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COMPUTER AND LABORATORY MODELLING OF THE ANALYSIS OF CLOSING UP OF METALLURGICAL DEFECTS IN INGOTS DURING FREE HOT FORGING

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Computer modelling using a FEM-based program, Forge 2D®, was carried out in the study. The influence of die shape and the main parameters of the forging process on closing up of metallurgical defects were determined.

Key words: *free forging, metallurgical defects, shape anvils, objective function*

Kompjutersko i laboratorijsko modeliranje analize sprečavanja metalurških grešaka na ingotima tijekom slobodnog toplog kovanja. U studiji je provedeno kompjutorsko programiranje uporabom programa Forge 2D® temeljenog na MKE. Utvrđen je utjecaj oblika matrica i glavnih parametara procesa kovanja na sprečavanju metalurških grešaka.

Ključne riječi: *slobodno kovanje, metalurške greške, profilni nakovnji, ciljana funkcija*

INTRODUCTION

Investigations into the methods of inducing the closing up of metallurgical defects (voids in cast material) in the cross-section of forgings are reported in several studies [1-5].

They show that closing up of metallurgical defects in deformed forgings is significantly influenced by main parameters of the forging process, such as relative high reduction (ε_h), feed, stock temperature, and the shape and dimensions of anvils.

Those studies aimed at the optimisation of forging process parameters and anvil shape for the purpose of obtaining forgings free from internal defects.

This paper presents the results of studies on the determination of the shape and tool geometry to obtain a homogeneous distribution of strain intensities and closing up of defects of metallurgical origin present in forgings during free hot forging.

TESTING METHODOLOGY

For the analysis of the forging process, the FORGE 2D® commercial software based on the finite-elements method was used [6]. It enables the thermo-mechanical simulation of the plastic working processes of metals to be performed in an axial and axially symmetrical states of deformation.

In theoretical examination and experimental tests, highly alloyed corrosion-resistant steel, X10CrNiTi18-10 according to the EN 10088-21995 standard, was used. The rheological properties of the steel are given based on reference [7].

In the study, radial anvils of a radius of R = 90 mm, asymmetrical rhombic anvils with α_1 = 120° (upper anvil) and α_2 = 135° (lower anvil) were used for theoretical examination and experimental tests in the first stage of the forging operation.

For conducting computer simulations of the stretch forging operation in the flat deformation state of ingots in shaped anvils, a stock of a round cross-section of $\varnothing$ = 80 mm was taken. During generating a finite-elements grid, five holes were arranged axially on the specimen in the program, which were to simulate defects of metallurgical origin, such as central porosity (Figure 1.). For laboratory tests, the same pattern of specimen was used, with the identical arrangement of holes of the same diameters.

For each of first stage anvils, the calculations of the following parameters were made: ε_h ranging from 15 to 25 %, the velocity of the upper movable anvil varying in the range from 10 to 20 mm/s, and the forging starting temperature ranging from 1100 to 1250 °C. When performing the calculations for particular cases of forging, the constant parameters of the operation were the rotation angle of the forging, φ = 90°, both for the first and the second forging stages.

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RESULTS OF THEORETICAL EXAMINATION

Below, selected results of the computer simulations of metallurgical defect closing-up are presented, for which the best results have been obtained.

Figures 2. - 3. show the distributions of strain intensity values over the cross-section of forgings, along with the traces of simulated metallurgical defects. For all forging cases presented below, the following parameters occurred. In the first stage of the stretch forging operation, ε_h = 25 %, an upper anvil speed of 20 mm/s, and a forging starting temperature of 1250 °C were used. In the second forging stage, a relative reduction of 20 % and an upper anvil speed of 20 mm/s were used, with the exception of the strain intensity value distributions shown in Figure 2. where the presentation of results is limited to the first stage of forging in shaped anvils only. The total surface area of metallurgical defects on the cross-section of simulated stocks before starting their deformation was 91,06 mm^2.

