Tool for programmed open-die forging – case study

Orodje za programsko vodeno prosto kovanje – študija primera

David Bombač[1], Matevž Fazarinc[1], Goran Kugler[1], Radomir Turk[1]

[1]University of Ljubljana, Faculty of Natural Sciences and Engineering,
Department of Materials and Metallurgy, Aškerčeva cesta 12, SI-1000 Ljubljana, Slovenia;
E-mail: david.bombac@ntf.uni-lj.si, matevz.fazarinc@arnes.guest.si,
goran.kugler@ntf.uni-lj.si, rado.turk@ntf.uni-lj.si

Received: November 26, 2007 **Accepted:** January 13, 2008

Abstract: An open-die forging process as referred to in the following assumptions is a process where plastic material is compressed in one main axis only and the spread into the two other main axes is not limited. In view of present competitive markets modern open-die forging plants are highly dynamic production plants and vastly explore possibilities of programmed forging. Computer aided technology tools for programmed forging is the basis for innovative and cost effective technology planning which consider the performance limits of forging equipment and material in order to achieve the optimum productivity.

Izvleček: Proces prostega kovanja, ki je obravnavan v tej študiji, je postopek, kjer je material tlačno deformiran v eni smeri, v ostalih dveh pa se prosto širi. Na današnjem izredno konkurenčnem trgu so obrati prostih kovačnic izredno dinamični obrati in široko izkoriščajo možnost programiranega kovanja. Računalniško podprta tehnološka orodja za programirano kovanje so osnova za inovativno in cenovno učinkovito planiranje proizvodnje. Ta preuči meje zmožnosti stiskalnice in mejne vrednosti materiala, ter na podlagi teh določi optimalne pogoje preoblikovanja.

Key words: hot forming, open-die forging, programmed forging, pass schedule, forging simulation
Ključne besede: vroče preoblikovanje, prosto kovanje, programirano kovanje, plan vtikov, simulacija kovanja

---

Scientific paper

INTRODUCTION

In metal forming, open-die forging is a metal forming process in which a workpiece is usually pressed between flat dies with a series of compressive deformation steps and manipulated and/or rotated. The open-die forging process as referred to in the following assumptions is a process where plastic material is compressed in one main axis only and the spread into the two other main axes is not limited. It has not lost its importance in recent times and is for steel manufacturing carried out under hot working conditions when the metal is deformed plastically above its recrystallization temperature. The open-die forging plants consist of a forging press and one or two rail-bound manipulators. The dies or tools are small compared with the overall sizes of the forgings. The process is carried out incrementally, where only a part of the workpiece is being deformed at each stage. The principle of such an incremental forging process is simply the compressing or upsetting of the material step-by-step until it reaches the final target shape. In the further development of this type of forming operation, the requirements are for accuracy of load prediction and metal flow[1-3].

In view of present competitive markets modern open-die forging plants are highly dynamic production plants and vastly explore possibilities of programmed forging. Apart from the pure production speed, the main focus today is on the achievement of minimum forging tolerances and a consistent level of quality. In the past procedures in open-die forging were based on the individual forgemaster's experience and observation of each forging stroke to determine both elongation and sideways spreading. An experienced forge master can develop a geometrical pass schedule quite easily, however; the optimization of a pass schedule to minimize forging time is quite difficult as it involves the consideration of numerous factors which influence the production rate. Computer aided technology tools for programmed forging is the basis for innovative and cost effective technology planning which consider the performance limits of forging equipment and material in order to achieve the optimum productivity. It must consider all of the important factors including spread behaviour, die geometry and the speeds of the press and manipulators. The required pressing force relative to the material resistance is calculated as a function of the instantaneous temperature and compared to the maximum available press force.

Optimization of the pass schedules in the open-die forging technology and activities for successful implementation of the computer aided forging technology demand close cooperation between forging plants and science. Technology developed in cooperation must be constantly maintained and adapted to the latest technological breakthroughs.

