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Studies on a Robotised Process for Forging Steel Synchronizer Rings in the Context of Forging Tool Life

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This paper proposes a solution not previously used in the forging industry, which aims to reduce the proportion of arduous human labour. The concept of a prototype robotic station for hot forging includes a system that allows the selection of batch material with its heating, the execution of the process of lubrication of forging tools and the forging itself, synchronised with the feeding and removal of material using full automation, in accordance with the idea of Industry 4.0. At the same time, by increasing the repeatability of the entire forging process and changing some of its key parameters, it will be possible to influence the durability of the tools used during its implementation. In order to verify the impact of such a modified technological process on forging tool life, computer simulations of forging were performed, where the currently applied technology using hand forging was compared with a conceptual automated process.

Keywords: Die Forging, Automation, Forging Simulation, Tool Durability, Industry 4.0

1 Introduction

From the available reports of Euroforge organisation for the period 2017-2018, the demand for high quality forging products showed an increasing trend, both globally and in Europe [1]. According to these data, the global forging market size increased from 27.184 million tonnes in 2017 to 28.065 million tonnes in 2018, and China was the largest producer of forgings with a 43% market share. In contrast, the size of the European market was estimated at 6.136 million tonnes in 2017 and 6.211 million tonnes in 2018. The production of Polish forges in 2018 accounted for about 5% of the European market share, which put the Polish forging industry in fifth place in Europe after Germany (45%), Italy (20%), France (8%) and Spain (7%). Despite the decline in demand for forged parts worldwide associated with the negative impact of the COVID 19 outbreak on the economy, the forging market is forecast to grow at a 4.8% CAGR in terms of value from 2021 to 2027 [2].

The leading market in exploiting the opportunities arising from the digitisation of forging production and implementing the Industry 4.0 concept is Germany. The first concept of this approach was presented at the Hannover Industrial Fair in 2011. Two years later, the German government, recognising the potential of the industry 4.0 concept, published a report which forms the basis for implementing its individual elements in practice [3]. According to an analysis by Beroe [4], the orientation of German forges towards investment in the above-mentioned solutions was due to the decline in capacity utilisation to a level of 60-70%. This resulted in the need to change the organisation of forge production towards increasing its flexibility, using IT techniques in planning, and developing new technologies. The concept of the production stand under consideration is not only aimed at designing and verifying the automation of forging in terms of forging tool life, but the idea is to develop the hot forging technology from the moment of collecting the batch material to the product in the form of a forging through a fully automatic system of selecting the batch material and the die, the parameters of induction heating, feeding to the die, lubricating the die and receiving the forging and its rapid verification. One of the key determinants of the innovativeness of the production process is its degree of automation and robotisation.

According to a report by Deloitte [5], 78% of companies surveyed have already implemented robotic process automation and another 16% intend to do so within the next three years. In turn, 13% of respondents confirmed that they have started implementing automation on a large scale. The growth of the global robotic process automation (RPA) market is estimated at 40.6% per year.

Companies in the SME sector that have not invested in industrial robots most often point to their production profile as the main reason for the absence of robotisation in the company [6]. This usually means that the specificity of the manufactured products or the organisation of the production processes in the plant simply does not require the installation of robots. Another frequently indicated reason for the lack of robotization is the small scale of production, or its low repeatability (relatively short, frequently changing series of products), which may lead the company managers to believe that the implementation of industrial robots would not be economically viable. The concept of a robotic hot forging station is designed to counteract this trend. The assumptions made allow proving that the combination of robotisation with an intelligent system/interface and a differentiated charge feeding system will enable, even for variable and not at all mass production, transformation of a forging stand into a stand compliant with the assumptions of Industry 4.0. Moreover, thanks to achieving the planned efficiency and repeatability, it will be economically justified and necessary to maintain competitiveness in the market.

Metal forming, but in particular the various forging methods, is one of the oldest and most widespread ways of manufacturing metal products. It would seem that this makes forging so well-known and described. However, in an ever-changing economic environment, the market places ever new and increased demands on forging manufacturers, primarily in terms of the price at which they offer their products, as well as their quality. Therefore, in die forging, particular attention should be paid to forging tools and the related issues of their wear and durability [7-10]. High costs of materials used for die producing, as well as complicated and time-consuming processes of their manufacture, significantly impact the price of the finished product [11-13]. Increasing the service life of forging tools, and thus reducing the number of sets of tools used for a given batch of products, is a solution to meet rising costs. Today's manufacturing techniques and methods offer a whole spectrum of possibilities for affecting the service life of forging tools [14-19], however, a common requirement as to the effectiveness of these procedures is the repeatability and stability of the forging process itself, which is in principle achievable only through the use of automation and robotisation.

