International Journal of Engineering, Management, Humanities and Social Sciences Paradigms (Volume 30, Special Issue of Nov 2018)
ISSN (Online): 2347-601X and Website: www.ijemhs.com

Review of the Study of Hot Forging Process Defects

Sai Gani Prasad [1*], Nabanit Panigrahi[2]

[1*]Professor, Department of Mechanical Engineering, Nalanda Institute of Technology, Bhubaneswar, Odisha, India

[2] Associate Professor, Department of Mechanical Engineering, Nalanda Institute of Technology, Bhubaneswar, Odisha, India

*Corresponding author e-mail: saiganiprasad@thenalanda.com

Abstract: **There is no information regarding the modelling of such faults using FEA software. The main problems are the formation of under fills due to air pockets between the forging and the tool. Thus, efforts are needed to create a numerical simulation of the process under analysis. The creation of a laminated crack defect that was discovered during the upsetting of a massive disk-shaped forging is the subject of a review research. Together with the distribution of stress, equivalent strain, and strain rate, the numerical stimulation review is investigated. To investigate the unconditioned deformation under trilateral compression, the distribution diagram of the stress state evaluation is examined. The primary cause of laminated crack defects is this. Large product surface cracks are repaired using the hot scarfing procedure after temporarily pausing the forging operation. Moreover, the forging process, which adds significant flaws, affects fatigue strength. This aids in identifying the areas of surface integrity that have the greatest impact on fatigue. Surface roughness, significant flaws, residual stresses, microstructure, and hardness are all pertinent to the main review. This paper's major goal is to evaluate the process used to create these faults and the research done to analyse it.**

Keywords: Hot forging, forging defect, surface crack, laminated crack, finite element method

1. Introduction

Material deformation is processed during forging using compressive stress. It can be done in a warm or chilly environment. The metal is heated to the appropriate or necessary temperature to achieve the plastic deformation during forging, which is a hot working process. A substance must be heated to the appropriate temperature. Burning a substance causes cohesiveness between atoms to be destroyed because of the high temperature. The temperature at which hot forging is performed must be higher than the recrystallization temperature, usually 0.6 Tmelt or higher (where Tmelt is the melting temperature). The temperature range for warm forging is between 0.3 and 0.5 Tmelt (Table.1). Lower loads are needed for hot forging [21] because flow stress decreases with increasing temperature. In hot working, strain rates could range from 0.5 to 500 s-1. Hot forging strains are The accurate production of forgings with complex shapes (connecting rods, worm gears, constant-velocity universal joints, turbines, levers, etc.) that meet the high quality standards of the customers takes a great deal of knowledge from designers, technicians, and machine operators. In an era of heightened global competition, forging enterprises work to minimise trash components through reliable procedures [18]. Careful process design utilising numerical methods can result in stable processes. There is a chance that a mistake will be made during each step of the forging process, leading to a flaw or forging defect. [16] For this reason, the entire forging process is designed and optimised using a variety of CAD/CAM/CAE tools (often based on FEM and physical modelling) and specialised measuring-control systems. [21,16]

Table.1.Forging Temperature of Various Materials

		Forging Temperature	
Sr No.	**Material**	**At start in 0^0 C**	**At start in 0^0 C**
1	Mild Steel	13300	800
2	Medium Carbon Steel	1250	820
3	High Carbon Steel	1180	850
4	Wrought Iron	1300	900
5	Stainless steel	1300	920
6	High Speed Steel	1300	950
7	Cu and its Alloys	850	680
8	Al and Mg Alloys	480	350

2. Investigation of actual forging Defects

Identify defects in selected die forging processes

In die forging processes the proper spacing of cross-sectional areas along the length of the straight axis of the preform (slug) and the preparation of the latter through forming is highly important for the proper filling of the cavity die by the material. Most of the cases the most common forging defects (underfills, folds) are the result of the improper geometry and/or incorrect position of the preform or the slug on the die insert. The ways in which defects propagated in the numerical model and in the physical model were compared. Numerical FEM modeling is used mainly to determine the optimal shape and dimensions of the preform and the slug. This is required when the forging has a complicated shape, as in the case of turbine blades, toothed gears, forked forgings, etc [19]. Most researchers and experienced forging engineers are inclined to agree that the most common forging defects (underfills, folds)[1] are the result of the improper geometry and/or incorrect position of the preform or the slug on the die insert. Such errors are often due to the unavailability of a particular bar section from the steel works or the lack of proper equipment resources for slug preparation. There are plenty of studies and papers on the selection, design and optimization of billet geometry, but only a few works are devoted to the application of numerical FEM modeling to the analysis of the causes of forging defects. Numerical FEM modeling is used mainly to determine the optimal shape and dimensions of the preform and the slug. This is required when the forging has a complicated shape, as in the case of turbine blades, toothed gears, forked forgings, etc. Today forges most often use numerical software based on FEM [3] to analyze the problem connected with the improper geometry and/or position of the preform. The producers of the current computing packages equip them with ever new functions enabling even better and more complete analyses of plastic working processes, making it possible, e.g., to detect defects in forgings and to analyze the durability of the tooling.[1,3]