THEORETICAL FRAMEWORK FOR PROGRAMMED FORGING

The open-die forging as mentioned before is incremental process where after one forging pass on a square bar the side faces take on an irregular shape, commonly termed barrelling, which is due to frictional constraint at the tool faces and to the influence of the adjacent undeformed portion of the bar. The influence of the machine operator experience on the monitoring of the process must be decreased in order to ensure reproducible process that increases productivity and improve quality of the forgings hence reducing machine operator experience related fluctuations. Moreover computer aided forging technology enables judgment of the characteristic forging capabilities of the plant and their influence on the productivity[4]. However the machine operator has ability to initiate corrections to the programmed forging schedule any time if it is necessary.

Pass schedule calculation is determination of relevant process data for processing a defined end piece from initial ingot. Such calculation is very demanding due to complexity of open-die forging process. For instance to enable a mutual harmonisation between forging press and manipulator a proper description of the material being pressed between two flat dies is required. Moreover material does not only deform in the forging direction but also towards the manipulator. In order to fully exploit capabilities of forging equipment manipulator feeding rate or manipulator bite has to be determined. This can be achieved by employing the empirical formula proposed by Tomlinson and Stringer[3] which is based on assumption of constant volume during plastic deformation and describes the relationship between manipulator feeding rate, material shape and reduction for steel. The change of length and width of a forging can be described by a spread factor and the reduction ratio. From practical experience with programmed forging it is known that the influence of reduction ratio on the spread is negligible[4].

To compute the forging pass schedules for bars and predict the changes of shape as well as other important parameters during the forging process empirical formulae have been proposed. The pass procedure for the forging of final shape depends on initial and final cross section shape of bar and are: 1) from square stock to a square bar, 2) from square to round, 3) from round to square and round to round, where same forging principle is used. Breakdown procedure is as follows 1) square to square process goes through next shapes: square – rectangular – square where the reduction ratio can be varied every second pass. A square forged down to a rectangular section with a certain reduction ratio, turned 90° and forged down again with the same reduction ratio and the same bite ratio, turns automatically into a new square with smaller size. To obtain sharp corners of bar decrease of the reduction ratio is required. 2) The process square to round follows the same breakdown routine square – rectangular – square, ending in four passes with an octagon, which have about 7 % more area than the final round. Finish to the round is made in a swaging die. 3) Forging pass schedule of round to square and round to round follows the same forging principle. Forging of rectangular cross sections requires a different technology, where shape factor of h/w (height/width) plays important role leading to a variation of the spread factor. For example rectangular bars where a shape factor exceeds 1/6 results in the normal forging range practically no spread but only elongation[4].