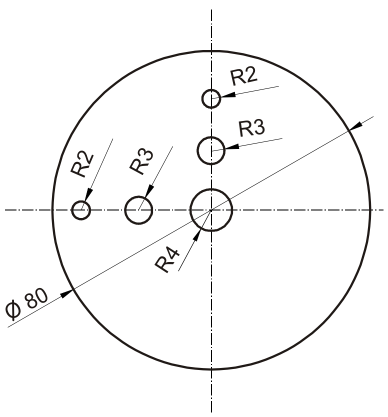

Figure 1. **View of the surface of a simulated specimen with the indication of the arrangement and diameters of holes**

Slika 1. **Pogled na površinu simuliranog uzorka s naznakom rasporeda promjera šupljina**

The data shown in Figure 2. indicate that the method of forging in radial anvils in the first stage and then in flat anvils results in a closing-up of metallurgical defects in the axial zones of the forging, while not bringing about the intended effect of defect elimination in the outer zones. A forging cross is visible, which has formed in the second stage of forging in flat anvils. The achieved effect of closing up metallurgical defects in the axial zone of the forging was caused by the application of radial anvils. It should be noted that defects of the largest diameters of 8 and 6 mm were simulated in the axial zone of the forging. During the deformation of metal in radial anvils, a high state of deformation can be induced in the axial zones of the forging at the smallest energy and force outlays, which is indicative of a forging-through of the material, this effect being the least desirable in a free forging operation.

This is a result of introducing a continuous force in the application of an external load. During the deformation of a stock in radial anvils, the flow of metal is forced by the working surfaces of the anvils in the direction of the stock axis, and the metal only flows freely in the directions parallel to the stock axis. By the proper selection of the radius of rounding of the working surfaces of radial anvils, the values of strain intensities in the axial zones of the forging being stretching forged can be rationally controlled during the stretch forging of ingots, with a resultant favourable effect on the closing up of metallurgical defects, such as central porosity, in the axial zone of the forging. Unfortunately, carrying out a stretch forging operation with the use of radial anvils with all parameters considered in the study did not result in the desirable effect of full closing up of all defects located axially on the cross-section of the deformed stock. The total surface area of defects on the cross-section of the forging after deformation for this case of forging was 2,23 mm^2.

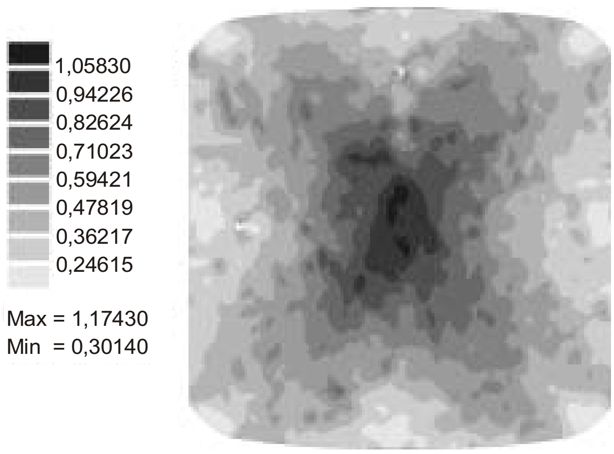

Figure 2. **View of the surface of a forging forged in radial anvils of a radius of R = 90 mm in the first stage, and in flat anvils in the second stage**

Slika 2. **Pogled na površinu otkivka u radijalnim nakovnjima s radijusom R = 90 mm u prvoj fazi i ravnim nakovnjima u drugoj fazi**