Best example for these defects i.e. underfills the operations of forging lever, the operations of forging lever and complicated in their shape conducted in Forge Jawor were subjected to analysis.Fig.1. Then numerical thermomechanical models were built for the two forging processes and numerical FEM simulations were run using the Forge 2011 computing package. [1, 3]

Fig.1. Lever forging after trimming

Defects in analyzed Lever forging

The macroscopic examinations of the lever forging showed numerous defects in the form of folds and cavity die underfills.Fig.2 show the forging with a marked underfill and Fig.3 show a place with a lap.[12]

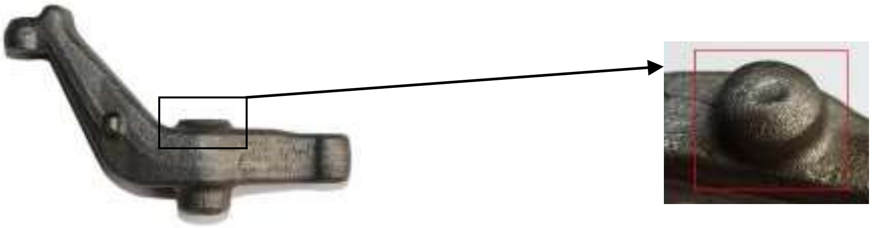


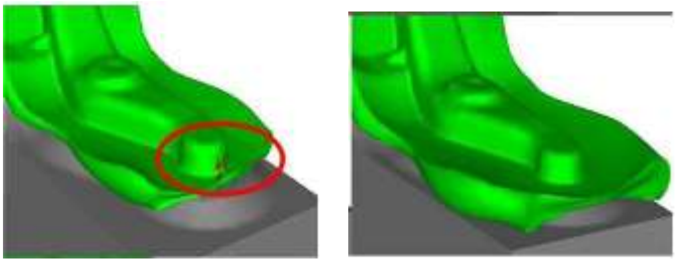
Fig. 2. Defects in lever forging: Underfill in lever forging.

Fig. 3. Defects in lever forging: lap in lever foot

Underfills also occur in the forging head. In addition, an extensive lap, caused by the improper flow of the material, appears in the lever foot Structural examinations of the lap in the plane perpendicular to the crack the structure of the forging to be typical of hypoeutectoid steel. The occurrence of oxides and bits of scale coming from the forging surface in this place can cause further cracking and damage to the element.[23]

Modeling and numerical simulations

For the purpose of a more in-depth analysis of the causes of defects, numerical simulations were carried out using the finite element method.3D models of the tools (the die inserts were modeled as elements with heat exchange) and the preforms were built. The ambient temperature and the temperature of the forging were assumed to amount to 30 °C and 1150 °C, respectively. Carbon steel C45 and hot-work tool steel 1.2344 were used for respectively the forged material and the die inserts. The material specifications, i.e. thermal expansion, specific heat, thermal conductivity were taken from the Materials Forming Properties Database The studies covered the temperatures: 650 °C, 750 °C, 850 °C, 1000 °C and 1150 °C and the strain rates: 0.1 s^{-1}, 1 s^{-1} and 10 s^{-1}. The temperatures and the strain rates were selected on the basis of an analysis of the industrial processes of forging. The coefficients of heat exchange between the billet and the tools and with the environment were assumed to amount to respectively 30 W/mm^2 K and 0.35 W/mm^2 K.[1,7]



(a) (b)

Fig. 4. a)Forging moved 28 mm away from die end — lap at process end, revealed by folds function,

b) Forging moved 10 mm away — no folds.

