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Enhancing Durability of Multi-Cavity Forging Tools through Process Automation

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The article highlights the promising potential of forging process automation to enhance the durability of multi-cavity forging dies. Entrepreneurs aim to boost production efficiency by increasing output per unit of time and reducing the degradation of forging dies and punches. The high costs associated with specialized materials and complex manufacturing processes for these tools elevate the final product price. Automation offers a viable alternative, ensuring consistent process parameters and reducing the physical strain on workers. This consistency leads to extended tool durability, even without the use of special manufacturing techniques for their production. The study simulates the durability of multi-cavity dies in automated operations, demonstrating substantial advantages compared to manual forging. Simulation programs for forging processes and tool durability offer significant cost savings by providing insights into potential fatigue cracks, aiding in decision-making, and verifying operational parameters and tool designs. These simulations reduce the need for extensive: real-world tests and modifications of the forging tools.

Keywords: Die forging, Forging simulation, Forging dies durability, Material fatigue, Multi-cavity dies

1 Introduction

Global economic uncertainty, initially triggered by the pandemic and subsequently by escalating armed conflicts, along with resulting supply chain disruptions and unprecedented increases in business operating costs in Europe, has led to significant changes in the long-term strategies of manufacturing enterprises, which are now focusing on maintaining their market competitiveness [1]. Manufacturing corporations are taking on the challenge of relocating their production facilities to regions considered more stable for conducting business, which also feature lower labor costs. This move further intensifies the pressure on companies to protect their business from losing competitiveness [2].

Companies focused on the production of die forgings can achieve cost efficiency by prioritizing the automation and robotization of their forging operations. This aims to reduce the amount of human labor required for performing arduous tasks, thereby improving the quality of work while also enhancing the efficiency of the forging processes. Another condition for cost efficiency is improving the durability of forging tools, as their production costs constitute one of the largest components of the final forging's price [3]. Therefore, any cost-effective material, technological, or organizational solution that significantly increases the number of forgings produced from a single set of forging tools is of great interest to all die forges. Addressing this perspective, research has been conducted to compare the durability of forging dies in manual forging operations using single-cavity dies with automated forging operations utilizing multi-cavity dies for products shaped from brass.

Die forging is one of the fundamental methods for shaping metal components. It allows the production of parts with high mechanical properties and complex shapes that would be difficult to achieve using other manufacturing technologies or would be economically unjustifiable. This explains the widespread demand for forged components in many strategic industrial sectors, such as aviation, automotive, energy, and construction [4-6].

The central organization for national forging associations across Europe (EUROFORGE), reports data showing a slight rise in the global volume of forged products (measured in metric net tons x 1000), from 29.675 in 2022 to a projected 29.880 in 2023. India is anticipated to see the most considerable growth, with a 15% increase in production volume (from 2.330 in 2022 to 2.680 in 2023). South Korea follows, with an estimated 11% increase (from 1.643 in 2022 to 1.820 in 2023), reflecting its strong economic expansion.

Production of forged products within Europe demonstrates a consistent upward trajectory, with volumes increasing from 3.708 in 2022 to a projected 3.771 in 2023. Germany remains the leading producer of forged goods in the region, with an anticipated output of 2.535 in 2023, followed by Italy, contributing an estimated 1.208. Turkey exhibits the most substantial year-over-year production growth, with a projected 16% increase, rising from 271 in 2022 to 315 in 2023. Poland holds the second-highest growth rate, marked by a 7% increase, expanding from 298 in 2022 to 319 in 2023 [7].

A markedly different perspective emerges when examining detailed data on Europe's total demand for brass used in production, including forging operations, in 2023. The estimated total consumption volume reached 710.000 tons, with Italy commanding the market at 57.2%, followed by Germany at 14.3%. Denmark, Sweden, Norway, and Finland collectively accounted for 4.9%, while France and Spain each represented 3.9%. The United Kingdom and Poland both held a 2.7% share, with remaining countries constituting the rest [8]. Projections anticipate a compound annual growth rate (CAGR) of 6% in market value for the forging industry by 2031 [9].

