SIMULATION-AIDED INVESTIGATION OF THE EFFECT OF A PRE-FORMING PROCESS ON THE INITIATION OF CRACKS, THE REQUIRED FORGING FORCES AND MATERIAL FLOWLINES FOR MINING GROUND SUPPORT CLAMPS' MANUFACTURE USING THE HOT-FORGING TECHNIQUE

S SIMULACIJO PODPRTA RAZISKAVA VPLIVA PROCESA PREDOBLIKOVANJA NA NASTANEK RAZPOK, ZAHTEVANIH SIL KOVANJA IN LINIJ TEČENJA PRI SPONAH RUDARSKIH PODPOR, IZDELANIH Z VROČIM KOVANJEM

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In this study, the influence of the number of forging stages on the crack formation and forging forces in the hot-forging process for mining support clamps that were produced from 31Mn4 material was investigated. In this context, a single-stage process has been considered and a multiple-stage forging process that included a pre-forming stage was fictionalized with the aim of preventing crack formation by obtaining crack-formation zones. It is aimed to improve the toughness properties of the final product by ensuring that the material flow lines are obtained in accordance with the product geometry as well as preventing the formation of cracks by the forging process design, including the preforming step of the mining support clamp. Designed dies and workpieces were simulated using the finite-volume method. According to the simulation results of forging process, the stress and strain variation of materials is obtained as max. 229 MPa and 3.969 MPa. Damage analysis of the sample with effective stress and strain is exposed as 0.438-1.0 flash surface of material. The increase in the forming step decreased the forging forces per step and the crack formation was prevented and the material flowlines can be arranged in accordance with the product geometry in the presence of the preforming stage in the hot-forging process and that this regulation has a reducing effect on the forging forces. The material flowlines of the samples obtained from real production were examined and validation of the simulations and actual production was provided.

Keywords: Toussaint-Heintzmann mining support clamp, hot forging, pre-forming, Cockroft-Latham simulation

Avtorji v prispevku opisujejo študijo vpliva števila stopenj kovanja na nastanek razpok ter sil pri procesu vročega kovanja med izdelavo spon rudarskih podpor, izdelanih iz jekla 31Mn4. Raziskovali so enostopenjski in večstopenjski proces kovanja. V drugem primeru so izvedli namišljeno predoblikovanje z namenom preprečevanja nastanka razpok v conah preoblikovanja. Namen naloge je bil izboljšati žilavost končnega izdelka z zagotavljanjem ustreznih linij tečenja v skladu z geometrijo izdelka, kakor tudi preprečevanje nastanka razpok med oblikovanjem v procesu kovanja, vključno s fazo predoblikovanja spon rudarskih podpor. Simulacije dizajna orodij in odkovkov so izvedli z metodo končnih volumnov. Rezultati simulacij procesa kovanja so podali variiranje napetosti in deformacij z maksimalnimi vrednostmi 229 MPa oz. 3,969 MPa. Analiza poškodb vzorca pri efektivnih napetosti in deformacijah 0,438-1,0 se je pokazala kot bleščeča površina materiala. Povečanje števila stopenj oblikovanja je zmanjšalo možnosti za nastanek razpok in linije tečenja materiala so potekale v skladu z geometrijo izdelka, kar je tudi zmanjšalo sile kovanja. Linije tečenja materiala so avtorji prispevka preverili tudi na vzorcih v pogojih dejanske proizvodnje in jih ocenili oz. primerjali z rezultati simulacij.

Ključne besede: Toussaint-Heintzmannove spone rudarskih podpor, vroče kovanje, predoblikovanje, Cockroft-Lathamova simulacija

1 INTRODUCTION

The magnitude of the investment capital in mining activities is important thanks to the properties of increasing employment and providing raw material for the industrial sectors.[1] Underground mining is a sector in which the studies based on reliability and productivity are conducted by mainly the mining engineering and other engineering disciplines due to the fact that it is the most risky profession in the world. The difficulty of the underground conditions requires a technical and systematical work, investment and organization for the mining activities to be able to be carried out.[2–4] A significant part of the fatal accidents occurring in mining happens due to the fall of materials such as stone-coal and the collapses occurring in a direct or indirect way and this condition directly shows the importance of ground supports. It is absolutely necessary that the ground-support systems are used for the underground orifices to have long-life span and to allow working in a safe way during its service life.[5]

