acquire optimum crankshaft profiles to near net shape forming, continuous metal grain flow patterns and good mechanical properties.

3. FE MODEL OF CONTINUOUS GRAIN FLOW FORGING OF HEAVY CRANKSHAFT

3.1. Dimensional parameters and material of model 601 crankshaft forging

As a case study, a heavy crankshaft modeled 601 was selected in the simulation. Multi-diameter billet and forging of model 601 crankshaft were shown in Fig. 4 and Fig. 5. As can be seen in Fig. 4 and Fig. 5, the compression on the crank web and bending offset of the crank pin of the crankshaft are *S* = 159 mm – 68 mm = 91 mm, *H* = 107.5 mm separately.

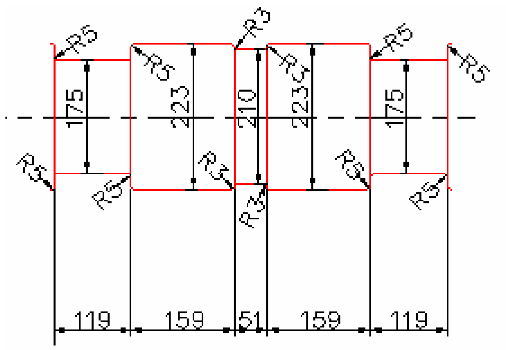


Fig. 4. Billet of model 601 crankshaft forging (mm)

Rys. 4. Materiał wyjściowy dla odkuwki wału korbowego typu 601 (mm)

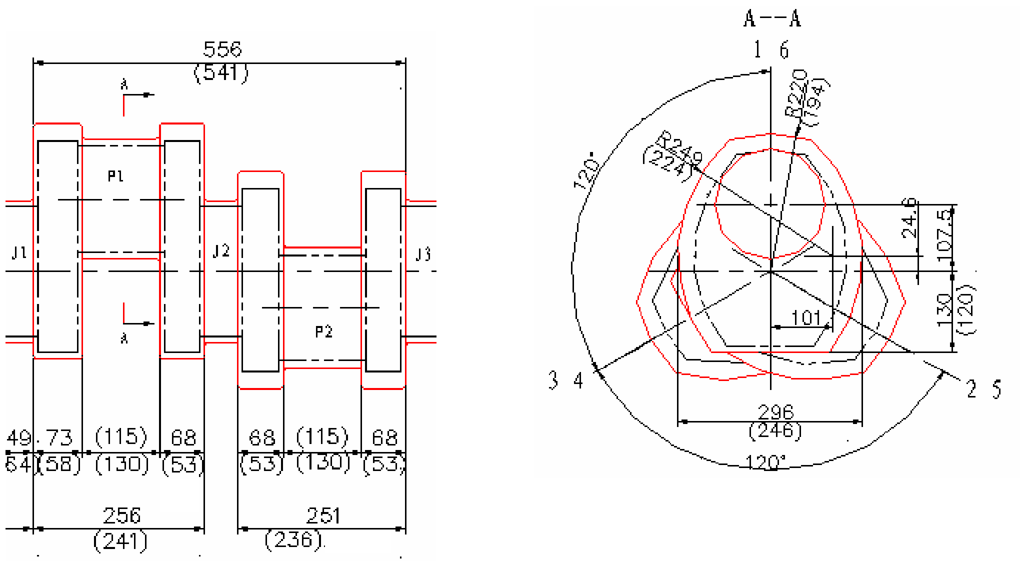


Fig. 5 Forging of model 601 crankshaft (mm)

Rys. 5. Odkuwka wału korbowego typu 601 (mm)