The presented data indicates that various forging methods are a promising and continuously evolving area of production using plastic forming techniques. Entrepreneurs who use forging technology aim to increase the efficiency of their processes by achieving a greater volume of produced goods per unit of time (utilizing multi-cavity dies and automation) and reducing the number of replicated tool sets (forging dies and punches) associated with their degradation, which prevents the attainment of consistent dimensional and qualitative products. In this context, numerous studies have already been conducted regarding the mechanisms contributing to the wear of forging tools [10-15]. However, the high costs of purchasing special grades of materials used in the production of forging tools, combined with often complicated and time-consuming manufacturing processes, along with the application of techniques to prevent their premature and excessive wear, significantly impact the high price of the manufactured set of forging tools. This is reflected in the higher cost of the final product offered by entrepreneurs. Therefore, it is worth considering the impact of implementing automation in the forging process, especially with the use of multi-cavity dies, on the durability of forging tools. The literature of the subject indicates gaps in this area. Automation of the forging process, aimed at achieving greater repeatability and stability compared to manual forging, but above all characterized by maintaining the required process parameters throughout the entire work interval, appears as a viable alternative that can substantially increase the durability of forging tools, even those that have not been subjected to special manufacturing techniques aimed at extending their working life or reducing excessive wear.

2 Methods for increasing the durability of forging tools

Durability of hot forging tools is influenced by a variety of factors during operation [16-19]. Table 1 presents these factors divided into those related to the forging, the die, and the operation.

Tab. 1 *Factors influencing the durability of hot forging tools*

Factors influencing the durability of hot forging tools		
Related to the forging:	**Related to the die:**	**Related to operation:**
forging material	die material (quality, type)	shape of the initial material or preform
forging weight	die hardness (type of heat treatment)	type of machine (size, strike velocity, technical condition)
forging shape	die construction	duration of the forging in the die
forging temperature	die dimensions	range of forging temperatures
dimensional tolerances	manufacturing technology	type of heating device and atmosphere within it
required surface condition	precision of manufacturing	heating of the forging (even, uneven)
	number of cavities in the die	influence of scale
	smoothness of die surface	type of die lubrication
	die temperature during operation	method of preheating the die before operation
	number of die regenerations	forging process (continuous, with brakes)
	method of die mounting in the press	skill and conscientiousness of the worker

Factors related to the forging and operation generally do not undergo significant changes and are often predetermined. Regarding the forging, the decisive parameter is its purpose. The contractor's scope of action is limited due to the multitude of requirements imposed by the customer (forging material, shape, dimensions, etc.). In the case of operation, the primary parameters are the technological and technical parameters of the forge, i.e., the available machinery. However, ensuring the repeatability of selected process parameters throughout the entire production batch is critical, so that they are as consistent as possible during the entire production run. This can be achieved through the use of automated forging presses, which, when maintained in good condition, allow for effective elimination of production downtime and smooth regulation of the process, thereby preventing, for example, a decrease in the temperature of the working tools. Automation, combined with factors related to the die, especially the material and technology used to manufacture the tools are critical in shaping the durability characteristics of the dies.

The attempt to prolong the durability of forging tools is a process that must be considered individually for a specific application or product family. The conducted analysis should encompass all factors influencing the life time of hot forging tools, but tailored to the technological, organizational, or financial capabilities of the enterprise where the particular product would be produced. The current array of methods aimed at enhancing the durability of forging tools spans a broad spectrum of options, depicted in Figure 1.

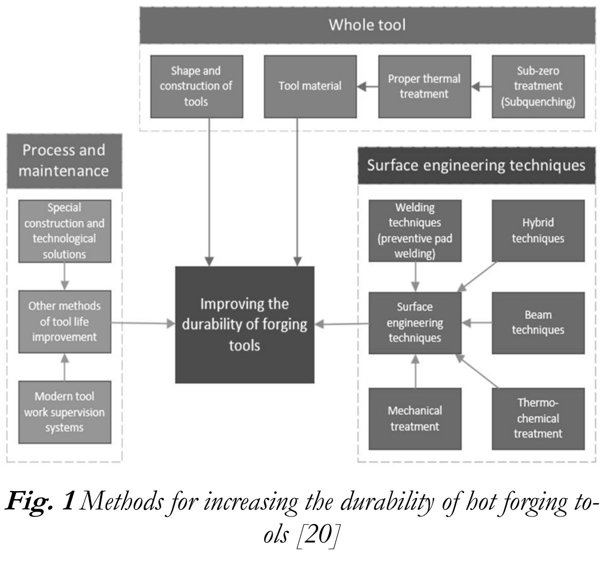

Fig. 1 *Methods for increasing the durability of hot forging tools [20]*

All initiatives aimed at prolonging the life time of hot forging tools fall under categories related to the process (parameters, monitoring, machine condition), surface engineering methods, and those concerning the tool shape or the material used for its production along with the heat treatment performed.