2 Hot forging of steel synchronizer rings

2.1 Currently used technology - hand forging station

Synchronizer rings for gearboxes used in trucks and buses are manufactured at Fabryka Armatur "Swarzędz" sp. z o.o. (FAS) located in Rabowice, Poland, from 16MnCr5 alloy steel. The exact chemical composition for a randomly selected material sample is shown in Table 1. The test was carried out using an optical emission spectrometer (quantometer) manufactured by ARL, Switzerland, type 3460.

Tab. 1 *Chemical composition of a steel sample from a selected synchronizer ring (*values marked above the AB 608 accredited range)*

Sample No.	Content [%] + expanded uncertainty [%]													
	C	Mn	Si	P	S	Cr	Ni	Cu	V	Mo	Ti	Co	Al	B
1	0,176	1,079	0,276	0,025	0,017	0,899	0,024*	0,042	0,008	0,006*	0,002*	0,007	0,017	0,001*
	±0,005	±0,030	±0,019	±0,009	±0,001	±0,013	±0,001	±0,002	±0,001	±0,001	±0,001	±0,001	±0,001	±0,001

The existing range of rings produced at FAS includes 142 types of synchronizers, whose diameter range (according to the external diameter of the toothing after machining) is from 87.3 to 205.1 mm. An example of a ring after the finishing operation is shown in Fig. 1.

Fig. 1 *Gearbox synchronizer ring after final machining operation*

Until the end of 2007, the steel used by the company for the production of synchronizer ring dies was WCLV hot-work tool steel (EN X40CrMoV5-1) with a hardness of 52-55 HRC, the chemical composition of which is presented in Table 2. The use of this material grade, combined with the subsequent process of ion nitriding of dies and punches to increase the abrasion resistance of these tools, enabled the production of approximately 2,000 synchronizer ring forgings.

Tab. 2 *Chemical composition of WCLV steel [20]*

Steel grade	Chemical composition [%]					
	C	Si	Mn	Cr	Mo	V
WCLV	0,39	1,1	0,4	5,2	1,4	0,95

In early 2008, following a market survey of new steels suitable for die producing and also promising to increase die durability, it was decided to use a steel with the trade name Unimax from Uddeholm.

Unimax is a chrome-nickel-molybdenum-vanadium alloyed steel (the exact chemical composition of this steel is shown in Table 3), which can be used for hot work tools, where high hardness as well as toughness is required. Unimax is characterised by [21]:

- excellent plasticity and ductility in all directions,
- good wear resistance,
- good dimensional stability during hardening,
- excellent through-hardening properties,
- good resistance to relenting tempering,
- good toughness at high temperatures,
- high resistance to thermal fatigue,
- excellent polishability.

Tab. 3 *Chemical composition of Unimax steel [21]*

Steel grade	Chemical composition [%]					
	C	Si	Mn	Cr	Mo	V
Unimax	0,5	0,2	0,5	5,0	2,3	0,5

After proper heat treatment, i.e. quenching and tempering, Unimax steel should have a hardness of (56-58 HRC). These values have been confirmed in the in-house laboratory of Fabryka Armatur "Swarzędz" sp. z o.o. by testing a sample made of this steel with dimensions Ø30x10. The measurement was made in three randomly selected places on the surface of the sample with a Rockwell hardness tester type KP15002P and the following results were obtained: 56 HRC, 57 HRC, 57 HRC.

High hardness and ductility combined with good dimensional stability during heat treatment processes, confirmed by tests carried out by the Uddeholm concern, make Unimax perfectly suitable for conducting, among others, the nitriding process to which all dies manufactured at Fabryka Armatur "Swarzędz" sp. z o.o. are subjected.

Ion nitriding, which is the process used to produce synchronizer rings dies at FAS, is performed at the Łukasiewicz Research Network - Poznań Institute of Technology in Poznań. It is one of the basic methods of increasing the service life of tools and machine parts. It contributes to the improvement of such properties of the processed elements as [22]:

- abrasion resistance,
- reduction of the friction coefficient,
- increase in fatigue strength,
- reduced tendency to adhere to the workpiece material,
- increased resistance to corrosion.