Forging is defined as the metal-forming method in which the workpiece is placed between the dies and the desired product shape is given under the pressing forces.[6,7] Hammers and presses are used during the forging process. The forging processes are used for the purpose of giving outstanding mechanical properties to the piece to be produced and realizing the production with a minimum rate of waste. The process starts with the workpieces having a basic geometry compared to the final product. The workpiece is subjected to plastic deformation in one or more operations and pieces with complex shapes are attained. While the forging processes give superior mechanical properties to the materials, compared to other production methods, some manufacturing defects could be observed as a result of the incorrect mounting of the forging process design.[6]

The forging process is the most popular method in metal forming. A significant part of the industrial pieces are produced by forging thanks to their conformity to mass production and the ability to give superior mechanical properties. The parameters such as temperature, raw-material geometry and die designs are efficient in increasing the quality of the products and decreasing the manufacturing costs.[7] The process of forming the geometry of a workpiece having a shape close to the final product geometry in hot forging is called as pre-forming. While the pre-forming process ensures a reduction in the material waste depending on the flash formation and the significant decrease in the machining processes, it decreases the die stress.[8] The performance of the designs of the pieces that is planned to produce with forging according to trial and error causes a great loss of time and manufacturing costs. The foreseeing of the material flow is only possible with computer-aided simulations.[7]

An important issue in metal shaping is being able to carry out the desired deformation without causing damage to the workpiece. Although the materials are formed without any crack with the empirical experiences of the designers in the industrial applications, sometimes high-cost trial and error productions are needed.[9] For this reason, foreseeing and preventing damage are the main properties in the forming process and the determination of the product quality.[10]

Today, new products and manufacturing methods are developed for the purpose of attainment as a result of low costs and short production processes. Although the design and optimization of the forming process are generally conducted by professionals having experience in the manufacturing operations, it is still obligatory for them to conduct trial and error. The use of numerical simulations for the purpose of avoiding this experimental procedure is an important tool for the improvement and development of the forming process.[11,12]

Most metal-forming methods are limited due to the internal or surface cracks of the workpiece.[10] Increasing the strength of the workpiece without any damage with

plastic deformation is limited to formability. The formability of the materials are followed by the workability of that material.[13] If the conditions causing the crack during the deformation of the workpiece could be foreseen; convenient process conditions could be selected, forming process could be changed and tough products could be obtained.[14,15]

In this study, the condition of real production in single or multiple stages by conducting the hot-forging simulations of the bottom-clamp component used in Toussaint-Heintzmann (TH) ground support systems with the infrastructure of finite volumes method has been examined within the direction of Cockroft Latham critical damage theory. Within the scope of the study, which has been conducted for the purpose of improving the surface, physical and mechanical properties of TH34 bottom-clamp which will be manufactured by the hot-forging processes and revealing the optimized sections; the process design, press selection, effect of raw material preparation, die design, final product geometry and the simulation of all the process and the material flow during the plastic deformation and the residual stress-strain distribution have been determined by examining the impact of temperature and the verification of the design has been ensured by pilot productions with the use of parameters attained as a result of the optimization works.

2 EXPERIMENTAL PART

The 31Mn4 steel is used in accordance with the DIN 21530-3 standard used for the final product within the scope of the study.[16] The chemical composition of the steel is shown in **Table 1**.

Table 1: Chemical composition of 31Mn4 according to DIN 21530, in mass fractions (*w*/%)

C	Si	Mn	P (max.)	S (max.)	Al (min.)	Cu
0.28-036	0.2-0.5	0.8-1.1	0.035	0.035	0.02	0.35