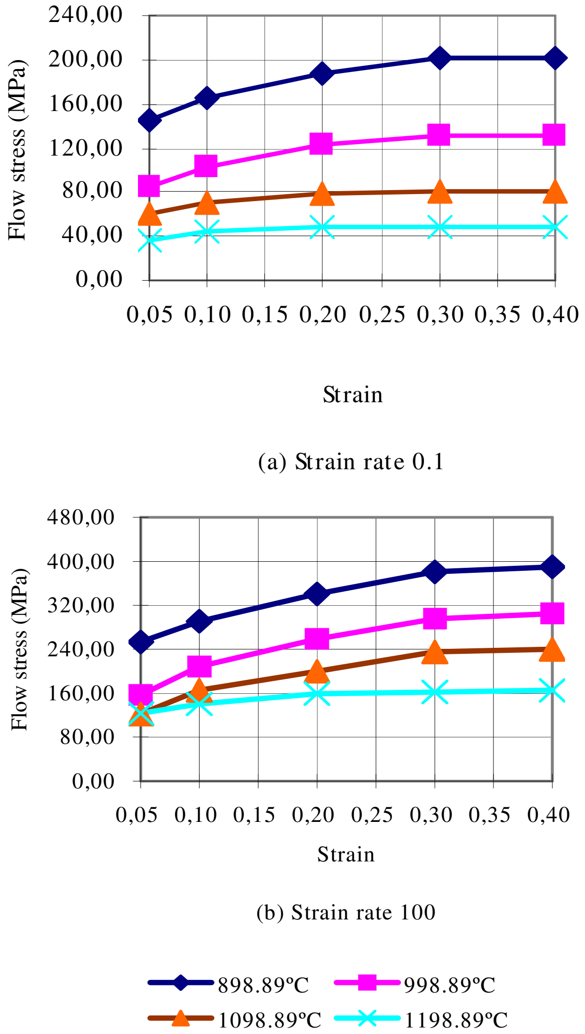


Fig. 6. Constitutive relationships of ANSI-1045 steel at strain rate 0.1 and 100

Rys. 6. Konstytutywne zależności stali ANSI-1045 przy prędkości odkształcenia 0,1 i 100

Material for the crankshaft is ANSI-1045 steel. The constitutive relationships of the material are shown in Fig. 6.

3.2. Process parameters for continuous grain flow forging of model 601 crankshaft

In order to compare and to optimize the parameters of the N-TR process, two groups of bending speed for the N-TR process were set up, of which Group 1 is stairsteped speed while Group 2 is linear speed (see Table 3 in Section 4). Other parameters of the N-TR process are shown in Table 1. The parameters of the RR process and the TR process are also presented in Table 1 as additional reference.

Table 1. Process parameters for N-TR, TR and RR

Tablica 1. Parametry procesu dla N-TR, TR i RR

Process parameter	Value
S_{bend} (mm)	91
S_{upset} (mm)	107.5
V_{press} (mm/s)	100
$t_{forming}$ (s)	1.075
L of N-TR and TR (mm)	225
λ_B of N-TR and TR (°)	31.5
λ_E of N-TR and TR (°)	68
θ of RR) (°)	40
V_{bend} of RR (mm/s)	83.9

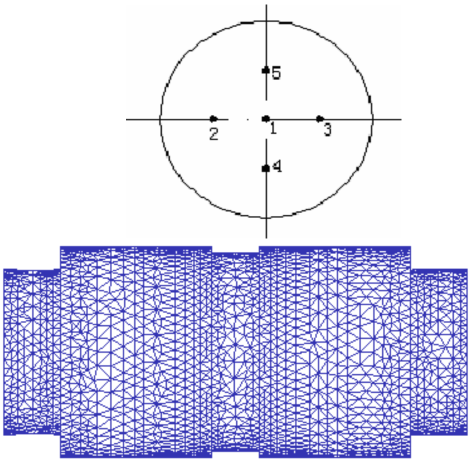
3.3. FE model for continuous grain flow forging of model 601 crankshaft

FE simulation of continuous grain flow forging of mode 601 crankshaft was carried out in the commercial finite element code DEFORM-3D [5]. The FE model is shown in Fig. 7. It consists of the billet, the bending punch and the upsetting die. Parameters for mesh, object type, contact friction, remesh criteria, thermal property and solution step definition of the FE model are shown in Table 2.

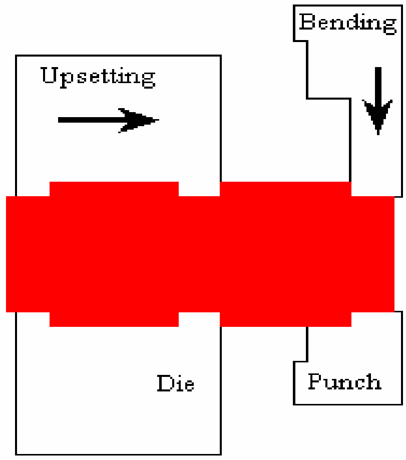
Table 2. Parameters of the FE model

Tablica 2. Parametry modelu MES

Parameter	Value
Element type	four-node tetrahedron
Number of elements	38819
Number of nodes	8759
Object type of workpiece	viscoplastic
Object type of dies	rigid
Contact friction type	shear
Shear friction factor	0.5
Remesh criteria (relative interference depth)	0.7
Temperature of dies and environment (°C)	20
Initial temperature of workpiece (°C)	1100
Thermal conductivity (N/s/°C)	46.67
Heat capacity (N/mm^2/°C)	3.9371
Thermal emissivity	0.1
Heat transfer coefficient (N/s/mm/°C)	11
Heat convection coefficient (N/s/mm/°C)	0.02
Number of solution step	100
Downward displacement of press upper beam per solution step (mm)	1.075