Ion nitriding also has the following advantages over other thermo-chemical surface treatment methods:

- shorter processing times compared to traditional gas nitriding,
- possibility and ease of precise regulation of the structure of the nitrided layer (obtaining layers without pores),
- possibility of low-temperature nitriding (from 400 °C),
- small dimensional changes of the nitrided pieces.

At the Metal Forming Institute, ion nitriding is carried out using a JONIMP 900/500 device (a view of the loading table with dies and punches is shown in Fig. 2).

Fig. 2 *View of the loading table of the Jonimp 900x500 nitriding furnace [23]*

The parameters of the nitrided layer produced on the dies for forging synchronizer rings are given in Table 4.

***Tab. 4** Parameters of nitrided layer produced on dies for forging synchronizer rings [23]*

Nitrided layer parameters	
Structure	diffusion layer
Diffusion layer thickness	0.2÷0.25 mm
Nitride layer thickness (so-called white layer)	4÷5 μm
Hardness	1000 HV
Method	ionic nitriding (t = 540°C, p = 5-10 hPa, τ = 600 min, atmosphere: $N_2 + H_2$)

The use of Unimax hot working steel, combined with a thermo-chemical treatment of this steel in the form of ion nitriding, in which a wear-resistant white nitride layer is produced on the surface of the workpiece material, characterised by a compact and durable structure, has made it possible to obtain an average of about 2800 forgings from a single die for forging synchronizer rings. Compared to the previously used WCLV steel, also ion nitrided, this represents an average increase of 40%. The hot forging operation for the products presented is carried out on a Šmeral LZK 1000 press. The LZK is a single-point vertical crank mechanical press with an overhead drive and with the main shaft positioned in the frame in the front-to-back direction (transverse to the technological direction of the forging process), with a nominal pressing force of 10,000 kN. A view of the hand forging station is shown in Fig. 3.

***Fig. 3** Station for the hand forging of steel synchronizer rings at FAS*

The complete station equipment consists of 1 – electro-devices of the heater, 2 – pallet with preforgings, 3 - induction heating device, 4 – two-point collection place for heated preforgings, 5 - controlling panel of the press, 6 – forging tools, 7 – vertical forging press, 8 – pallet with finished forgings, 9 – manual lubrication device, 10 – jack of two-handed launching, 11 – lubrication tank.

2.2 Concept of a new robotised station - automatic forging

The concept presented here concerns process innovation in the field of forging technology for a wide range of synchronizer rings and the possibility of adapting the technology to the requirements of Industry 4.0. The entire production cycle has been analysed in terms of potential modification, automation, and integration into a remote-control system, starting with batch material feeding, automated lubrication, forging and collection of the forged part. The concept includes first of all the design of a prototype station equipped with: a selective charge feeding system, an innovative induction heater equipped with heating chambers with the possibility of using protective gases, a system for feeding and collecting preforgings and forgings from forging presses, a control-command system for the whole station equipped with measurement sensors and a specially developed program (interface) enabling, among others, remote control with full product tracking.

Considering the quantity of various batch materials, the number of forged products (approx. 70 types currently manufactured at FAS), it was necessary to design the future station in such a way that it would be possible to understand and implement the basic principles of material and information flow on a global scale for the entire manufacturing process of a product such as a synchronizer ring.

The batch material delivered by an external supplier and stocked in the warehouse is stored in containers appropriately labelled for the batch. The concept includes the development of a conveyor and binder system into which an employee will pour the batch material and register it at the same time. In the binder, the ring will be properly positioned and conveyed to the place of collection by a storage gripper (movable in three axes). The gripper will pick up each piece and place it on top of the other in several rows, five columns each, at the same time registering the number of pieces and the put-away location (strictly assigned to each semi-finished product). The put-away place is the so-called supermarket (in the sense of broadly understood Lean Manufacturing) of products waiting for their processing ensuring FIFO (First In First Out) and standing directly at the production line. The number of pieces and batch types has a predetermined maximum and minimum level, which is directly linked to the production plan. It is anticipated that the supermarket will provide batch material for 48 hours of forging press operation. If the minimum level is reached in the supermarket, information is automatically sent to the warehouse and the stock is replenished. The supermarket will hold a predetermined number of types of batches, e.g. for three consecutive orders in the production schedule.