A preliminary analysis of the FEM simulation results revealed that the position of the initial material has a significant influence on the proper filling of the cavity die. In the first case (Fig. 4a), when the billet is moved 28 mm away from the bottom insert cavity die, a lap appeared in the lever foot. This is caused by the curling of the material in the final stage of preliminary forging. Through the next numerical simulations, in which the distance from the end of the cavity was changed at every 2 mm, the optimal preform position was selected whereby folds no longer appeared in the lever foot. [23]The flow of the material was significantly improved when the slug was positioned at a distance of 10 mm from the end of the bottom insert cavity die (Fig. 4b). FEM simulations showed that the further shifting of the preform towards the end of the insert would result in an underfill in the upper part of the forging (the lever head). Fig. 4a shows the stages in the appearance and growth of folds in the tested element, revealed by the folds function.[1,23]

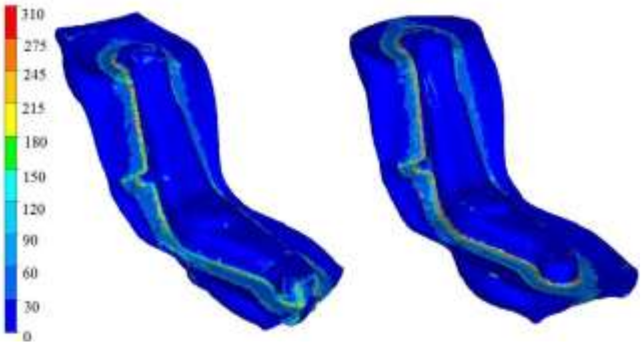


Fig. 5. Rate of flow during preliminary forging: a) lever with lap, b) lever without lap.

The material flow shown in Fig. 4 as well as the rate of material flow Fig. 5 for the different billet positions confirm the risk that a lap may appear in the lower part of the lever. An analysis of the simulation results shows that as the pressure in the closed space increases, it becomes more difficult to fill the die insert, which may result in underfills in the forging (Fig. 2).[1,23]

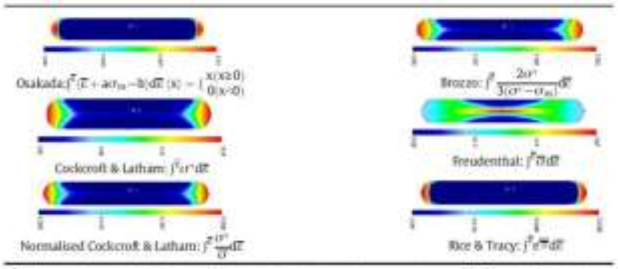
Laminated crack defect

The forming of the disk-shaped forgings is carried out by forging, and mainly upsetting. In the upsetting process, the defects of the cast dendritic microstructure and shrinkage porosity [27] will be fixed by larger forging ratio in order to improve the quality of forgings. According to the theory of plasticity, if friction is ignored, the upsetting between flats can be simplified to be the single compression. However, the existence of friction leads to complex changes of the stress–strain state in the forgings, many problems cannot be solved, and even cannot be qualitatively analyzed. Therefore, there were some misunderstandings on the upsetting of cylinder between flats in a long period of time, namely state of tri-lateral compressive stresses is always produced in the centre of deformation body, regardless the ratio of height to diameter (transient state) of the forging.[25-28]

Criterion of ductile fracture

Aiming at failure mode of engineering materials and structures, many kinds of strength theories have been proposed. Besides, many scholars have proposed different forms of expression on criterion of ductile fracture about local material failure of work piece in metal plastic forming process. Different damage results were obtained and shown in Table 2 after the finite element models of cylinder upsetting between flats were carried out using the above criterions. Table 2 shows the damage distributions in symmetry plane using different criterions of material ductile fracture in the upsetting process. Through the comparison of the above results, it can be found, except Freudenthal Criteria, [27] that other criteria's damage results are basically larger within circumferential drum area. The maximum principal stress is regarded as dominant mechanics factor of material failure for most of these criteria, which can describe crack on the surface of drum-type area of the upsetting cylinder. However, it cannot explain the laminated crack defect within the forgings. Freudenthal Criteria reflects the plastic work of material deformation. When the effect of friction is ignored during upsetting, cylindrical workpiece is the single compression deformation, and the laminated crack defect will not occur, but the plastic work evenly distributes in the work piece, and large value can be achieved too. To summarize, this criterion cannot be used for the defect.[26,27]

Table 2. Processing and simulation parameters.



σ^* is the maximum principal stress, $\bar{\sigma}$ is equivalent stress, σ_m is average stress, and $\bar{\varepsilon}$ is equivalent strain.