(a) Initial FE mesh of workpiece and tracking point for mean stress



(b) FE model

Fig. 7. FE model for continuous grain flow forging of model 601 crankshaft

Rys. 7. Model MES dla kucia wału korbowego typu 601 z zachowaniem ciągłości włókien
a) siatka MES dla materiału wyjściowego oraz punkty odczytu naprężeń,
b) model MES kucia wykorbienia

4. RESULTS AND DISCUSSIONS

RR, TR, and N-TR processes were simulated with model 601 crankshaft. The major defect of continuous grain flow forging of crankshaft is insufficient die filling at corner of the shoulder seat for balance weight. Table 3 shows the results of FE simulation of forming status of continuous grain flow forging of mode 601 crankshaft. As can be seen in the table, TR of maximum gap to die cavity of 3.56 mm is superior to RR of maximum gap to die cavity of 6.67 mm, in the die filling property. The die filling of N-TRs, compared to TR and N-TR themselves, varies significantly from worse to better via different bending speed graphs.

The die filling of N-TR with the stairsteped bending speed graphs (Group 1), varies from worse to full filling as the bending speed changes from 150/0 mm/s (NTR 01/Group 1) at stroke time 0.717s (corresponding to upper beam downward displacement 71.7 mm) to 0/150 mm/s (NTR 05/Group 1) at stroke time 0.358s (corresponding to upper beam downward displacement 35.8 mm); and the die filling of N-TR with the linear bending speed graphs (Group 2), varies from better to worse as the bending speed changes from 150/0 mm/s (NTR 01/Group 2) to 0/150 mm/s (NTR 04/Group 2) in the stroke of 107.5 mm. It shows that lower bending speed in the beginning stage and higher speed in the ending stage benefit the die filling. The best die filling is achieved with the stairsteped bending speed graph of NTR 05/Group 1.

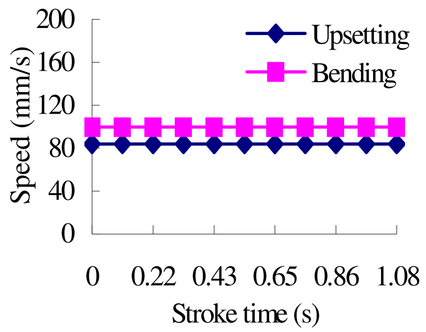
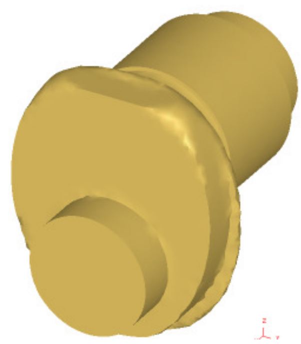
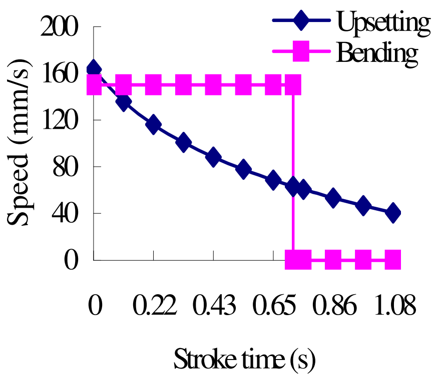
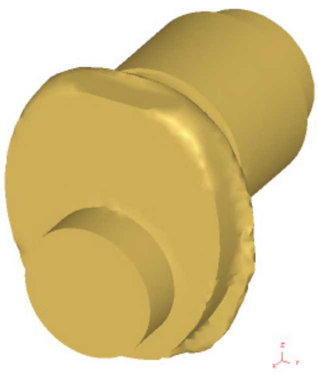
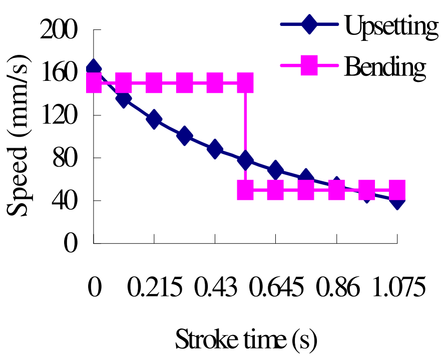
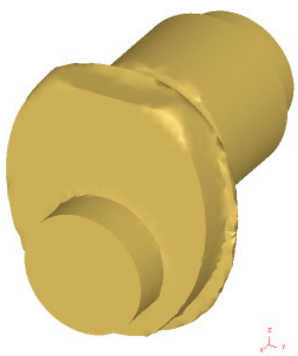
From the viewpoint of engineering feasibility, stairsteped bending speed is easy to control. An engineering feasibility oriented stairsteped bending speed pattern can be obtained by revising bending speed graph of NTR 05/Group 1, which is NTR 06/Group 1 as shown in the table. In NTR 06/Group 1, the uniform speed step of 150 mm/s is left ward moved 0.05s stroke time (corresponding to upper beam displacement 5 mm). This will prevents additional tensile stress in the arm of the cranks due to control error that bending stroke ends later than upsetting.