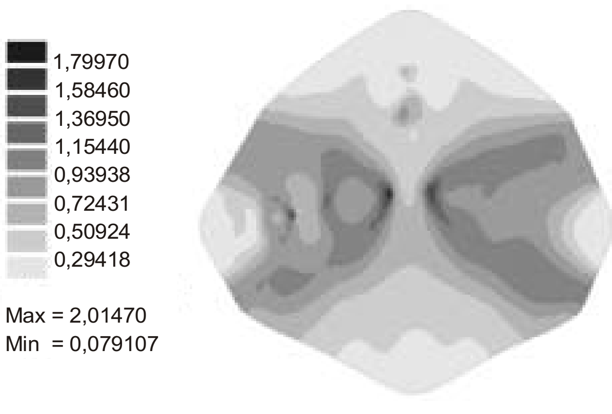

Figure 3. **View of the surface of a forging forged in asymmetric rhombic anvils with α_1 = 120 and α_2 = 135**

Slika 3. **Pogled na površinu iskovanog otkivka u asimetričnim romboidnim nakovnjima s kutom od α_1= 120° i α_2 = 135°**

The data shown in Figure 3. indicate that the use of asymmetrical rhombic anvils during carrying out of the stretch forging operation with ε_h = 25 % and an upper anvil advance speed of 20 mm/s for a forging starting temperature of 1250 °C has caused a complete closing-up of metallurgical defects in all zones of the forging. This is the effect of using an appropriate shape of the inner working surface of the anvils. The forging of a metal in rhombic anvils forces the metal to flow in the direction of forging axis during deformation. Blocking the metal flow in directions other than the direction parallel to the stretch forging direction by increasing the opening angle of the lower anvil results in a high concentration of the maximum values of strain intensities in locations of the horizontal and vertical axes of the forging being deformed. Defects of central porosity type have been completely closed up for this case of forging, as they were distributed along the lines of the horizontal and vertical axes of the stock. The use of asymmetrical rhombic anvils for conducting a stretch forging operation is very effective in terms of closing up metallurgical defects, such as central porosity, as during forging in this type of anvils a total closure of defects on the surface of the simulated specimen in the first forging stage was brought about as early as in the first forging pass without having to apply any finishing operations, in this case, the second stage of forging in flat anvils. The total surface area of defects on the cross-section of the forging after deformation was 0,0 mm^2 for this case of forging.

DETERMINATION OF THE LINEAR OBJECTIVE FUNCTION OPTIMIZING SELECTED TECHNOLOGICAL PARAMETERS OF THE STRETCH FORMING OPERATION IN ASYMMETRICAL RHOMBIC ANVILS

To optimize the process of closing up metallurgical defects, a statistical analysis was performed by the experiment planning method for a selected case of forging in asymmetrical rhombic anvils.

By applying the 2^3 experiment planning method, whose description is given in literature [8], for the initial operation of stretch forging ingots of steel X10CrNiTi18-10 asymmetrical in rhombic anvils, a linear objective function was determined, which optimizes the parameters of the stretch forging operation, in order to close up defects of metallurgical origin. It is described by relationship (1) below.

$$Y_p = 106{,}5 - 7{,}71\,X_1 - 4.00\,X_2 - 0.09\,X_3 + 0{,}33\,X_1 X_2 + 0{,}0068\,X_1 X_3 + 0{,}0036\,X_2 X_3 - 0{,}0003\,X_1 X_2 X_3 \quad (1)$$

where:

Y_p - the total surface area of defects on the forging cross-section,

X_1 - the upper anvil speed,

X_2 - the relative high reduction,

X_3 - the forging starting temperature.

The use of technological parameters during the stretch forging operation for particular cases of forging in the first stage of deformation in shaped anvils is presented in Table 1.

The results of optimization of the stretch forging operation in asymmetrical rhombic anvils performed in order to find proper technological parameters that would lead to closing up of metallurgical defects in a deformed ingot are shown in Figures 4. - 6.