In terms of the material used for the tools, the hard working conditions prompt the use of high-alloy steels for hot working tools. Such steels should be characterized by high hardness, good mechanical properties, and excellent resistance to wear at high working temperatures [21-24]. Additionally, it's important for them to be properly forged and free from surface and internal defects. Other properties that such steels should meet include:

- high resistance to deformation when heating individual parts of the die above the tempering temperature,
- relatively low coefficient of linear expansion and minimal dependence on temperature within the heating range of the dies,
- the ability to undergo deep hardening with minimal alteration in shapes and dimensions,
- high thermal conductivity,
- low tendency to adhere to the deforming metal,
- good machinability.

Meeting all these requirements simultaneously, sometimes contradictory to each other, for a specific grade of steel is impossible. Considering that steels intended for dies are relatively expensive due to the high content of alloying elements, influencing their durability solely by increasing the content of alloying elements in the material becomes economically undesirable and often creates a technological barrier. Therefore, the task of technologists is to select the material for dies in such a way that it largely meets the expectations associated with the specific conditions in which it will be used.

Reducing the impact of factors causing tool wear and damage seems to be a more rational idea, although not necessarily easier to implement. A fundamental step in this direction is the application of appropriate tool lubrication. By introducing a lubricating substance between the interacting surfaces and the associated transition from dry friction to mixed or fluid lubrication, a beneficial effect on the durability of dies is exerted. The die material is isolated from direct contact with the forged material, resulting in reduced friction. As a result, the surface temperature of the die is lowered, which in turn reduces erosion, oxidation processes, and the intensity of material destruction due to thermal fatigue. Achieving the correct lubrication effect can only be reliably ensured through automated application, eliminating imperfections associated with manual forging, such as omitting or applying inconsistent amounts of lubricant, uneven lubrication of the die cavity, or lubrication performed at an inappropriate stage of the forging cycle. Automating the process also results in higher stability of the tool's operating temperature, which, combined with proper tool lubrication, should translate into extending their life time.

All processes that contribute to the degradation of forging die materials (plastic deformation, abrasive wear, thermal-mechanical fatigue, erosion) are localized in the surface layer of the tooling. Therefore, the next logical step to increase the durability of forging dies is shaping the properties and structure of the surface layer. This shaping occurs through the formation of diffusion layers or coatings with specific properties, resulting in the construction of a barrier that limits the impact of destructive factors and provides the material with desired operational properties. The intensive development of surface engineering in recent years, especially in the field of hybrid technologies for modifying the properties of the surface layer, provides an opportunity for effectively increasing the durability of forging dies [25-30]. The problem with such solutions lies in their full implementation in industrial practice, where barriers include the high costs of applying surface engineering methods in forging dies, limited availability of commercial solutions, and long lead times for related services.

3 Analysis of forging tool durability during the hot forging process of brass slide blocks

Slide blocks in car gearboxes are used and made of brass CW617N (CuZn40Pb2). Their Polish manufacturer is Fabryka Armatur "Swarzędz" (FAS) which is headquartered in Rabowice.

Chemical composition for this grade of brass is presented in Table 2 according to the material certificate received along with the delivery of the brass rods. Delivery condition according to EN 12165. Sample taken from a rod with a diameter of 16 mm and a length of 3000 mm.

***Tab. 2** Chemical composition of brass sample from CW617N*

Sample No.	Content [%]						
	Cu	Pb	Fe	Sn	Al	Ni	Zn
1	57.3	2	0.2	0.2	0.0	0.0	rest

Currently, FAS produces over 50 types of slide blocks. An example of a finished slide block after machining operation is shown in Figure 2.