The material in the supermarket flows in a defined volume and at a defined time through a conveyor to an induction heater, alternately distributed to the appropriate inductor. The hot forging process requires a heat source that heats the preforging to the forming temperature in the shortest possible time. The most common methods for steel products are induction heating methods, sometimes resistance heating or using chamber furnaces. Induction heating is the most efficient method. The presented concept includes the development of a heating station in terms of the shape and positioning of inductors, enabling alternate heating of at least two semi-finished products in a time allowing smooth forging, increasing the productivity (in relation to the current one) by at least 2 times (averaged value for all ring shapes). A side issue is the considered possibility of using protective gases in the heater in order to obtain less scale and decarburisation.

The material is taken from the heater by a robotic arm and deposited in the forging blank. After being forged by the arm of another robot, this time receiving, it is transferred to a container with forged products. The execution of the forging operation itself will be coupled with an automatic die lubrication system, synchronised with the product infeed and outfeed system, enabling a significant improvement in the forging process itself as well as precise dosage and distribution of a thin layer of lubricant on the forging tools working surface, which will take place through the use of another robot, this time a lubricating one. A schematic of the automatic forging station is shown in Fig. 4.

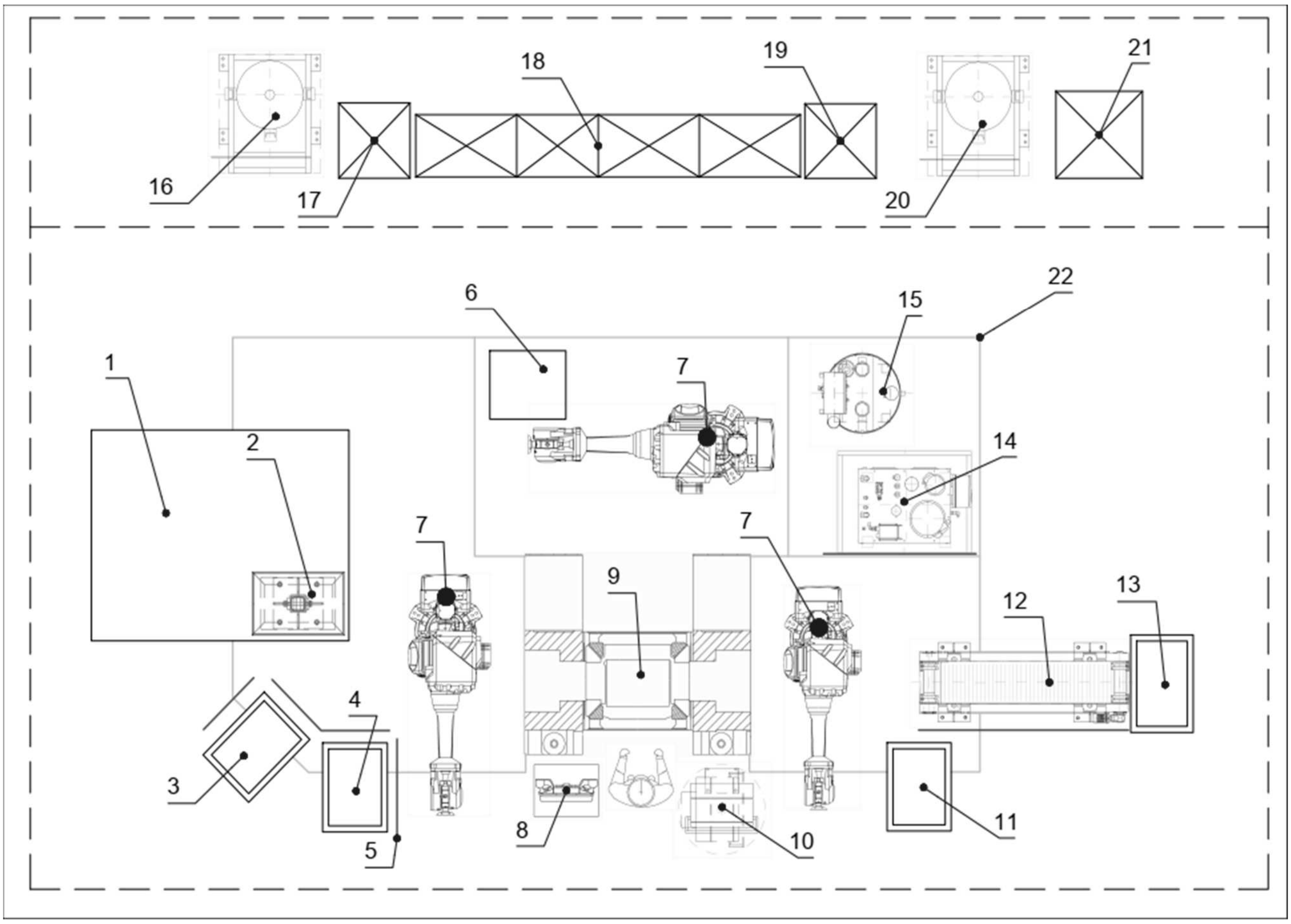


***Fig. 4** Conceptual station for automatic forging of steel synchronizer rings*

The fit-out of the station consists of: 1 – induction heating device of annulitical semi-products, 2 - positioner of warmed semi-products, 3 - pallet of scrap material (overheated), 4 - pallet of scrap material (cool), 5 - shielding of thermal radiation, 6 - tails tank for lubricating head, 7 - feeding, lubricating and collecting robots, 8 - jack of two-handed launching, 9 - vertical forging press, 10 - controlling panel of the press and robots, 11 - pallet of finished forgings (emergency fall), 12 - conveyor belt, 13 - pallet of finished forgings, 14 - hydraulic aggregate of lower ejector of the press, 15 - lubrication tank, 16 - pressure tank of the press, 17 - distributors of robots, 18 - electric distributor, 19 - distributor of controlling system of robots, 20 - pressure tank for blowing and lubricating of dies, 21 - lubrication filler, 22 – safety fence.