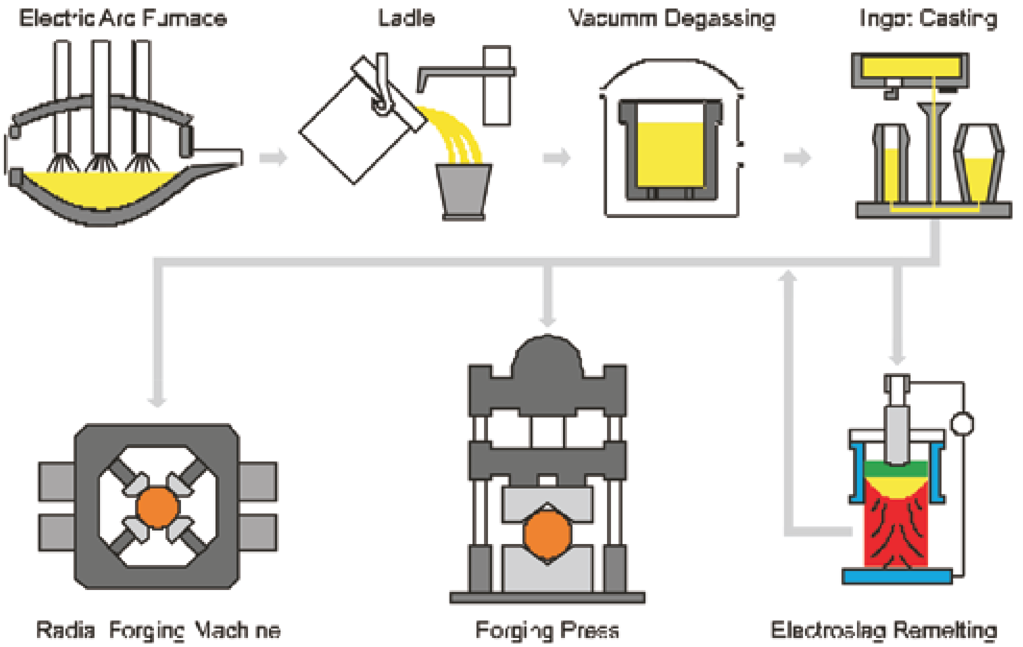

Figure 1. Material flow for open-die forged products
Slika 1. Tok materiala pri prostem kovanju

Ingots are extensively used as forging stock in the open-die forging of large components. In Figure 1 typical steelmaking material flow from electric arc furnace to forging press is shown. Whenever ingots are used it is often mandatory to adopt a forging procedure that will remove the cast structure in the finished forging.

Another important aspect of calculation and optimisation of apt pass schedule is to be aware of limits of ingots, products, materials and technology. When all properties are collected and stored to databases we can start calculating efficient pass schedule.

Use of computer aided technology, as depicted in Figure 2 for development and optimization of pass schedules in open-die forging requires some input of forging know-how. This applies particularly to the reduction factor which has to take care of the shape of the ingot, surface conditions, and brittleness of the material and in most cases must be varied with the dropping forging temperature. Also important is the bite ratio which defines the depth of deformation and grain change in the forging. Grater bite ratio is better but leads to increase of forging force, which is limited with equipment.

RESULTS AND DISCUSSION

HFS software fundamentals for calculation of pass schedules are models where some of them are physically based e.g. temperature. Other models are deductions

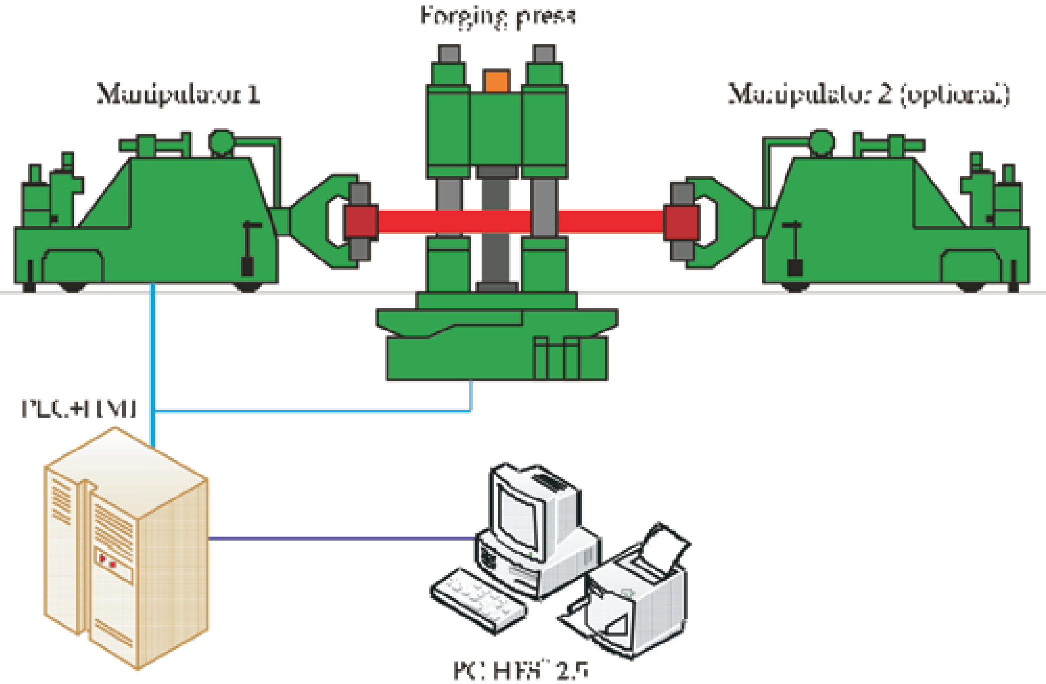

Figure 2. Modern open-die forging plant with additional PC for virtual aided technology
Slika 2. Moderen obrat kovačnice za prosto kovanje z dodatnim računalniškim vodenjem tehnologije