Negative mean stress is an important beneficial factor to healing of porosity and loose defects of large forgings. Figures 8 (a)-(d) show mean stress vs. stroke at the five tracking point defined in Fig. 7 (a) in continuous grain flow forging of mode 601 crankshaft. As can be found in the figures, mean stress of RR, TR and N-TR has almost the same level in the early stage with small positive value; while in the final stage, mean stress values of TR show greater negative value. Mean stress of N-TR 05/Group 1 and 06/Group and RR are in the same level.

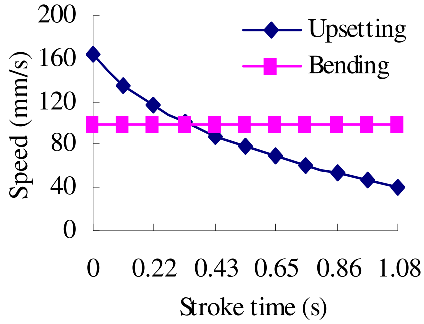
Figures 9 (a)-(d) show bending and upsetting load vs. stroke in continuous grain flow forging of mode 601 crankshaft. As can be found in the figures, maximum bending and upsetting load appears at or near the ending stage of the processes; the ascending sequence of maximum bending load is RR, TR and N-TR; and the ascending sequence of maximum upsetting load is RR, N-TR and TR. N-TR possesses greater bending load and medium upsetting load as compared to RR and TR. The bending load of RR is charactered by a drop in value near the end of the process, which means a compressive buckling occurred. The bending load of TR keeps almost constant until the ending stage of the process. The upsetting load increases slowly before the ending stage and rapidly in the ending stage of upsetting stroke. As the upsetting load is greater one order of magnitude than the bending load, total tonnage of hydraulic press for N-TR would be less than or equivalent to that for TR, and surely less than that for RR.

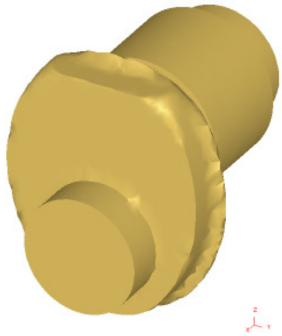
Table 3. FE simulation results of forming status of continuous grain flow forging of mode 601 crankshaft

Tablica 3. Wyniki symulacji MES kształtu odkuwki wału korbowego typu 601 z zachowaniem ciągłości włókien

<table>
<tr><th>No./ Group</th><th>Bending speed graph</th><th>Forming status</th><th>Maximum gap to die cavity (mm)</th></tr>
<tr><td>RR</td><td>
</td><td></td><td>6.67</td></tr>
<tr><td>NTR 01/ Group 1</td><td>
</td><td></td><td>6.67</td></tr>
<tr><td>NTR 02/ Group 1</td><td>
</td><td></td><td>5.56</td></tr>
</table>

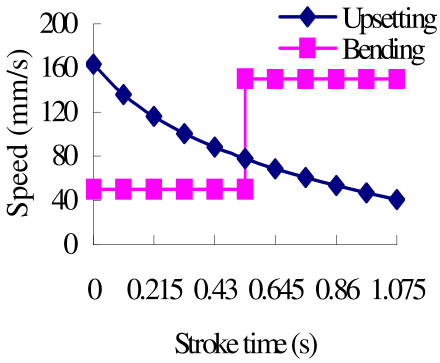
NTR 03/ Group 1

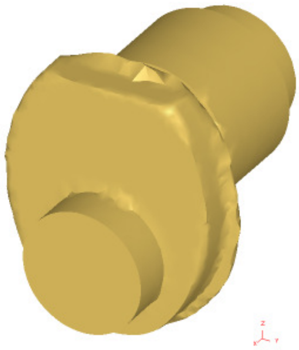




3.56

NTR 04/ Group 1





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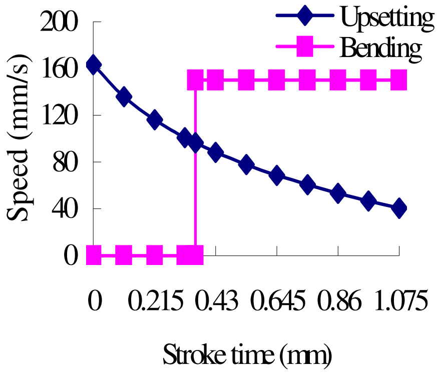
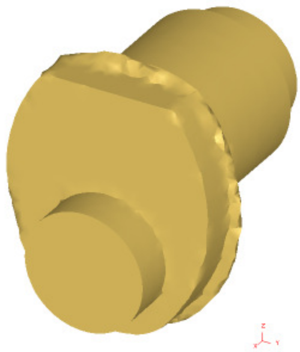
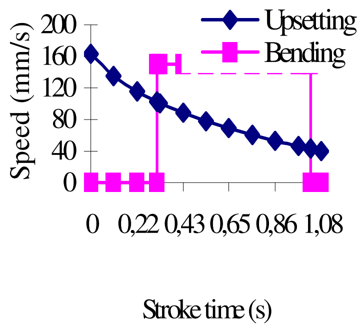
NTR 05/ Group 1