The overall concept includes the design and implementation of a control management system with an open structure for the supply of updating data, including a program for remote process management. The system will be fully integrated with the production plan and the supermarket located at the forging station. It will provide real-time information about the status of the supermarket, its minimum and maximum levels for a given blank, and the need to feed the supermarket. Blanks will move according to the FIFO principle, first in, first out. This system will be linked to the shaping tool control system and will keep it informed of the shaping tools necessary for the next workpieces in the production plan, in order to fully speed up press changeovers. Above all, the system must be flexible, easily extendable and link the elements communicating with each other (warehouse-supermarket-heater-robot-press-robot-lubrication-system-tools) together with the outside world and ensure full traceability.

3 Tool wear during hot forging of gearbox steel synchronizer rings

The estimation of forging tool life for the currently used manual process at FAS, compared to the conceptual process based on full automation, was carried out using the QForm UK 10 program. This is a sophisticated program for the simulation of forming, design, analysis of die forging operations and estimation of forging durability. For this purpose, a model set of tools (clamp + die + punch) was built, corresponding to the actual one used in the current manufacturing operations, and the initial conditions for individual processes were determined, which are summarised in Tab. 5.

Tab. 5 *Conditions for manual and automatic forging simulation*

Forging process assumptions		
Forging type	manual	automatic
Punch + die material	UNIMAX	UNIMAX
Forging material	16MnCr5	16MnCr5
Preforging: cooling in air [s]	4	2
Preforging: cooling on tool [s]	5	2
Tool cooling in air [s]	30	8
Lubrication: graphite + water	non-repeatable	repeatable
Prepreg heating temperature set [°C]	950	1050
Clamp starting temperature [°C]	130	130
Die starting temperature [°C]	200	200
Punch starting temperature [°C]	200	200

Due to the fact that the process performed manually by a human being is characterised by a lower repeatability of lubrication, a longer production cycle and definitely greater difficulty in estimating the value of the temperature of the heated preforging before the operator performs the forging operation, for the simulation of hand forging the average values observed in the course of the real process were adopted, while for the simulation of automatic forging the target values of the parameters in which the process of forming the synchronizer ring should take place were assumed.

One of the primary factors influencing the durability of forging tools is their initial temperature value prior to the start of the forging process. For this reason, a separate verification of the correctness of the adopted temperature assumptions for the tested set of forging tools was confirmed using a thermal imaging camera (FLUKE TiS45), where Fig. 5 presents the result of temperature measurement for the forging punch, and Fig. 6 for the die with the clamp, after the process of heating using a gas burner for a time of 30 min.