The DIN 21530 standard that determines the structure and properties of the ground support systems that also includes the TH supports is the standard that regulates the issues related to the quality and safety of the mine pit supports in the underground mine pits. It could also be used for the ground support of the space areas under the ground having no relation with mining and it ensures the realization of the function of the mine-pit supports in accordance with the plan both in terms of safety and operation by taking the standards into consideration. The TH34 Bottom clamp has been modeled with the use of the Solidworks 2014 program according to the measurements **in Table 2** within the direction of DIN 21530-2 standard and the image belonging to the attained design is shown in **Figure 1a**.[17]
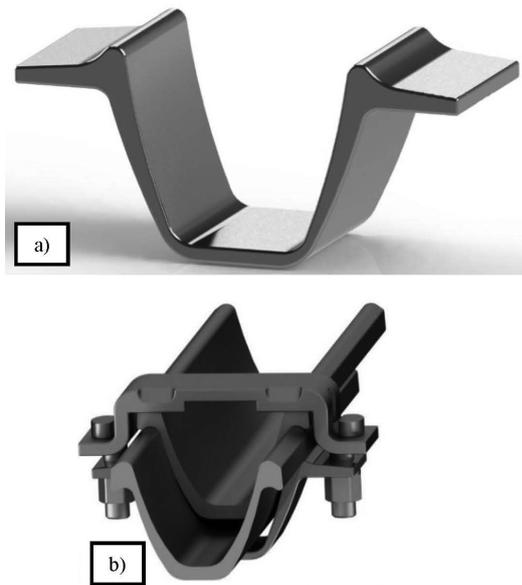
Figure 1: a) TH34 bottom clamp solid model, b) TH34 ground support assembly solid model

Figure 2: 31Mn4 material flow curves created in the JmatPro program

Table 2: TH34 Bottom Clamp Dimensions According to DIN 21530

Bottom clamp	Profile class	a (mm)	b (mm)	c (mm) min.	$\varnothing d$ (mm)
G400 - G40	34	212^{+2}_{0}	212^{+1}_{-4}	111	30

In **Figure 1a** following the design of the final stage of final product of TH34 bottom clamp has been dealt during the stage of the hot-forging process. The flash design of the forged piece was conducted by taking as the basis the equations developed by Voigtlander, Doege and Awiszus and the sections and forging dies belonging to all the other stages have been designed.[18–20] Following the determination of the flash dimensions, a shrinkage allowance of 1.5 % has been given to the final product geometry in the forging design of the final product for the purpose of meeting the volume changes of the

material during cooling.[21,22] The sections and forging dies have been designed by taking the design principles of hot-forging dies.[20–23]

The 31Mn4 flow curves shown in **Figure 2** by using 31Mn4 alloy properties as input in the JmatPro program environment have been attained for usage in simulation works. The 31Mn4 alloy formed in the computer environment has been integrated in Simufact forming program.

Hot-forging simulations of the TH34 bottom clamp used in Toussaint–Heintzmann ground supports within the scope of simulation activities and process optimization works have been carried out within the direction of the parameters shown in **Table 3**.[24]

Kang et al. and Han et al. analyzed the friction behavior by using the Coulomb friction model in the environment of FE simulations.[7–9] However; because this model loses its validity in the event that the friction sliding stress increases the material shearing strength, its implementation area is limited. A constant sliding fric-

Table 3: Process parameters used in simulation studies

Simulation 1 and 2		Simulation 3	
Number of stage	1	Number of stage	3
Type of raw material	31Mn4	Type of raw material	31Mn4
Raw material temperature	1200 °C	Raw material temperature	1200 °C
Die temperature	350 °C	Die temperature	350 °C
Ambient temperature	50 °C	Ambient temperature	50 °C
Friction factor	0.1	Friction factor	0.1
Mesh type	Surface mesh	Mesh type	Surface mesh
Mesh element type	Triangles	Mesh element type	Triangles
Mesh element size	2 mm	Mesh element size	2 mm
Mesh element count		Mesh element count	
Simulation 1	13748	First pre-forming stage	13748
Simulation 2	14086	Second pre-forming stage	36460
-	-	Finisher forging stage	92378
Press Type and Tonnage	Friction press 1200 t	Press type and tonnage	Friction press 1200 t

tion model is frequently used in 3D FE simulations of the forging process.[10–15]

The deformation processes in the industrial applications were applied according to the experimentally determined ductile fracture criterion. Today, the Cockroft-Latham damage criterion has become convenient for the metal-forming simulations. Generally, the critical damage value is taken as equal to the flow limit of the material. However, Cockroft and Latham have not explained the issue of whether critical damage value is dependent on the temperature and strain rate.[5,9] By using the Cockroft-Latham criteria, the fracture formation risk of the formed piece could be examined.