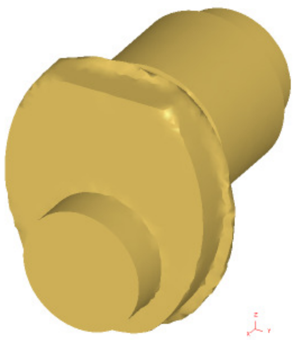




0

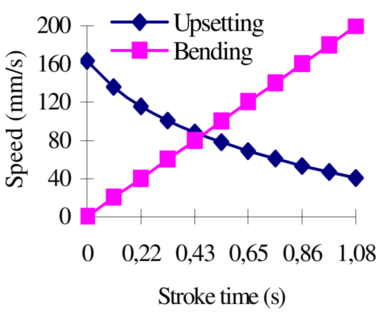
NTR 06/ Group 1

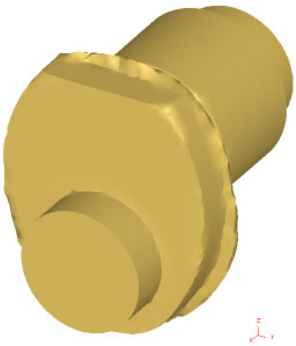




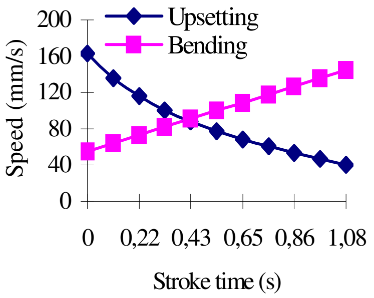
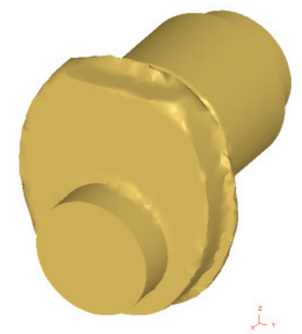
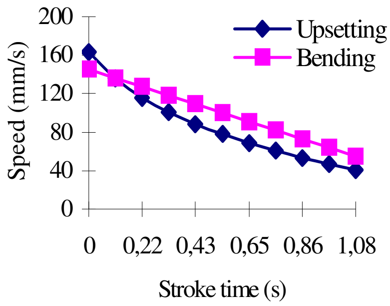
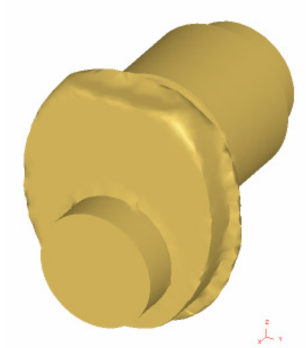
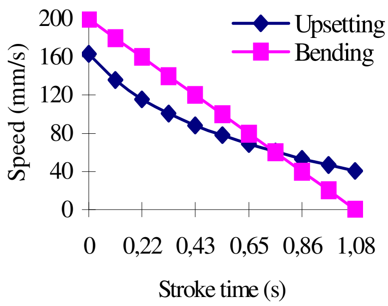
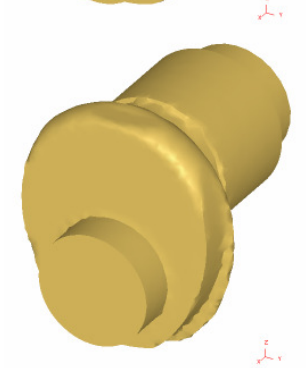
2.22