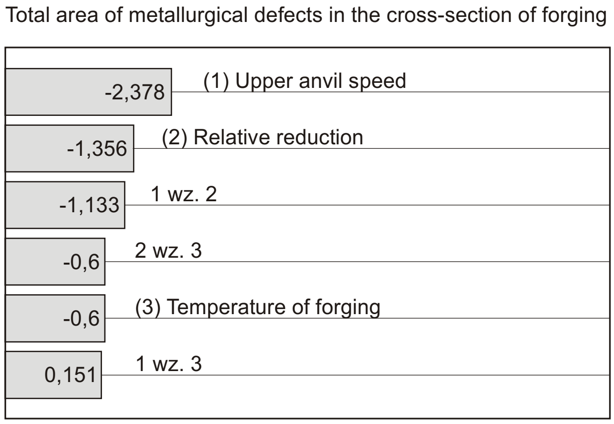

Figure 4. **Pareto chart of the effects of relationships and correlations of the examined quantities on the magnitudes of surface area of metallurgical defects occurring on the surface of a forging after deformation**

Slika 4. **Paretov dijagram utjecaja odnosa i korelacija ispitivanih količina na magnitude površinskog područja metalurških grešaka koje se pojavljuju na kovanoj površini nakon oblikovanja**

The analysis of the data in Figure 4. and of relationship (1) shows that the greatest influence on closing up of metallurgical defects in ingots during a stretch forging operation is exerted by the upper anvil speed and then by the relative high reduction, whereas the forging starting temperature has the smallest effect. Also, the correlation of the relative reduction and the upper anvil speed has a great influence on the reduction of the total surface area of defects on the cross-section of ingots being deformed. The correlation of the upper anvil speed and the forging starting temperature has the smallest effect.

The analysis of the data shown in Figure 5., representing an optimum surface, indicates that the bests effects in terms of closing up defects and discontinuities of metallurgical origin for asymmetrical rhombic anvils were achieved with the use of an upper anvil speed of 20 mm/s and a forging starting temperature of 1250 °C for a preset relative reduction 25 %. Undesirable effects were obtained when using an upper anvil speed of 10 mm/s and a forging starting temperature of 1100 °C for the deformation of ingots, with the same relative reduction applied.

Table 1. **Selection of technological parameters for particular simulations of the ingot stretch forging operation**

Tablica 1. **Odabir tehnoloških parametara za konkretne simulacije operacija kovanja ingota istezanjem materijala**

Number of Experiment	Parameters used			Total surface area of defects on the cross-section of a forging after forging
	v / mm/s	ε_h / %	T / °C	
1	10	15	1100	6,0
2	10	15	1250	4,3
3	10	25	1100	5,3
4	10	25	1250	4,5
5	20	15	1100	2,9
6	20	15	1250	3,6
7	20	25	1100	1,9
8	20	25	1250	0,0

The analysis of the data presented in Figure 6., representing an optimum surface, shows that the best effects in terms of closing up defects and discontinuities of metallurgical origin for asymmetrical rhombic anvils were achieved with the use of an upper anvil speed of 20 mm/s and ε_h = 25 % for a forging starting temperature of 1250 °C. Undesirable effects were obtained when using an upper anvil speed of 10 mm/s and ε_h = 15 % for the deformation of ingots, with the same forging starting temperature applied.

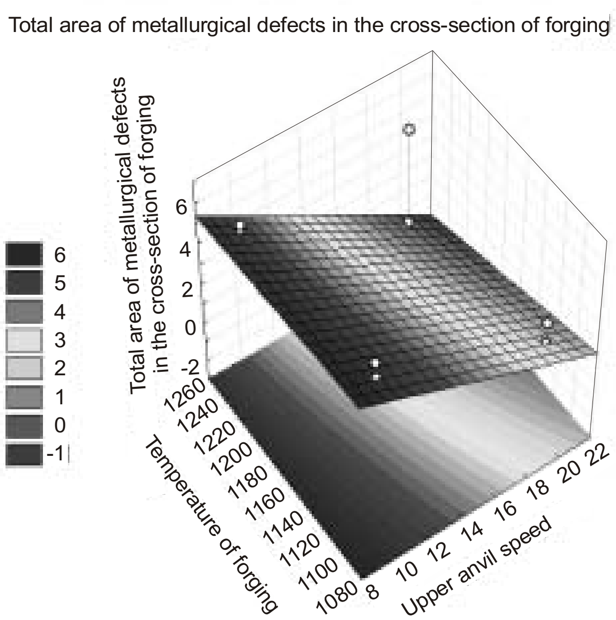

Figure 5. **Diagram of the function of the total surface area of defects on the forging surface versus the upper anvil speed and the forging starting temperature for a relative reduction of 25 %**