Cockroft and Latham have developed the accumulated damage theory in which variable loading conditions could be successfully applied.[12–14] As a result of many studies conducted by Cockroft and Latham, they have examined the change between the applied equivalent strain and the effective stress (σ) of the maximum tensile strength (σ_T) of the damage in plastic deformation, in Equation (1):

$$C = \int_0^{\bar{\varepsilon}_f} \frac{\sigma_T}{\bar{\sigma}} d\bar{\varepsilon} \tag{1}$$

$\bar{\varepsilon}_f$ is the total equivalent strain at the end of forming process.

The magnitude of C should not exceed C_{max} (critical damage value) for the non-occurrence of any damage. When the C value is compared to C_{max}, material damage risk is assessed during the process. Equation (1) should be turned into a separate expression that is convenient for FE code for the purpose of calculating the C value with FE simulation, Equation (2):

$$C = \int_0^{\bar{\varepsilon}_f} \frac{\sigma_T}{\bar{\sigma}} \frac{d\bar{\varepsilon}}{dt} = \int_0^{t_f} \frac{\sigma_T}{\bar{\sigma}} \dot{\bar{\varepsilon}} dt \cong \sum_0^{t_f} \frac{\sigma_T \dot{\bar{\varepsilon}} \Delta t}{\bar{\sigma}} \tag{2}$$

where $\dot{\bar{\varepsilon}}$ is the equivalent strain rate as Equation (1) calculated from the individual principal strain-rate components, and Δt is the variable time increment used in the FE analysis. Cockroft Latham constant (C_{max}) is dependent on the same material parameters on which the forming limits are dependent. While the metallurgical properties such as microstructure, alloy constant, grain dimension and particle structure and non-metallic inclusion content have a little impact on the strength and hardness, they have a significant impact for the critical damage value.[15] In order to predict the occurrence of surface fracture, the value of the Cockroft-Latham equation expressed by means of Equation (1) is calculated at the integration point inside the elements.

A symmetrical half of the piece has been taken for the purpose of shortening the solution period in all the simulation works due to the fact that the TH34 bottom clamp aimed to be attained in hot-forging simulations has a symmetrical geometry. The workpiece attained at the end of each forging stage has been used as the input of the next stage, together with all the deformation properties. In simulation 1 and simulation 2, the raw material with the dimensions Ø50 × 286 mm has been forged at a single stage, as shown in **Figure 3a**.

In simulation 3, the section designs of the forged piece were conducted within the direction of the principle of volume stability, die designs convenient for the section designs have been made and the forging process has been realized in three stages, as shown in **Figure 3b**. The optimized parameters of simulation 3 were used in the pilot production without any modification and the bottom clamp was manufactured, as shown in **Figure 4**.

In order to observe the forging flowlines in the process of deformation of the workpiece, the specimens were prepared by using a wire erosion machine which were manufactured by the hot-forging method. In accordance with the ASTM E381-01 standard, 50 % HCl and 50 % purified watered etchant was prepared. The specimens were macro-etched for 15 min at 80 °C in a temperature-controlled heating table.
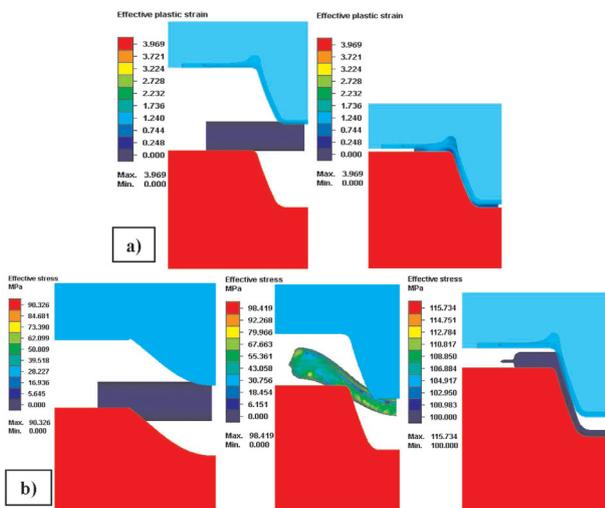
Figure 3: Schematic view of simulations: a) simulation 1 and simulation 2, b) simulation 3
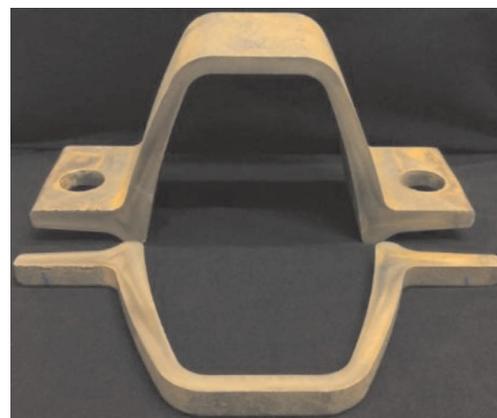
Figure 4: TH34 bottom clamp after pilot production