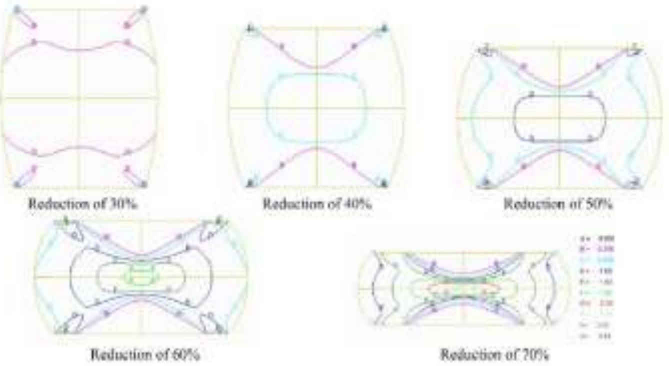


Fig. 6. Contour line distribution of the equivalent strain.

By the above qualitative analysis, deformation in the front of the rigid area has a significant effect on the production of laminated crack defect. Finite element simulation of the forging process is used for further research on the deformation mechanism of the front of rigid area under large reduction. Based on the analysis of equivalent strain of forgings during upsetting, the contour line distribution of the equivalent strain in Fig. 6 indicates that with the increase of reduction, contour line around cone-shaped top of the rigid area becomes dense, this means that the gradient of equivalent strain increases. Especially after reduction reaches 60% and 70%, contour line in front of the rigid area increases and becomes very dense. The equivalent strain rate on the central axis (ε), as shown in Fig. 7, is similar to the distribution of equivalent strain, namely the change of ε from the top to the horizontal symmetry first slowly, then faster, and then slowly increases again. After reaching a certain value, it remains basically unchanged. In the range away from the horizontal symmetry plane, equivalent strain rate remains relatively high. For instance, under reduction of 40%, the value of ε increases with the increase of reduction in a large unchanging range of equivalent strain rate, but the scope of the unchanging reduces. It indicates that deformation rapidly increases within a very small region close to the horizontal symmetry plane when a larger reduction is applied. So, it is consistent with the analysis results of equivalent strain.[25-27]

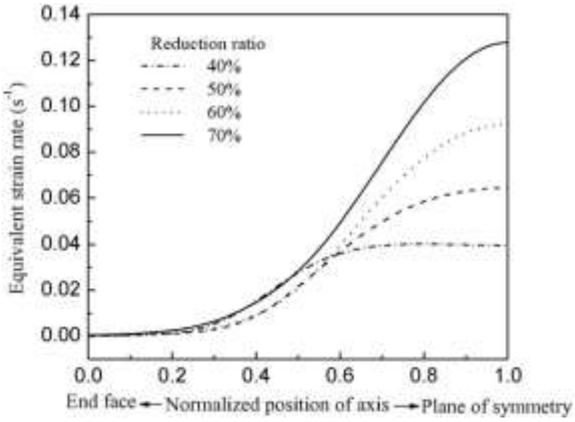


Fig. 7. Distribution of equivalent strain rate in axial direction.

Experimental verification

In order to verify reasonableness and accuracy of the combination model, casting aluminum rod with size of Φ38 × 80 mm is used in upsetting test in this study. Work piece is preheated to 300 °C, different reductions, respectively 50% and 65%, were carried out in the upsetting and the results are shown in Fig. 8.[17,27]

Fig. 8. Upsetting results under different reductions.

Fig. 9. Simulation result of morphology and distribution of laminated crack.

According to simulation results of finite element modeling based on experimental conditions, the corresponding values located at the peak of equivalent strain rate gradient on the axis are selected as critical parameters. After modeling with reduction of 65% was carried out, the simulation result of crack morphology distribution was obtained and shown in Fig.9. The upsetting test work piece was anatomized along the central axis, and observed along the central axis under the optical microscope after polishing the section. The work piece with reduction of 50% is not unusual, however, crack was found in work piece with reduction of 65%, as shown in Fig. 9. Black spots in the base material shown in Fig. 10 are the forged porosity defects. At the position of severe deformation in the axial direction, including drastic changes in the spatial location and deformation rate, pores are torn to expand and form crack.[4,5] Even for homogeneous materials without flaws, this location is also prone to be damaged under the same conditions. Fig. 10 shows the location and morphology of cracks, coinciding well with the simulation result, which indicates that the determining method of expression and threshold of model can be used to predict the laminated crack defects in upsetting process.[27,28]