Slika 5. **Dijagram funkcije površine cijelog područja grešaka na kovanoj površini u odnosu na brzinu gornjeg ukovnja i početnu temperaturu kovanja za relativnu redukciju od 25 %**

RESULTS OF EXPERIMENTAL TESTS

Below, selected results of experimental tests are presented, as a verification of the theoretical examination for the identical parameters of the stretch forging operation, which were taken for computer simulation of closing up of metallurgical defects.

The performed tests found that the best effect of closing up artificially made defects was obtained during forging in asymmetric rhombic anvils (Figure 8.), whereas forging in radial anvils (Figure 7.) turned out to be totally undesirable. The testing results confirmed the conclusions of theoretical analyses that recommended the use of shaped anvils in the initial stage of the forging process, as these do not cause a dramatic forging-through into the material and a large material extension toward the planes not limited by the anvil surfaces.

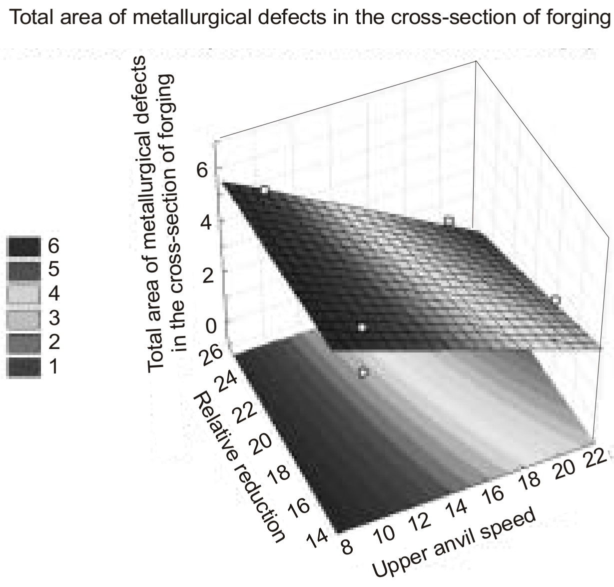

Figure 6. **Diagram of the function of the total surface area of defects on the forging surface versus the upper anvil speed and the relative reduction for a forging starting temperature of 1250 C**

Slika 6. **Dijagram funkcije površine ukupnog područja grešaka na kovanoj kovane površini u odnosu na brzinu gornjeg ukovnja i relativnu redukciju za početnu temperaturu kovanja od 1250 °C**

After having been pre-forged with shaped anvils, the material is forged out at the borders and does not flow so freely as it does during forging in the both stages in flat anvils. As a result, in flat anvils used as finishing anvils, the material forges throughout closing up the artificially made defects that have not been lost to the borders of the material (Figure 8.).

Often, the use of flat anvils for pre-forging in industrial practice causes the holes not to flatten and, under the effect of metal flow, pass toward the planes not limited by the anvil surface during free forging [8]. In that case, it is purposeful to use shaped anvils in the initial stages of forming a forging.