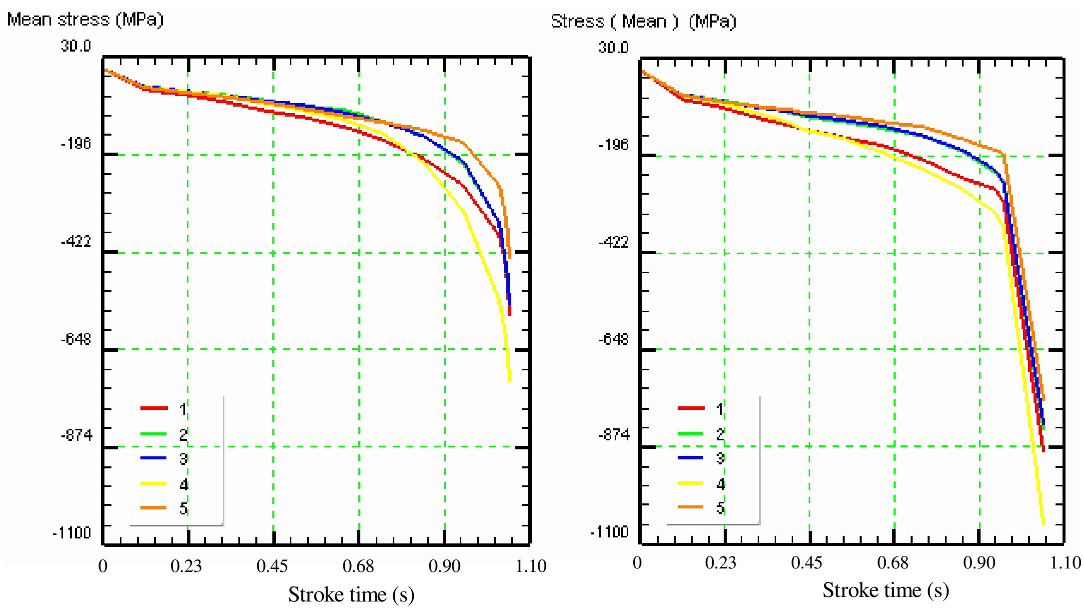
NTR 01/ Group 2



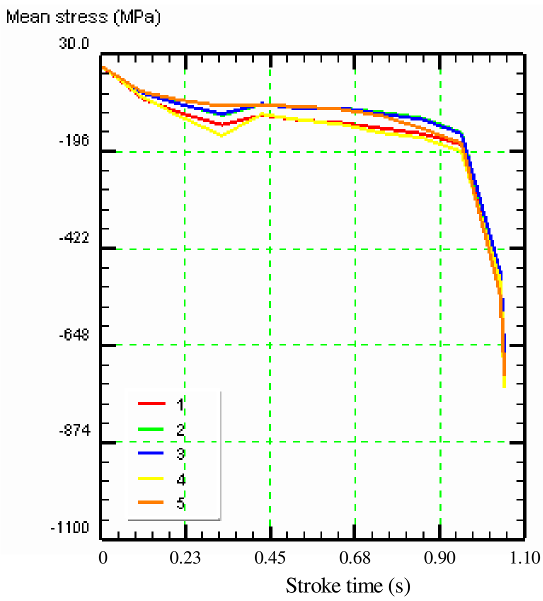


3.33

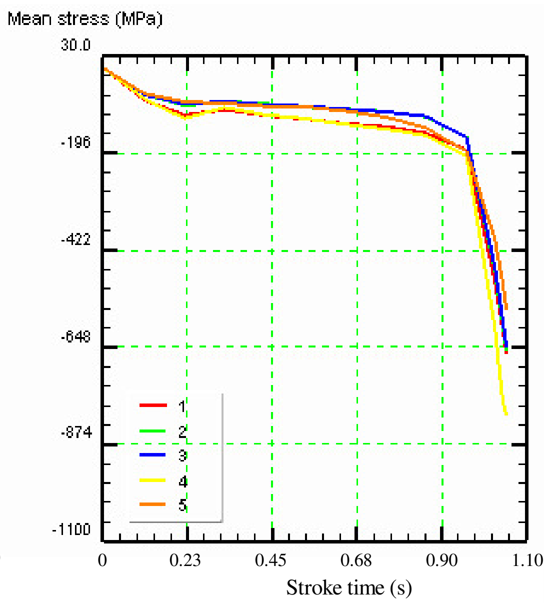
NTR 02/ Group 2			4.44
NTR 03/ Group 2			5.56
NTR 4/ Group 2			8.89



(a) RR (b) TR (03/Group 1)