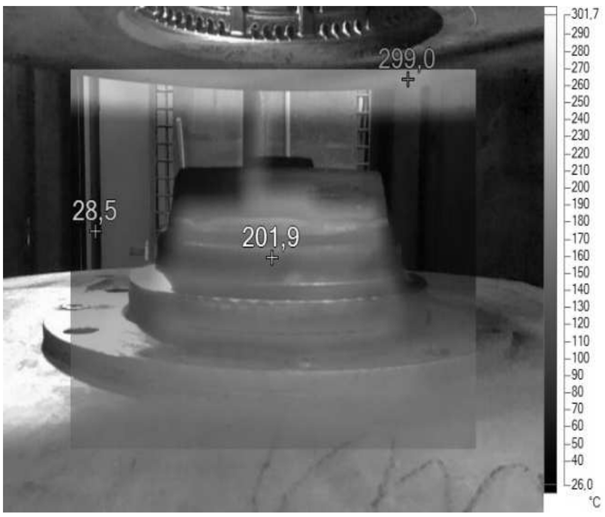


Fig. 5 *Temperature value prior to the start of the forging process for a forging punch*

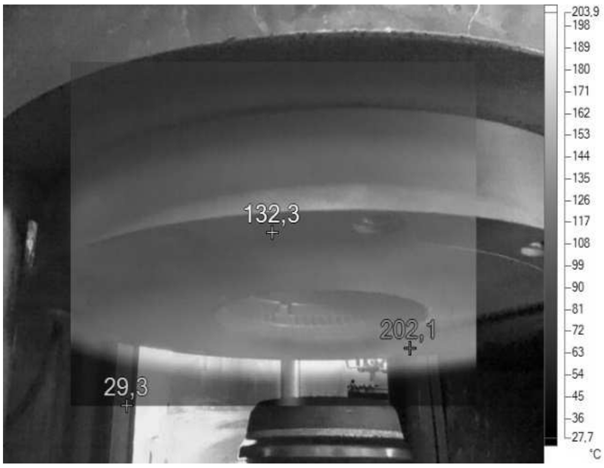
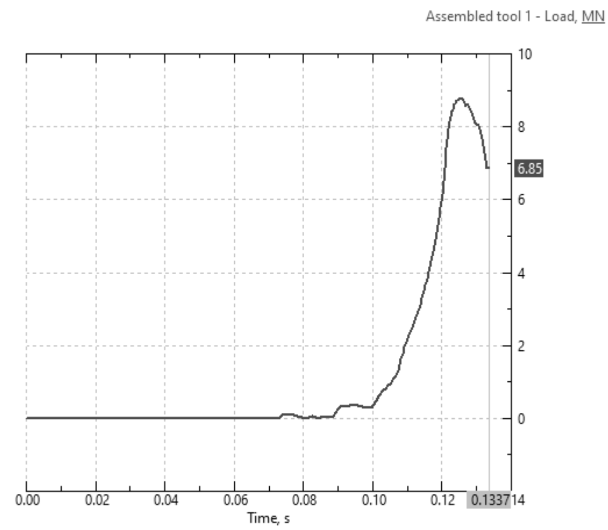
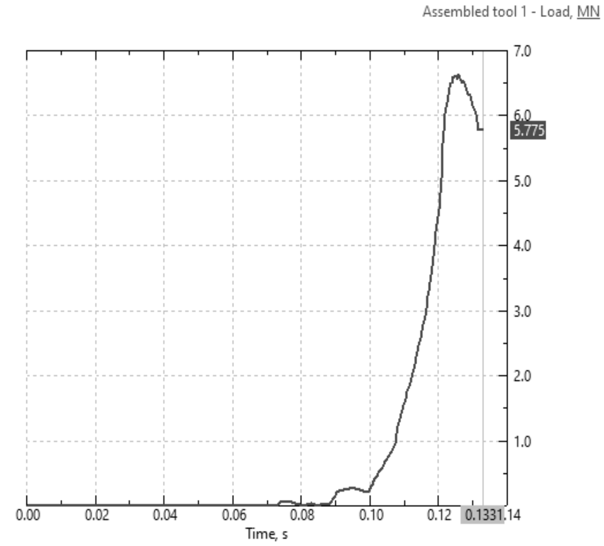


Fig. 6 *Temperature value prior to the start of the forging process for a die pressed into a clamp*

For thus defined boundary conditions, the first simulation was carried out to determine the press force required for die forging, during the first forging cycle after tool heating, as shown in graph 1 for the hand forging process and in graph 2 for the automatic forging process.