from experience e.g. material spreading. In software database also technological characteristics of the forging equipment e.g. maximum press force, press velocity and acceleration, manipulator velocity and acceleration, etc are stored. Users of HFS software have possibility and are limited to change only input data that are stored in input databases as follows. *Ingot database* where all geometrical characteristics of ingots are stored. *Product database* allows users to specify and store shape and dimensions of products. In *materials database* physical characteristics regarding hot workability, radiation and thermal properties for desired materials are stored. *Technological database* includes data linked to technological parameters used according to specific forging schedule e.g. shape and size of forging tool. For accurate pass schedule calculation user must constantly update parameters stored in input databases. Specifically important are parameters influencing calculation of temperature e.g. density, specific heat and radiation coefficient. Figure 3a shows influence on temperature calculation regarding specific heat, whereas in Figure 3b depicts influence of radiation coefficient on temperature respectively. Figure 3 shows that lowering specific heat coefficient decreases calculated temperature, on the other hand lowering radiation coefficient increases calculated temperature. All calculations plotted in Figure 3 were performed using upseted 24t ingot and material AISI H13.

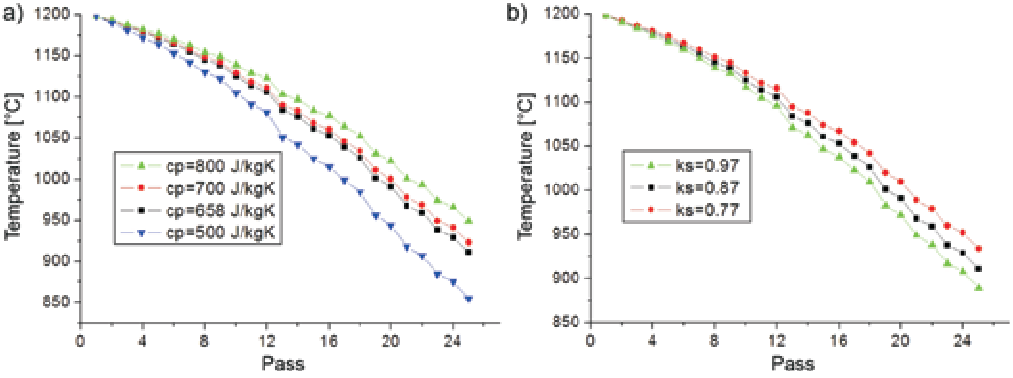

Figure 3. Influence of (a) specific heat and (b) radiation coefficient on temperature after passes while forging flat product from upseted 24t ingot to product dimensions of 1000×500

Slika 3. Vpliv (a) specifične toplote pri konstantnem tlaku cp in (b) koeficienta sevanja na potek temperature po različnih vtikih pri kovanju ploščatega izdelka iz 24t nakrčenega ingota za izdelek 1000×500

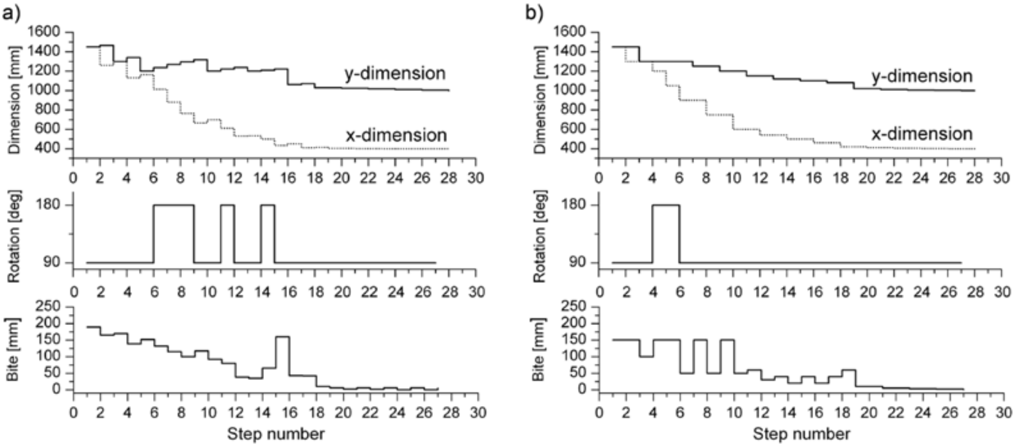

Figure 4. Graphical presentation of forging pass schedule for billet dimensions 1000×400; a) calculated pass schedule and b) acquainted forge masters pass schedule