3 RESULTS

Analyses have been realized for simulation 1 fictionalized within the direction of the process parameters shown in **Table 3** and the effective stress, effective strain and critical damage value results belong to simulation 1 are shown in **Figure 5**. As shown in **Figure 5**, the unfilled zones of the die as a result of the forging of the raw material with the dimensions Ø50 × 286 mm at single stage and the zones with the critical damage value regarding Cockroft-Latham criterion in **Figure 5**.

Because it is clear that the die has not been filled within the direction of the results attained in simulation 1, the raw-material dimensions were increased as Ø50 × 292 mm and simulation 2 has been carried out.
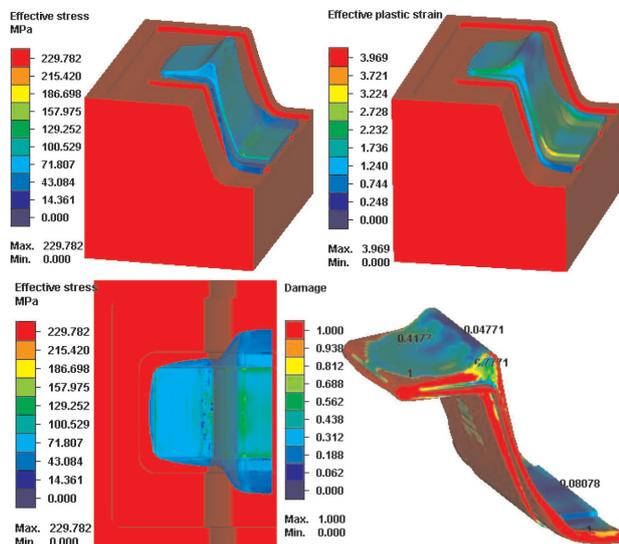
Figure 5: Effective stress, plastic strain and critical damage value distribution in simulation 1
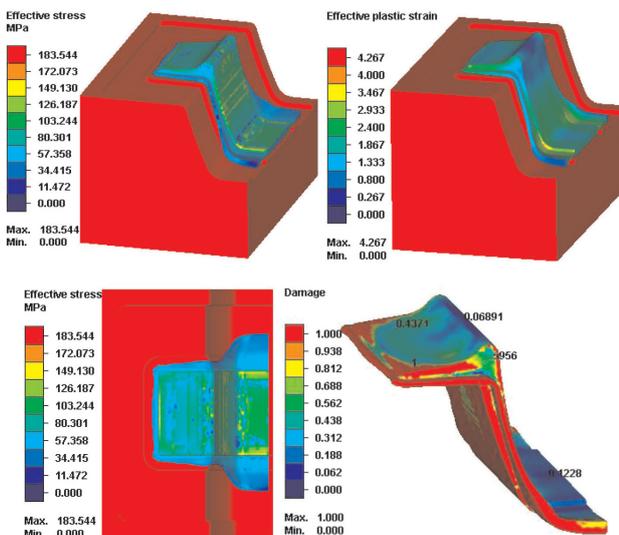
Figure 6: Effective stress, effective plastic strain and critical damage value distribution in simulation 2
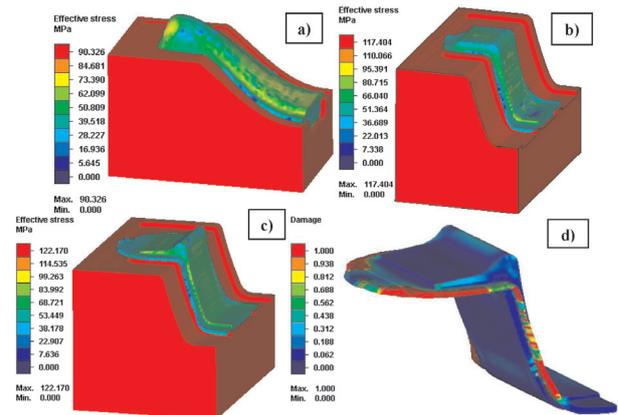
Figure 7: Effective stress and critical damage values: a) first pre-forming stage, b) second pre-forming stage, c) finisher forging stage

The effective stress, effective strain and critical damage value results attained as a result of simulation 2 are shown in **Figure 6**.