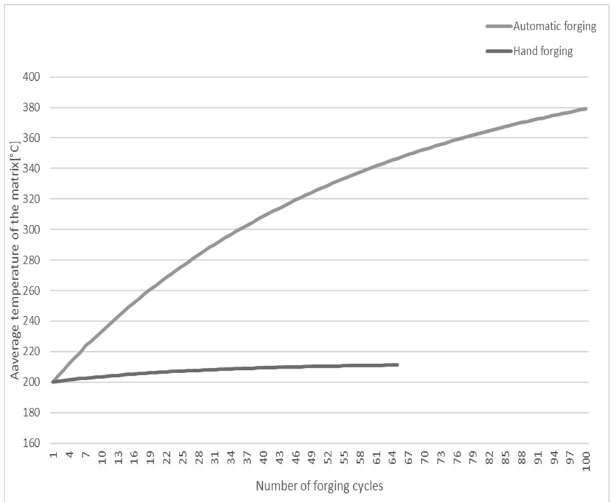


Graph 1 *Press force value in time for forging the first piece of synchronizer ring for hand forging operation*



***Graph 2** Press force value in time for forging the first piece of synchronizer ring for automatic forging operation*

The results obtained show that from the outset of the hot forging operation, the value of the force required to carry out the process correctly is lower for automatic forging than for hand forging, which should definitely translate into an increase in forging durability. In order to carry out the final simulation of tool life, it was necessary to determine after how many forging cycles the average temperature of the matrix stabilises, as shown in the graph 3.



***Graph 3** Average die temperature for a given number of die forging cycles*

The results obtained show that for hand forging the average working temperature of the die stabilises around 211 °C after 65 production cycles, while for the automatic forging it is significantly higher and tends to stabilise after 100 production cycles and reaching a temperature of 380 °C. Further increases in the number of forged pieces for both forging processes analysed were of marginal significance for the increase in the forging tool operating temperature value and were therefore omitted from subsequent simulations. However, as is clear from the graph presented, there is a significant difference in the temperature conditions of the die for hand forging and automatic forging. This is due primarily to the shorter time of the automatic cycle itself, but also to the higher temperature of the preforging itself repeatable in each production cycle, which means that the forging tools do not have time to release the accumulated heat so quickly. These working conditions should also have a positive effect on tool life extension.

By defining the boundary conditions for the forging process, as well as obtaining data on the average value of the die temperature for individual die cycles, it was possible to simulate the durability of the die. The QForm software includes built-in tools and algorithms to estimate the number of cycles until the first fatigue crack occurs and to determine the minimum and maximum stress in the tool in this case. After simulation, the values obtained for hand forging are presented in Fig. 7 and Fig. 8, respectively, and for automatic forging in Fig. 9 and Fig. 10.

The analysis of the computer simulation results shows that the initiation of fatigue cracking of the die for hand forging operation occurs in the 809th production cycle, and the maximum stress then occurring in the die is 1672.98 MPa. For automatic forging, on the other hand, fatigue crack initiation occurs in the 2336th cycle with a maximum stress in the die of 1263.27 MPa. This once again proves that a short and repeatable production cycle for automated forging, carried out under higher temperature conditions, allows for a potential increase in die life of almost 3 times compared to hand forging, which is also augmented by lower maximum stresses of almost 410 MPa simulated for automated forging compared to hand forging.

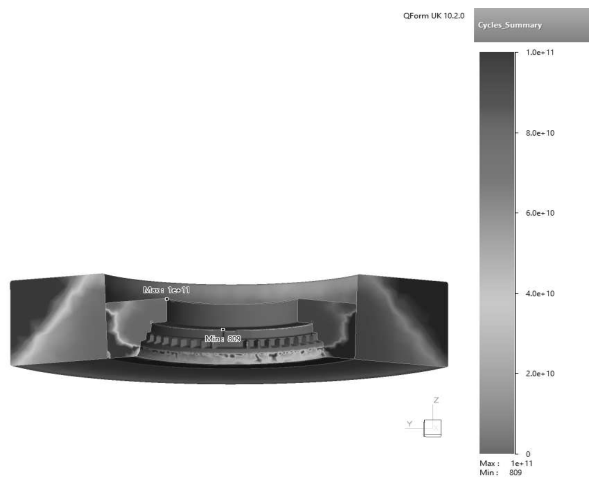


***Fig. 7** Minimum number of cycles until fatigue cracking occurs - hand forging*

Fig. 8 *The value of minimum and maximum stress occurring in the die at the fatigue crack initiation cycle - hand forging*