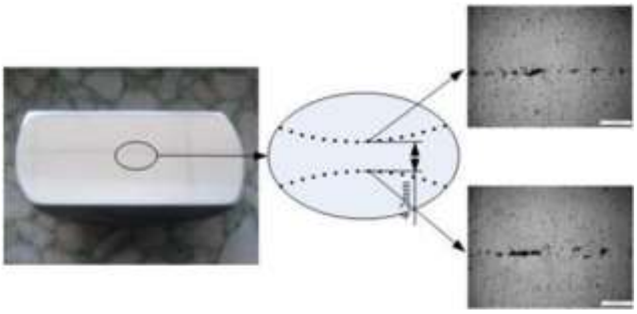


Fig. 10. Experimental result of morphology and distribution of laminated crack.

Surface crack generation in large hot forging process

Since surface cracks are regarded as significant defects, suppression of the surface crack generation is important issue. There are various factors for crack generation, such as reduction ratio, forging temperature, anvil shape, ingot surface integrity and so on. When tensile stress is applied to minor defect during forging operation, it is expected that a crack will be generated from the minor defect which is regarded as a stress concentration point. It is important to prevent minor defect generation on the surface. Cross section shape of the billet was square. The billet was heated upto 1250 °C and was kept 1hr. After that it was cooled down to about 800 °C. 800 °C was the temperature [10] that was observed a lot of surface defects in actual cogging process. Then, the billet was forged 23% reduction ratio. The billet was cut at the center of the longitudinal cross-section after the cogging test.[9.10]

Table.3. Chemical composition of test material (SF60) (wt%).

C	Si	Mn	Cr
0.45	0.25	0.80	0.15

The cross-sectional shape and metal flow of billet obtained from the experiment are shown in Fig. 11. It shows minor defect was occurred at anvil lap part. Since minor defect area had metal flow, it was suggested the possibility of preventing minor defect generation by metal flow control.[8,9]

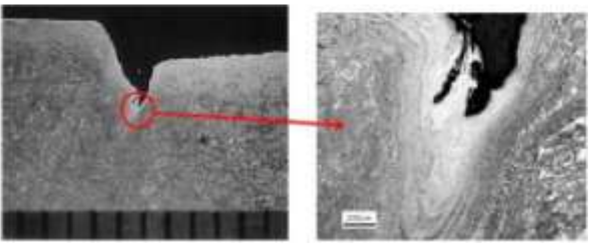


Fig. 11. Cross-sectional shape and metal flow of billet obtained from experiment.

In order to confirm deformation behavior of forged surface, simulation is applied to the cogging process using FE analysis.[12]The calculated result is good agreement with experiment one. The deforming behavior of forged surface obtained from FE analysis is shown in Fig. 12. It shows that the minor defect was formed at anvil lap part by material flow with stroke during forging.[13]

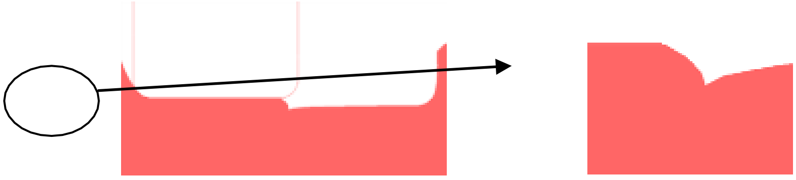


Fig. 12. Deforming behavior of forged surface obtained from FE analysis.

Relation between reduction and minor defect depth obtained from FE analysis is shown in Fig. 13. The minor defect depth is increased with increase of reduction. When the reduction is 150 mm, on the other hand, the minor defect [14, 15] depth is reduced with increase of edge radius. Since the edge part shape of forged surface come close to flat with increase of edge radius, the minor defect depth was reduced. In order to organize, therefore, the relation between the edge part shape on forged surface and minor defect depth, aspect ratio was defined. The definition of the aspect ratio illustrated in Fig. 13. The aspect ratio is the parameter that the edge part shape was regarded as quantitative value. The minor defect depth is increased with increase of aspect ratio. In order to minimize surface crack generation, the anvil edge shape which can minimize aspect ratio is effective.[14,15]]

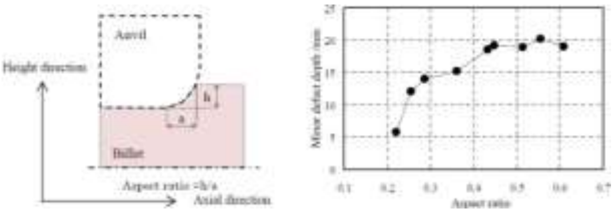


Fig. 13. Definition of aspect ratio and relationship between aspect ratio and minor defect depth.