It is clear that the die has been completely filled. as shown in **Figure 6**, in the forging process realized with the raw material with the dimensions Ø50 × 292 mm. The zones having critical damage value regarding Cockroft-Latham criterion are shown in **Figure 6**.

The flow lines have been added to the material section during the forging process in simulation 2 and the final situation of the material flow attained as a result of the forging process at single stage is shown in **Figure 8**.

Analyses were carried out for simulation 3 fictionalized as forging of the raw material with the dimensions Ø50 × 286 mm in three stages within the direction of the
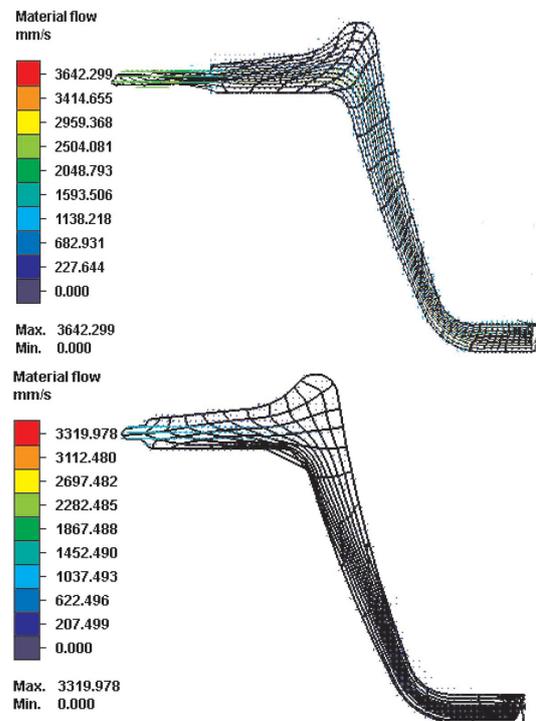
Figure 8: Material flow and flowlines results in simulation 3 and simulation 2
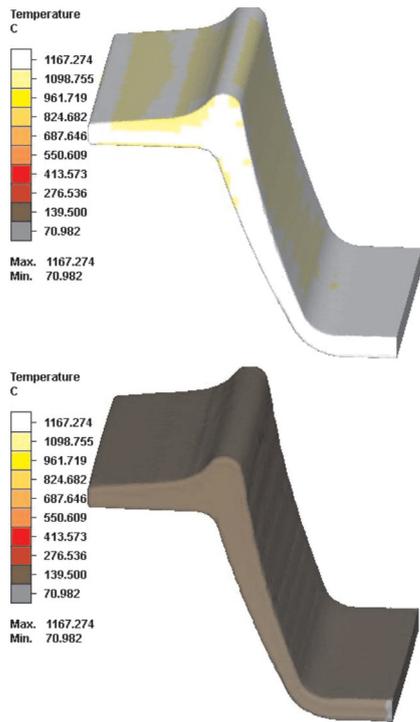
Figure 9: a) Clamp temperature distribution after forging, b) clamp temperature distribution after cooling

process parameters shown in **Table 3** and the results belonging to simulation 3 are shown in **Figure 7**.

It was observed that the die has been completely filled, as shown in **Figure 7**, in the forging process realized with the raw material with the dimensions Ø50 × 286 mm. The zones having critical damage value regarding the Cockroft-Latham criterion are shown in **Figure 7d**.

Flow lines were added to the material section during the forging processes in simulation 2 and simulation 3 and the final situation of the material flow attained as a result of the forging process is shown in **Figure 8**.

The forged piece attained at the end of simulation 3 has been taken to the trimming die for the purpose of taking its flashes and this process has been carried out. The TH34 bottom clamp with high temperature shown in **Figure 9a** was cooled down in air with the ambient temperature of 50 °C and the distribution of the surface temperatures regarding the clamp attained at the end of the cooling of 30 min is shown in **Figure 9**.

The force and energy data regarding the hot-forging simulations are shown in **Table 4**.