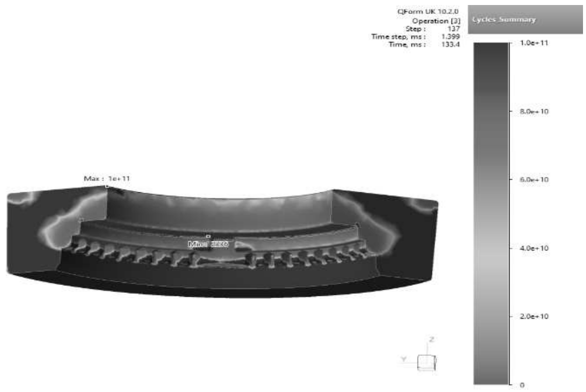


Fig. 9 *Minimum number of cycles to fatigue crack appearance - automatic forging*

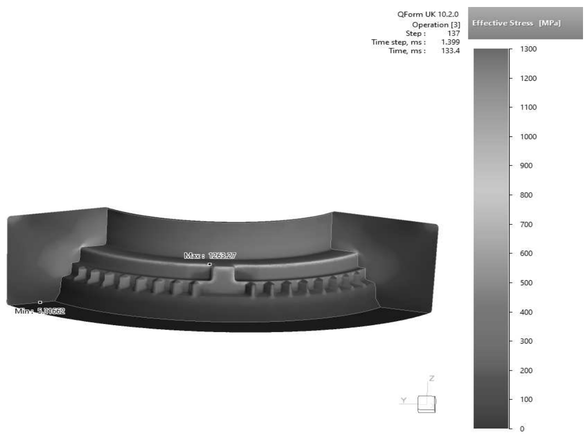


Fig. 10 *The value of minimum and maximum stress occurring in the die during the fatigue crack initiation cycle - automatic forging*

4 Conclusions and perspectives

The main reason for the robotisation of enterprises is the need to increase productivity, understood as cost reduction and increasing the number of manufactured products per time unit, as well as maintaining their quality repeatability for each production cycle. Robots are suitable for workstations where a constant high precision of product manufacture is required, and physical work performed by humans does not ensure such precision or is demanding in terms of effort put into it [24]. Therefore, the proposed concept of the station for the automatic forging of synchronizer rings should definitely have an impact on increasing the quality of the final product, which is of vital importance for the customers of any forge, since a large share of faulty or carelessly manufactured products may expose the company to the loss of business partners and generate above-standard costs.

It is also crucial to use the company's resources (human, machine, material, financial) to design and manufacture forging tooling. The use of programs for simulating the forging process and determining the durability of forging tools allows for definite savings in this respect. Although, thanks to research and analyses conducted with the use of IT software, it is not possible to predict the moment of forging tool failure due to all the destructive factors that may affect it, but the very determination of when and in what place a potential first fatigue crack is initiated is a valuable indication for the technologist responsible for die forging.

It is worth noting that, according to production practice, the mere appearance of a fatigue crack in a die does not necessarily mean that the forging process cannot continue. It is then necessary to assess individually whether the damage to the forging die, and consequently the transfer of a particular type of defect to the forging, disqualifies the product, either by making it impossible to carry out further technological operations or by failing to meet the quality requirements. The location of the crack and the attempt to assess its effect on the product is also successfully applied in other manufacturing techniques [25-26]. However, when it comes to die forging, often from the initiation of a crack to the decision to scrap the forging tools, they may work effectively for quite a number of cycles, which is strongly connected with technological conditions in which the process is conducted. Carrying out simulation tests determining, e.g. the moment of fatigue crack initiation and forces that are exerted on the tool at that time, allows to compare the course of individual forging processes, but first and foremost serves to verify the assumptions made as regards the parameters of performing the forging operation itself, as well as to verify the designed shape and dimensions of the forging tools. It is at this stage that it is possible to clearly observe whether the simulated life of a die and a punch will be within the assumed number of cycles worked, and what is more, how the modifications introduced concerning the parameters of the forging process and the shape, dimensions or material of the tools can shorten or extend their life.

This will save a considerable amount of time and costs associated with the elimination of real production tests and the performance of necessary modifications to tools when they do not meet expectations, which has been the basic practice in the forging industry so far.

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