Slika 4. Grafični prikaz plana vtikov za gredice dimenzije 1000×400; a) izračunan plan in b) izmerjen plan kovaških mojstrov

Table 1. Detailed characteristics of pass schedules for billet dimensions 1000×400

Tabela 1. Natančen prikaz planov vtika za gredico z dimenzijami 1000×400

Calculated pass schedule					Acquainted pass schedule				
Step	Height	Width	Bite	Rotation	Step	Height	Width	Bite	Rotation
1	1450	1450	189.43	90	1	1450	1450	150	90
2	1260	1464.07	164.61	90	2	1300	1450	150	90
3	1299.46	1299.46	169.76	90	3	1300	1300	100	90
4	1129.69	1339.02	139.02	90	4	1200	1300	150	180
5	1200	1164.22	152.1	90	5	1050	1300	150	180
6	1012.13	1236.74	132.23	180	6	900	1300	50	90
7	879.9	1268.24	114.95	180	7	1250	900	150	90
8	764.95	1295.32	99.93	180	8	750	1250	50	90
9	665.01	1317.36	117.36	90	9	1200	750	150	90
10	1200	700	91.53	90	10	600	1200	50	90
11	609.09	1220.84	79.57	180	11	1150	600	60	90
12	529.51	1238.28	38.28	90	12	540	1150	30	90
13	1200	533.68	34.7	90	13	1120	540	40	90
14	498.99	1207.66	65.19	180	14	500	1120	20	90
15	433.8	1221.09	159.53	90	15	1100	500	40	90
16	1061.57	451.5	42.74	90	16	460	1100	20	90
17	408.76	1070.83	42.05	90	17	1080	460	40	90
18	1028.78	413.58	10	90	18	420	1080	60	90
19	403.58	1028.78	6	90	19	1020	420	10	90
20	1022.78	403.58	2	90	20	410	1020	10	90
21	401.58	1022.78	6	90	21	1010	410	5	90
22	1016.78	401.58	1.58	90	22	405	1010	5	90
23	400	1016.78	6	90	23	1005	405	3	90
24	1010.78	400	0	90	24	402	1005	3	90
25	400	1010.78	6	90	25	1002	402	2	90
26	1004.78	400	0	90	26	400	1002	2	90
27	400	1004.78	4.78	90	27	1000	400	0	90
28	1000	400			28	400	1000		

HFS simulator allows prediction and verification of pass schedules for automatically and manually operated open-die forging technology. To certify and confirm calculations of recently developed virtual aided tool for simulation of hot open die forging, HFS, a comparison of calculated and industrial pass schedules is necessity. For later pass schedules of most experienced forge masters from industry were selected. Industrial equipment used to validate accuracy of developed software package was a forging plant with 25/30 MN forging press and one railbound forging manipulator.

The calculated forging plan shows good correlation with the acquainted forging plan as one can see from comparison of Figure 4a and Figure 4b and Figure 5a and Figure 5b. The bite rate is much more equally distributed through the passes. The 180° rotation of the billet is more often used compared to acquainted plan. This results in a straighter billet because the deformation is more evenly distributed. The HFS calculated forging plan also takes into account the spread of billet in the direction normal to forging direction as can be seen as the increase of dimension in direction square to forging direction in Figure 3a and in Figure 4a. Detailed values for forging pass schedule for billet with dimensions 1000×400 are given in Table 1 and for billet with dimensions 1000×500 in Table 2.