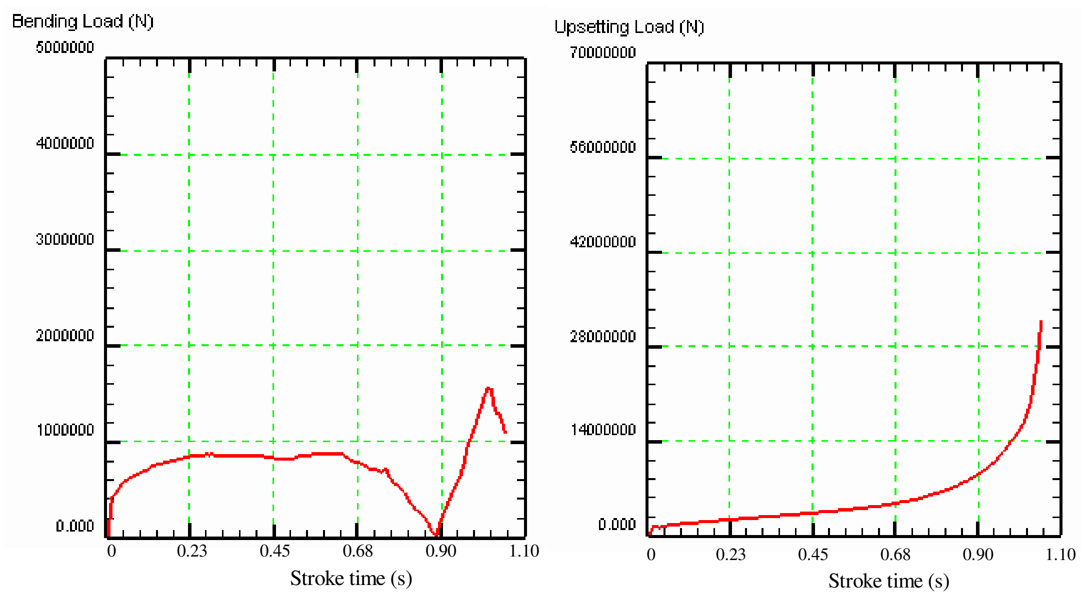
(c) NTR 05/Group 1



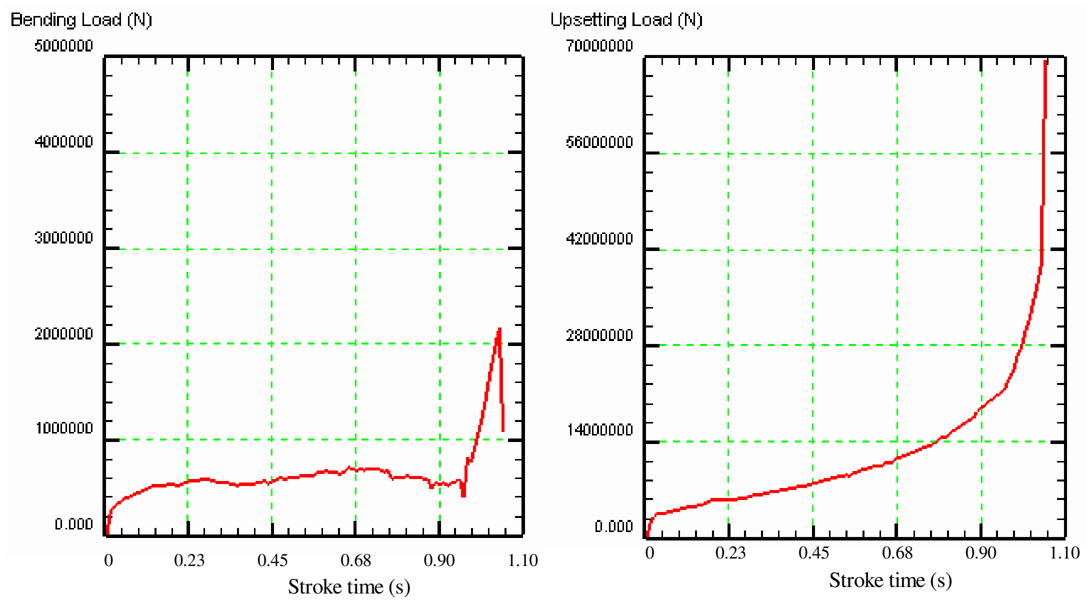
(d) NTR 06/Group 1

Fig. 8. Mean stress vs. stroke in continuous grain flow forging of mode 601 crankshaft

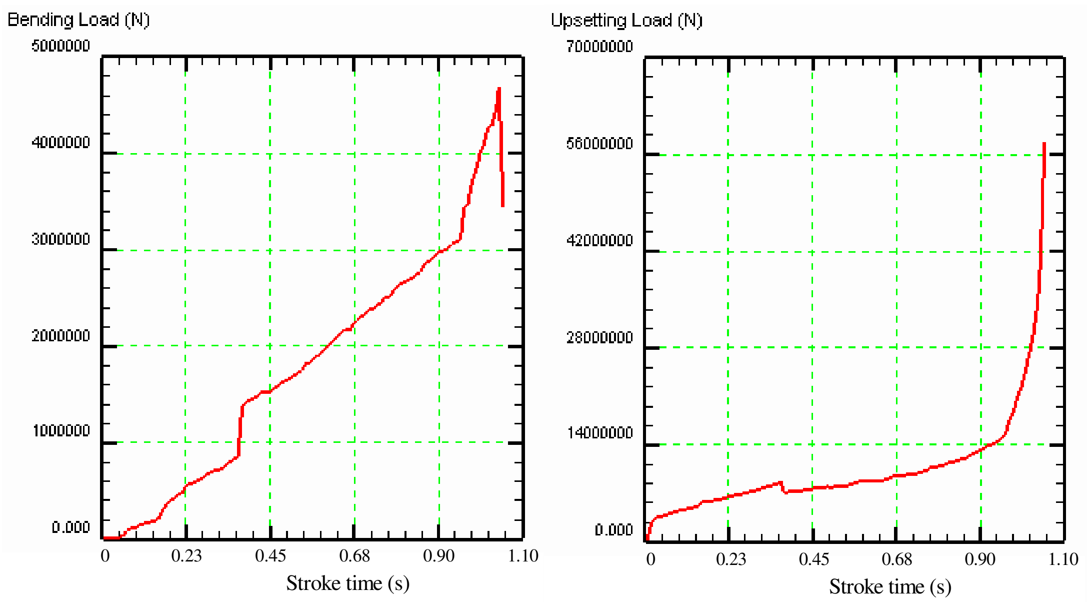
Rys. 8. Średnie naprężenie w funkcji skoku podczas kucia wału korbowego typu 601 z zachowaniem ciągłości włókien