Table 4: Force and energy data regarding the hot-forging simulations

Simulation name	Stage name	Stroke (mm)	Force (kN)		Energy (kJ)
			Bottom die	Top die	
Simulation 1	Finisher forging	140.4	−13449.8	14081.4	65.6
Simulation 2	Finisher forging	140.4	−18963.5	19299.9	71.3
Simulation 3	First pre-forming	61.52	−2208.5	1965.7	14.6
	Second pre-forming	91.97	−11743.3	12033.8	34.3
	Finisher forging	26.3	−15270.1	15216.2	27.6

As shown in **Figure 4**, the TH34 bottom clamp was produced by using the hot-forging process and the macro-etching sample was obtained according to the standards. The regions where the material flowlines are observed and the flowlines obtained as a result of the macroscopic examinations are shown in **Figure 10**.

4 DISCUSSION

Section and die designs have been completed for the hot-die forging processes planned to be carried out in single and multiple stages and realized upon the final product measurements of the TH34 ground support bottom clamp. According to the performed designs, the
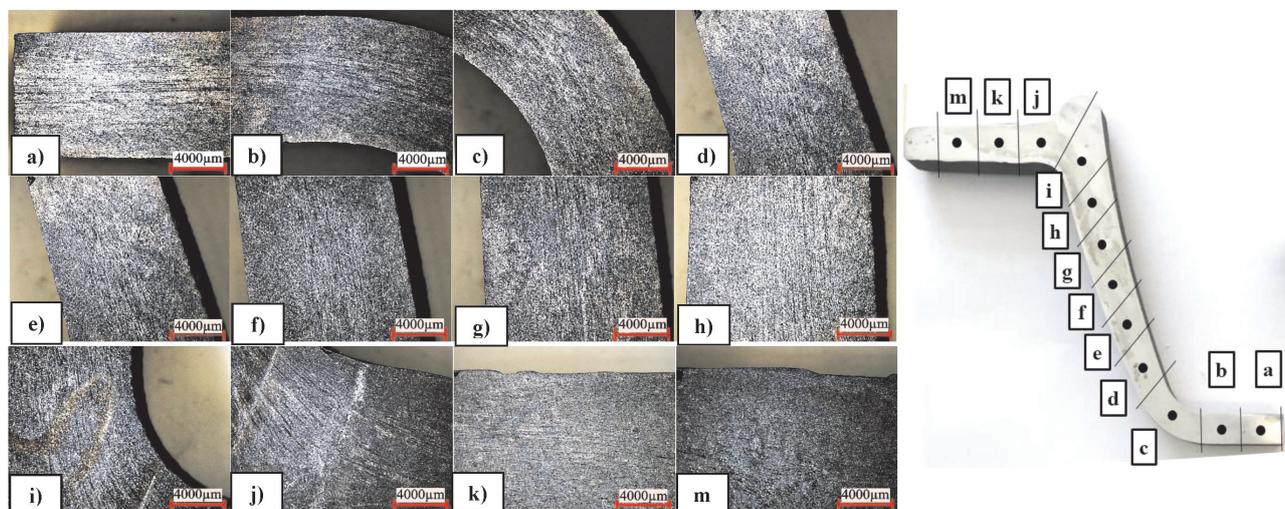
Figure 10: Macroscopic flowlines examination after the macro-etching process

installation of the simulation was completed and the following results were obtained:

Firstly, the flash design has been carried out within the direction of the forged piece design made according to the volume calculation principles of hot forging die making and it has been determined that the flash dimensions should be 4 mm × 16 mm according to the calculation made according to Voigtlander, Doege and Awiszus and the volume of the raw material should be 561,560 mm³ within the direction of the fact that the shrinkage allowance peculiar to steel material should also be given.[19,20]

It has been determined that the shrinkage allowance added to the piece in the forging design has been correctly assigned, as seen in the measurements as a result of cooling the workpiece in air at the end of hot-forging process.[25]

When simulation 1 which includes the forging of the workpiece with the dimensions of Ø50 × 286 mm in single stage is examined; it has been determined that 13449.8 kN forging force has an impact on the bottom die and 14081.4 kN forging force has an impact on the upper die. It has been determined that 65.6 kJ is needed for the production of the TH34 bottom clamp with hot die forging method from the workpiece with the dimensions of Ø50 × 286 mm. As can be seen in **Figure 5**, as a result of the forging simulation, it has been observed that the flash formation increases in the base zone of the material due to not being able to direct the material flow and for this reason, the die is not filled. The critical damage value of this piece forged in single stage and the zones with the probability of damage formation have been examined. It has been determined that the Cockroft-Latham critical damage value reached 1 and the zones with the probability of damage formation include the majority of the material.