The analysis of an abnormal crack of a forging plate

The plate was produced and hot forged by a steel company. Forging process was carried out as following: start-forging temperature was 1150^{0} C and finish-forging temperature was 850 ^{0} C. When forging process was finished, annealing process was carried out. The crack was found several days after that when the buyer received the plate. It was the user's authorization that we do failure analysis for the failure 12Cr13 steel plate. The size of the plate we received is like 200 mm x 200 mm x 30 mm. The crack is shown in Fig.14 and it crosses the plate. The plate shown is cut from a forging ingot and the crack is about 1.5 in. in depth. [20, 22]

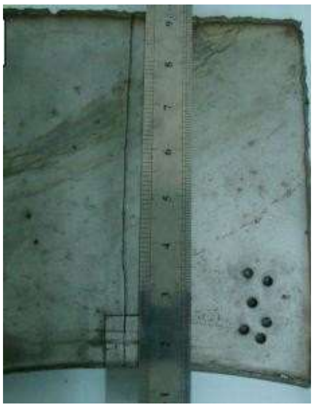


Fig. 14. Crack position and depth in the forging plate.

Evaluation Fracture Mechanism

Fractographic valuation constitutes a powerful analytical technique dedicated to identify the fracture mechanism in the context of failure analysis of machine components. The overall view of the fracture surfaces observing by SEM of the forging plate is presented in Fig. 15. Fractography characteristics shown in Fig. 15 indicate the intergranular feature and cleavage feature[11] of the fracture surface, which means it, is brittle fracture. Cleavage fracture is a transgranular, low-energy fracture that occurs primarily by separation of atomic bonds on low-index atomic planes.[25,26]

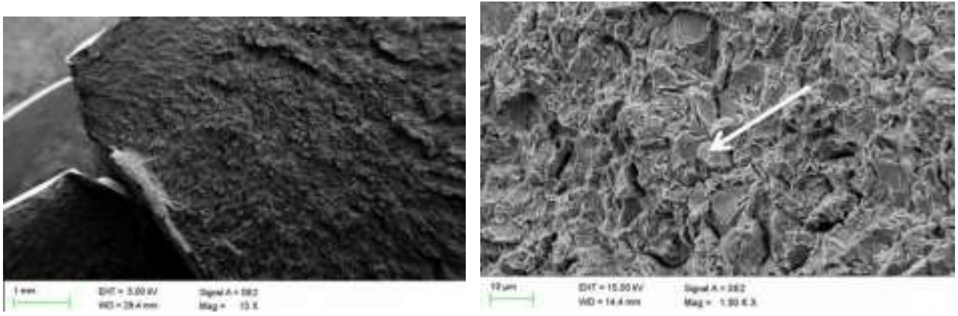


Fig.15. Fractography characteristics of forging plate.

A sample was cut from the plate fracture zone. This sample was metallographically prepared and observed in an optical microscope, in no etched and etched conditions. The microstructure, without etching, revealed low quantity of defects such as micro-pores and non-metallic inclusions. Measured and specified compositions of the plate are shown in Table 4. It can be seen the overall composition of the forging plate is in accordance with the standard value. The distributions of composition were examined respectively by using electron probe microanalysis (EPMA-1600), as shown in Fig.16. It is obvious that there is phosphorus segregation in the failed steel.[24,29]

Table.4. Chemical composition of the forging plate, wt. %.

Material	C	S	Si	Mn	P	Cr	Ni	Cu
Obtained	0.14	0.0016	0.75	0.68	0.019	12.85	0.59	0.014
Expected	≤0.15	≤0.030	≤1.00	≤1.00	≤0.040	11.50–13.50	≤0.60	–

This forging 12Cr13 stainless steel is caused by phosphorous segregation. Phosphorous segregation weakens the bond strength of grain boundary and crack initiates from phosphorous segregation grain boundary when forging. It is important to dephosphorizing the steel and uniform the structure.