After deformation in asymmetrical rhombic anvils and then in flat anvils, the artificially made defects have closed

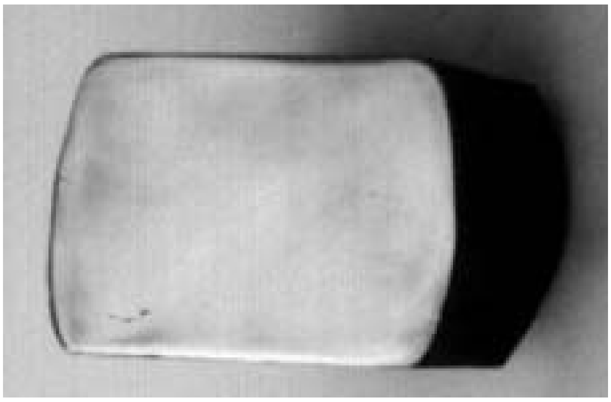

Figure 7. **View of a macrosection forged initially in radial anvils, and then in flat anvils**
Slika 7. **Pogled na makrostrukturu iskovanu najprije u radijalnim nakovnjima a onda u ravnim nakovnjima**

up entirely (Figure 8.). In contrast to the theoretical model (Figure 3.), in the physical model, where finishing forging in flat anvils was no longer used, a closure of simulated

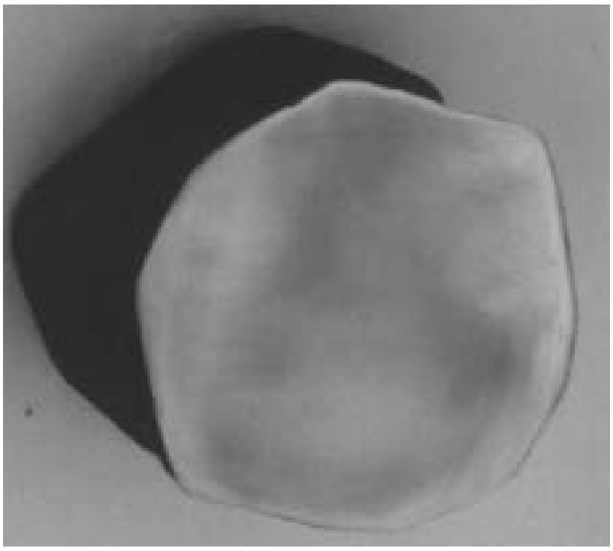

Figure 8. **View of a macrosection forged initially in asymmetrical rhombic anvils, and then in flat anvils**
Slika 8. **Pogled na makrostrukturu iskovanu najprije u asimetričnim romboidnim nakovnjima, a zatim u ravnim nakovnjima**

defects is already visible after working in shaped anvils. On the other hand, the defects deformed in radial anvils were curvilinear in character and, as a result of an undesirable metal flow kinematics, which is caused by flat anvils, were displaced onto the forging borders (Figure 7.).

CONCLUSIONS

On the basis of theoretical examination and experimental tests it can be stated that the use of shaped anvils in pre-forging operations has a favorable effect in terms of improving the homogeneity of strain intensities over the cross-section of a forging, as well as in terms of the removal of defects of metallurgical origin. This is important in view of the fact that free forging operations carried out so far in Polish forges have only used either flat or combined anvils.

Investigation results obtained in the study indicate that we are able to substantially control the kinematics of metal flow during a forging forming process with tool shape and the proper technological parameters of the forging process.

The uniform character of deformation which is achieved in the initial stages of forging ingots in shaped anvils has a favorable effect on closing up of defects and discontinuities of metallurgical origin. The presented results of investigation suggest that flat anvils should be used during the final forging stages to improve the elimination of defects, such as central porosity.

The use of asymmetry in the application of an external load in the initial stage of forging favourably influences the process of closing up of metallurgical defects.

A statistical analysis performed by the experiment planning method has found that the best results in terms of defect closing-up are achieved for a relative high reduction of 25 %, an upper anvil speed of approx. 20 mm/s, and high forging starting temperatures in the order of 1250 °C.

Heating ingots up to a temperature of 1250 °C prior to starting forging operations, as opposed to the present industrial practice, where ingots are heated up to a maximum temperature of 1150°C, is also desirable.

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