The volume of the raw material has been increased by 11781 mm³ for the purpose of being able to terminate the deficient filling problem of the die in simulation 1 and simulation 2 has been realized. When the results of simulation 2 has been examined; it has been determined that 18963.5 kN forging force has an impact on the bottom die with an increase of 41 % and 19299.9 kN forging force has an impact on the upper die with an increase of 37 %. It has been determined that 71.3 kJ is needed for the production of the TH34 bottom clamp with the hot die forging method from the workpiece with the dimensions of Ø50 × 292 mm. As can be seen in **Figure 6**; as a result of the forging simulation in which the volume of the work piece has been increased by 11781 mm³, it has been observed that the die has been completely filled. The critical damage value of this piece forged in single stage and the zones with the probability of damage formation have been examined. It has been determined that Cockroft-Latham critical damage value reached 1 and the zones with the probability of damage formation include the majority of the material.

When simulation 3, which includes the forging of the workpiece with the dimensions of Ø50 × 286 mm in 3 stages, was examined, it was observed that the final stage die has been completely filled, flash formation has been distributed in a more homogenous way when compared to simulation 1 and simulation 2. When the forces having impact on the dies belonging to 3-stage forging simulation have been examined; it has been determined that 15270.1 kN forging force has an impact on the bottom die and 15216.2 kN forging force has an impact on the upper die at the final forming stage in which the greatest forces occur. It is shown in **Table 4** that the maximum energy requirement is 34.3 kJ in the 3-stage forging process for the production of TH34 bottom clamp. When the critical damage value of this piece forged in three stages and the zones with the probability of damage formation have been examined; it has been determined that Cockroft-Latham critical damage value has reached maximum 1 in the flash zone as shown in **Figure 7c** and the maximum critical value is 0.5 in the areas covering the clamp. As a result of the attained data, it is expressed that the amount of Cockroft-Latham criterion is within the range 0.7-0.8. The flashes of the forged piece have been taken in the trimming die following the realization of the hot die forging process of TH34 bottom clamp. The forged piece has been cooled for 30 min in the ambient temperature of 50 °C. At the end of 30 min, it has been determined that the temperature is 80 °C in the maximum zone of the surface temperature as shown in **Figure 9** in which the distribution of the surface temperatures of the forged piece is given. It has been observed that the zones in which critical damage may occur are not existent in the clamp examined at the end of the trimming and cooling process.

When the formation of the material flow lines belonging to the products attained as a result of simulation 2 and simulation 3 have been examined, it was clear that the material flow lines attained in simulation 2 are not in accordance with the final product geometry. The attainment of the flow lines in accordance with the product geometry has an importance in the improvement of the strength and toughness of the product attained with forging.[6] When the material flow attained in simulation 3 has been examined, it is seen that the material flow in accordance with the final product geometry has been realized. It has been determined that when the flow lines at the end of the macro-etching processes of the samples taken from the pilot production performed in the direction of the parameters obtained in Simulation 3 are examined, similar material flow lines are obtained with simulation 3.

5 CONCLUSIONS

It has been determined that subjecting the raw material belonging to the piece to be produced with mould hot forging method to the pre-forming stage is an

important factor in attaining the minimum forging forces and the minimum raw-material wastes and with the impact on the complete filling of the die.

It is seen that in the hot-forging process, determining the forging steps in such a way that the total forging force required for the forging operation is evenly as distributed as possible is the most suitable method for forging operations.

The direction of the material flow in the forging in accordance with the final product geometry both improves the mechanical properties of the final product and it also decreases the energy needs during the forging process.

While the increase in temperature decreases C, which is the strength constant, it increases the strain-rate sensitivity (m). Because the forming process is applied at high temperatures, it is necessary to decrease the deformation speed as much as possible. The attainment of products is possible with a press or hammers with low capacity by increasing the forging stages and decreasing the energy needs per stages in the conditions in which the infrastructure of the establishment is insufficient in the attainment of the pieces planned to be produced in the hot-forging industry.

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