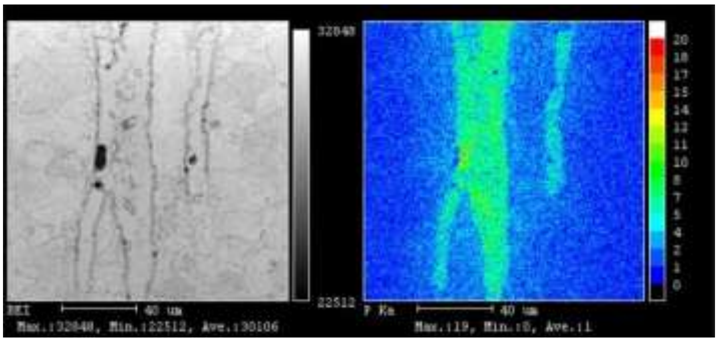


Fig.16. Distributions of composition nearby the crack.

3. Discussions

In the presented paper improper position of the preform (the lever forging simulation) and the improper flow of the material have been identified as the causes of defects. The results of the structural examinations and the numerical simulations have a utilitarian character and indicate a need for identifying the causes of folds and underfills in the cavity die in hot forging processes. By eliminating forging defects or limiting their occurrence to a minimum one can significantly reduce the production costs. The identification of the causes of defects is needed to properly design the technological process and eliminate the defects. In order to properly design the forging process so that it enables the manufacturing of a series of repeatable forgings free of defects one must select optimal process parameters, properly design and manufacture (which includes the choice of a material and its thermal treatment) the tools and optimize the shape of the preform and the slug. The number and complexity of the factors having a bearing on the correctness of the forging process make their assessment difficult. Numerical modeling proves to be highly valuable for identifying heterogeneous deformations complicated in their shape, which often pass unnoticed during regular visual inspections in the forge.

It was proposed that the difference of deformation gradient in the upsetting process of large forgings will lead to inhomogeneity of order and speed of metal flow, and poor compatibility of material deformation, which is the main reason of laminated crack defect. According to gradient of equivalent strain and gradient of strain rate, a combined estimation model of laminated crack defect was established and successfully obtains morphology and distribution of laminated crack in the centre of forgings. The reliability criterion of the model is verified by aid of physical simulation experiment of small forgings. In addition, it was found the minor defect depth correlate with the edge shape of anvil. In order to minimize surface crack generation, the anvil edge shape which can minimize aspect ratio is effective. However, optical microstructure and SEM also indicate element segregation around crack zone, which turns out to be P segregation tested by EDS and EPMA. It is illustrated above that phosphorus harms ductility by segregating to grain boundaries.

4. Conclusions

With little to no scrap, the forging process creates finished goods in a very short amount of time. As a result, there are material and energy savings. Forgings can be more expensive than parts made using other procedures, but they yield parts that are more dependable and have superior mechanical and metallurgical qualities. As a result of the high rejection rates caused by defects, it is crucial to move any process towards perfecting itself as a part of a successful continuous improvement programme. It is preferable to comprehend and manage the process so as to prevent defects than to scrap the defective parts during final inspection.

References

[1] Marek Hawryluk , Joanna Jakubik, Analysis of forging defects for selected industrial die forging processes Engineering Failure Analysis 59 (2016) 396–409).

[2] Z. Gronostajski, M. Kaszuba, M. Hawryluk, M. Zwierzchowski, A review of the degradation mechanisms of the hot forging tools, Arch. Civ. Mech. Eng. 14 (4) (2014) 528–539.

[3] Z. Gronostajski, M. Hawryluk, M. Kaszuba, A. Niechajowicz, S. Polak, S.Walczak, D. Jablonski, Die profile optimization for forging constant velocity joint casings,Arch. Metall. Mater. 56 (2) (2008) 551–558.

[4] Nisbett EG. Steel forgings: design, production, selection, testing, and application. USA: ASTM International; 2005..

[5] GB/T 1220-2007 stainless steel bars. Beijing, China: Standards Press of China; 2007.

[6] A. Kocańda, in: A. Piela, F. Grosman, J. Kusiak, M. Pietrzyk (Eds.),Określenie trwałości narzędzia w obróbce plastycznej metali 2003, pp. 213–256.

[7] M. Kopernik, A. Milenin, Numerical modeling of substrate effect on determination of elastic and plastic properties of TiN nanocoating in nanoindentation test, Arch. Civ. Mech. Eng. 14 (2) (2014) 269–277.