In Tables 1 and 2 the calculated pass schedule appears to be as good as that of the best forge master and in some cases even better regarding number of pass steps to obtain final dimensions. HFS also calculates spreading later used for press management and much more accurate and therefore the calculated dimensions for height and width are given in decimal numbers. Forge masters pass schedule does not consider spreading and the values were measured by press control program and are therefore rounded.

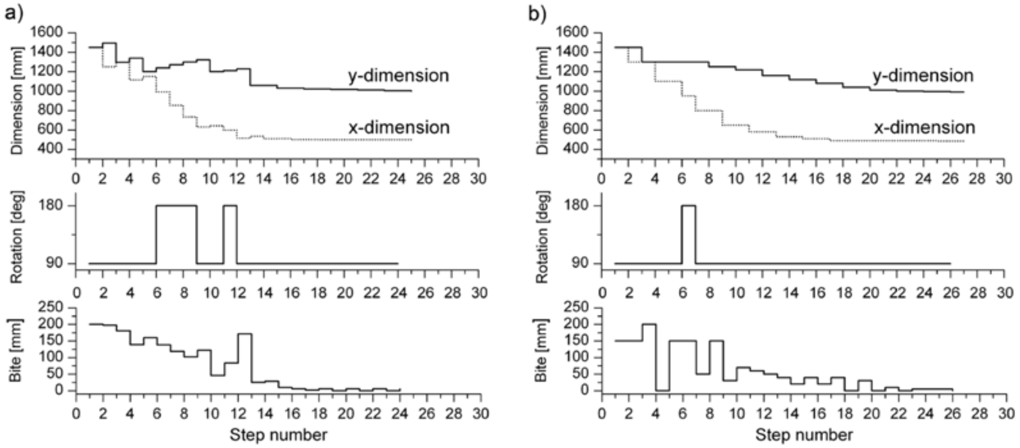

Figure 5. Graphical presentation of forging pass schedule for billet dimensions 1000×500; a) calculated pass schedule and b) acquainted forge masters pass schedule

Slika 5. Grafični prikaz plana vtikov za gredice dimenzije 1000×500; a) izračunan plan in b) izmerjen plan kovaških mojstrov

Table 2. Detailed characteristics of pass schedules for billet dimensions 1000×500
Tabela 2. Natančen prikaz planov vtika za gredico z dimenzijami 1000×500

Calculated pass schedule					Acquainted pass schedule				
Step	Height	Width	Bite	Rotation	Step	Height	Width	Bite	Rotation
1	1450	1450	200	90	1	1450	1450	150	90
2	1250	1494.48	197.62	90	2	1300	1450	150	90
3	1296.86	1296.86	180.64	90	3	1300	1300	200	90
4	1116.22	1339	139	90	4	1100	1300	0	90
5	1200	1150.94	160.32	90	5	1300	1100	150	90
6	990.62	1238.72	138	180	6	950	1300	150	180
7	852.63	1271.57	118.77	180	7	800	1300	50	90
8	733.87	1299.52	102.22	180	8	1250	800	150	90
9	631.65	1322.03	122.03	90	9	650	1250	30	90
10	1200	644.21	45.54	90	10	1220	650	70	90
11	598.67	1210.37	83.39	180	11	580	1220	60	90
12	515.28	1228.71	171.15	90	12	1160	580	50	90
13	1057.56	534.22	24.94	90	13	530	1160	40	90
14	509.27	1057.56	28.38	90	14	1120	530	15	90
15	1029.17	511.95	10	90	15	515	1120	40	90
16	501.95	1029.17	6	90	16	1080	515	10	90
17	1023.17	501.95	1.95	90	17	505	1080	40	90
18	500	1023.17	6	90	18	1040	505	0	90
19	1017.17	500	0	90	19	505	1040	20	90
20	500	1017.17	6	90	20	1020	505	0	90
21	1011.17	500	0	90	21	505	1020	10	90
22	500	1011.17	6	90	22	1010	505	0	90
23	1005.17	500	0	90	23	505	1005	5	90
24	500	1005.17	5.17	90	24	1000	505	5	90
25	1000	500			25	500	1000	0	90
					26	1000	500	0	90
					27	500	1000		

A case study comparison was made between a calculated and measured pass schedule for two different billet sizes. The calculated pass schedule shows good correlations with the measured one and is in some cases even better than that of the best forge masters, resulting in less passes needed for reaching the end dimensions of the forged billet. The bite rate in calculated pass schedule is much more evenly distributed between the passes thus resulting in more evenly distributed deformation and should provide better material properties and minimise the risk of an onset of cracks.