At the turn of 2023/2024, hot working tool steel PN WCLV (EN X40CrMoV5-1), whose chemical composition is presented in Table 3 was used in FAS for producing dies for forging slide blocks. The selection of this material for dies in manual forging operations, allowed for an average production of 80,000 forgings per tool set before it was considered for scrapping or regeneration, if feasible.

At the beginning of 2024, following market analysis regarding new steel grades suitable for manufacturing dies for brass components, while also promising increased life time, the decision was made to utilize a steel commercially known as Dievar, produced by the Uddeholm group.

Dievar is a high-performance chromium-molybdenum-vanadium hot working tool steel whose chemical composition is presented in Table 4, known for its excellent resistance to thermal cracking, total cracking, plastic deformation and hot wear. Dievar is known for [32]:

- superior ductility and toughness in all directions,
- excellent resistance to tempering,
- high strength at high temperature,
- exceptional hardenability,
- reliable dimensional stability during heat treatment and coating application.

***Fig. 2** View of the machined slide block*

Tab. 3 *WCLV steel - chemical composition [31]*

Steel grade	Content [%]					
	C	Si	Mn	Cr	Mo	V
WCLV	0.39	0.9	0.4	5.2	1.4	0.95

Tab. 4 *Chemical composition of Dievar steel [32]*

Steel grade	Content [%]					
	C	Si	Mn	Cr	Mo	V
Dievar	0.35	0.2	0.5	5.0	2.3	0.6

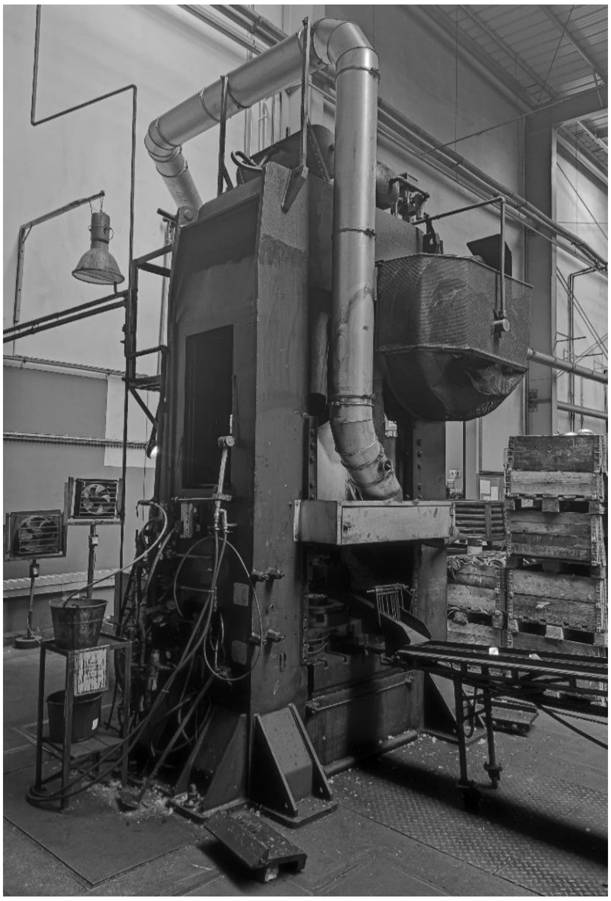

Fig. 3 *Manual forging station for brass slide blocks at FAS – MECOLPRESS 350 mechanical press*

The durability of forging tools in FAS's manual forging process (as shown in Figure 3) was assessed against a fully automated forging station (as illustrated in Figure 4) using QForm UK 10.3.3 software. This software is equipped to simulate shaping, design, analyze forging processes, and estimate tool durability. A new multi-cavity tool set (upper die + lower die) was designed and produced specifically for this study, with specific parameters outlined in Table 5.