[8] Takefumi Arikawaa, Daisuke Yamabeb, Hideki Kakimotoc, Influence of anvil shape of surface crack generation in large hot forging process, 11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014,Nagoya Congress Center, Nagoya, Japan

[9] Wei-min Guo a, Na Xu a, Ning Ding a, Jun-bo Shi a, C.M. Lawrence Wua,b, An analysis of crack evolution of a 12Cr13 stainless steel during forging processs. Case Studies in Engineering Failure Analysis 4 (2015) 94–99.

[10] J.J. Park, N. Rebelo, S. Kobayashi, A new approach to preform design inmetal forming with the finite element method, Mach. Tool Des. Res. 23 (1) (1983) 71–79.

[11] G. Banaszek, A. Stefanik, Theoretical and laboratory modelling of the closure of metallurgical defects during forming of forging, J. Mater. Process. Technol. 177 (1–3) (2006) 238–242.

[12] A.J. Wilby, D.P. Neale, Defects introduced into metal during fabrication and service, Adv. Mater. Sci. Eng. 3 (2012).

[13] Pantazopoulos G, Bazdirvanidis A, Rikos A. Analysis of abnormal fatigue failure of forklift forks. Case Stud Eng Fail Anal 2014;2(1):9–14.

[14] Arikawa T., Kakimoto H,. Takahashi Y., Matsuda M., Yoshida T., Yamabe D., 2009. The 60th JSTP Joint conference 2009, 91-92.

[15] Yamabe D., Ikegami T., Arikawa T., Takahashi Y., Matsuda M., Yoshida T., 2009. The 60th JSTP Joint conference 2009, 81-82.

[16] S. Mok, C.K. Kwong,W.S. Lau, A hybrid neural network and genetic algorithmapproach to the determination of injectionmoulding, Int. J. Adv.Manuf. Technol. 18 (2001) 404–409.

[17] Yulin Shi, Study on Forging Process of the Squeeze Roll of Whole Forging, Huazhong University of Science and Technology, Wuhan, 2006 (in Chinese).

[18] Danian Wang, Principles of Metal Forming, China Machine Press, Beijing, 1986 217–236 (in Chinese).

[19] Hongde Cao, Plastic Deformation Mechanics Basis and Principle of Rolling, China Machine Press, Beijing, 1983 113–118 (in Chinese).

[20] Zhubai Liu, LiandongWang, Guohui Liu, Physical simulation of tension stress theory of a rigid plastic mechanical model for upsetting a circular cylinder, Chin. J.Mech. Eng. 6 (2) (1993) 102–105 (in Chinese).

[21] Mahendra G. Rathi, Nilesh A. Jakhade,An Overview of Forging with their Defects, International Journal of Scientific and Research Publications, Volume 4, Issue 6, June 2014 1,ISSN 2250-3153

[22] Zhubai Liu, Shaomin Nie, Liandong Wang, A new theory for upsetting a cylinder between flat platens, Chin. J. Mech. Eng. 5 (4) (1992) 297–303 (in Chinese).

[23] Zhubai Liu, New Technology of Plastic Forming and Its Mechanics Principle, : China Machine Press, Beijing, 1995 1–52 (in Chinese).

[24] Ishiguro N., Abe E., Ueno K., Yukawa N., Fujihara M., Yoshida H., Ishikawa T., Journal of the JSTP, 54, 634, 993-997.

[25] G. Banaszek, A. Stefanik, Theoretical and laboratory modelling of the closure of metallurgical defects during forming of a forging, Journal Materials Processing Technology 177 (1–3) (2006) 238–242.

[26] Liandong Wang, Zhubai Liu, Mechanical slab method of the stress field calculation for a cylinder (H/D N 1) being upset, J. Plast. Eng. 1 (3) (1994) 20–28 (in Chinese).

[27] Yudong Yang, Control on Inner Crack Defect of Forged Cold-roller of High Carbon and Chrome Steel, University of Science and Technology Beijing, Beijing, 2007 12–18 (in Chinese).

[28] MintingWang a,b, Dongying Li a, FanWanga, Xinliang Zang a, Xuetong Li a, Hong Xiao a,Fengshan Du a, F.C. Zhangc, Zhengyi Jiangb, Analysis of laminated crack defect in the upsetting process of heavy disk-shaped forgings, Engineering Failure Analysis 59 (2016) 197–210.

[29] Jingtao Han, Jiongjun Zhang, Zhongli Zhao, Yongdong Xue, Junxian Liu, The forging process of controlling the inclusion defects for heavy disk forgings and its application, Heavy Casting Forging 2 (2007) 34–36 (in Chinese).`