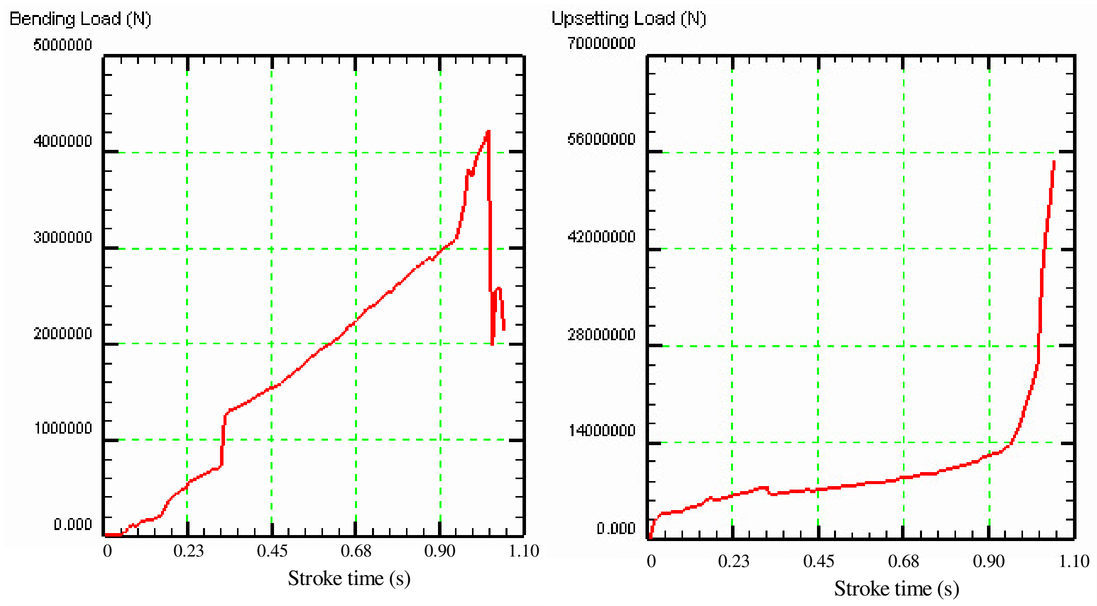
(a) RR



(b) TR



(c) NTR 05/Group 1



(d) NTR 06/Group 1

Fig. 9. Load vs. stroke in continuous grain flow forging of mode 601 crankshaft

Rys. 9. Obciążenie w funkcji skoku podczas kucia wału korbowego typu 601 z zachowaniem ciągłości włókien

5. CONCLUSIONS

As the mechanical coupling of upsetting and bending action is decoupled, N-TR process provides the feasibility of process optimization. In the case study of model 601 heavy crankshaft via FE simulation, relationship of die filling versus bending speed-stroke parameters was acquired, which shows that lower bending speed in the beginning stage and higher speed in the ending stage benefit die filling. Optimum die filling and engineering feasible speed-stroke parameters was acquired, as are NTR 05/Group 1 and NTR 06/Group 1 in Table 3 respectively. Mean stress and forging load analyses shows that mean stress in N-TR is equivalent to that in RR, N-TR possesses greater bending load and medium upsetting load as compared to RR and TR.

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Nomenclature

S_{bend}	stroke of upsetting
S_{upset}	stroke of bending
V_{press}	speed of upper beam of the press
$t_{forming}$	time of forming (s)
L	toggle arm length of N-TR and TR setups
V_{bend}	speed of upsetting of RR setup
P	working load of the press
W	bending load
Q	upsetting load.

Greek letters

λ	toggle angle of N-TR and TR setups
λ_B	beginning toggle angle of N-TR and TR setups
λ_E	ending toggle angle of N-TR and TR setups
θ	inclined angle of RR setup