Ability of HFS is also spread calculation of a billet. This can be later on used for a complete automation of a forging press leading to minimisation of the cost of open-die forging process and increase the yield.

Conclusions

Efforts to increase productivity and improve quality of technological processes are of a high importance in open-die forging. The investments costs of open-die forging equipment are high and profitability depends to large extent on intensive and flexible use. Automatic forging sequences ensure higher productivity and better quality of products. The developed software for open-die forging HFS allows the calculation of pass schedules and gives support for selection and verification of optimal pass schedule. Technology engineer using the HFS program has a good control over open-die forging process, thus resulting in an opportunity to select optimal process parameters for each product and material. Accuracy of calculated pass schedules largely depends on accurate initial data needed in HFS software.

Analysis and detailed comparison of data obtained online in open-die forging plant and calculated offline using HFS software shows good agreement. We believe that are possible further technological optimizations of pass schedules and therefore savings when technologists familiar with open-die process and equipment abilities when HFS in used.

Povzetek

Orodje za programsko vodeno prosto kovanje – študija primera

Poizkusi za povečanje produktivnosti in izboljšanje kvalitete tehnoloških procesov so izrednega pomena v obratih prostega kovanja. Cene investicij za opremo, ki je potrebna za prosto kovanje so izredno visoke zato je dobičkonosnost odvisna predvsem od razširjenosti in fleksibilnosti uporabe. Avtomatizirni postopki kovanja zagotavljajo večjo produktivnost in boljšo kvaliteto končnih izdelkov.

Z razvita programsko opremo HFS je moč izračunati plan vtikov in s tem nudi oporo pri optimalni izbiri plana. Tehnolog, kateremu je v pomoč HFS, ima dobro kontrolo nad procesom prostega kovanja. Tako se lahko osredotoči na izbiro optimalnih parametrov za vask proizvod in material. Natančnost izračuna s programom HFS pa je v veliki meri odvisna od natančnsti začetnih podatkov v programu.

Narejena je bila študija primera med izračunanim in izmerjenim planom vtika za dve različni dimenziji gredic. Izračunan plan kaže dobro ujemanje s planom, ki je bil izmerjen pri ekipi najboljših kovaških mojstrov. V nekaterih primerih je ta celo boljši, saj je bilo potrebnih manj vtikov za dosego končnih dimezij.

Stopnja odvzema je pri izračunanem planu bolj enakomerno razporejena med prevleki. S tem je dosežena tudi bolj enakomerna razporeditev deformacije med prevleki, kar ima za posledico boljše materialne lastnosti in preprečuje vrjetnost nastanka razpok.

Program HFS izračunava in upošteva tudi širjenje gredice. Vse te lastnosti je moč uporabiti kasneje za avtomatizacijo preše za prosto kovanje. To bi zmanjšalo stroške prostega kovanja in povečalo končni izplen.

REFERENCES

[1] AKSAKAL, B., OSMAN, F.H., BRAMLEY, A.N. (1997): Upper-bound analysis for the automation of open-die forging. *Journal of Materials Processing Technology.*; Vol. 71, pp. 215-223.

[2] CHOI, S.K., CHUN, M.S., VAN TYNE, C.J., MOON, Y.H. (2006): Optimization of open die forging of round shapes using FEM analysis. *Journal of Materials Processing Technology.*; Vol. 172, pp. 88-95.

[3] TOMLINSON, A., STRINGER, J.D. (1959): Spread and elongation in flat tool forging. *Journal of Iron Steel Institute.*; Vol. 193-2, pp. 157-162.

[4] PHANKE, H.J. (1983): Grundlagen des programmierten Schmidens. *Stahl und Eisen.*; Vol. 103, pp. 547-552.