Fig. 4 *Automatic forging station for brass slide blocks at FAS – MECOLPRESS 350 hydraulic press*

Tab. 5 *Comparative simulation setups for manual and automated forging processes*

Assumptions for the forging process		
Type of process operation	manual	automatic
Tool material	Dievar	Dievar
Forging material	CW617N	CW617N
Preform: cooling in air [s]	4.5	2
Preform: cooling on tool [s]	3	2
Die cooling in air [s]	13	8
Lubrication: water + graphite	non-repeatable	-
Lubrication: oil + graphite	-	repeatable
Preform heating temperature set [°C]	750	750
Starting process temperature - Upper die [°C]	200	200
Starting process temperature - Lower die [°C]	200	200

The view of the lower die cavity for the single manual forging is shown in Figure 5, and the view of the lower die for the multi-cavity automatic forging is shown in Figure 6.

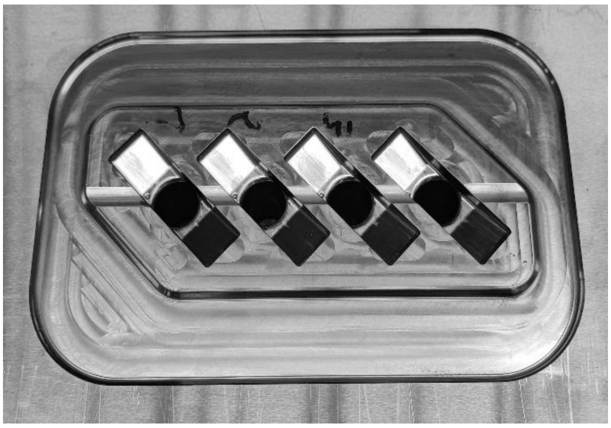

Fig. 5 *View of the single cavity for the slide block in the lower die for manual forging process*

Fig. 6 *View of the multi-cavity for the slide blocks in the lower die for automatic forging process*

Given the variability in lubrication and the extended production cycles in manual forging, accurately estimating the pre-forging temperature before forging is challenging. Therefore, average values observed during actual manual processes were used for the simulation. Conversely, in the simulation of automated forging, the anticipated target parameter values for shaping the brass slide block were applied. One of the primary factors influencing the durability of forging tools is the temperature at which they are initially preheated before the forging process begins. Hence, the accuracy of temperature estimates for the tested forging dies in both manual and automated forging processes was individually confirmed for the upper and lower dies using the FLUKE TiS45 thermal imaging camera. Figure 7 shows the temperature measurement result for the upper die, and Figure 8 for the lower die, after being heated with a gas burner for 30 minutes, during the execution of a standard production batch forged manually. Figure 9 shows the temperature measurement for the upper die, and Figure 10 for the lower die, both also heated with a gas burner for 30 minutes, but during the execution of a test batch in an automatic cycle.

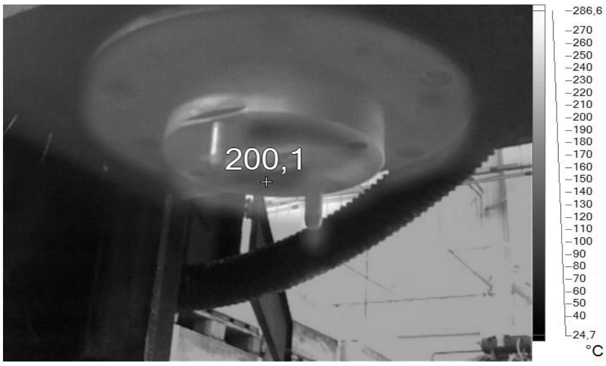

Fig. 7 *Temperature reading before commencing manual forging for the upper die*

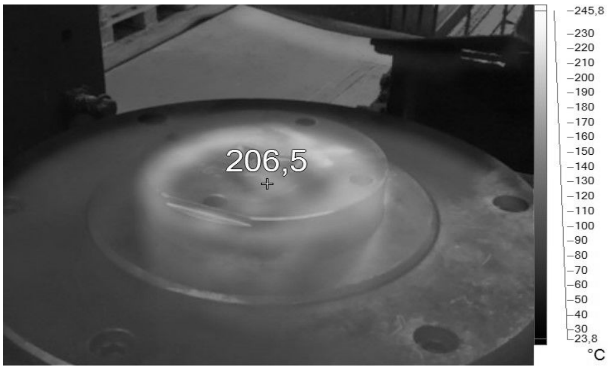

Fig. 8 *Temperature reading before commencing manual forging for the lower die*

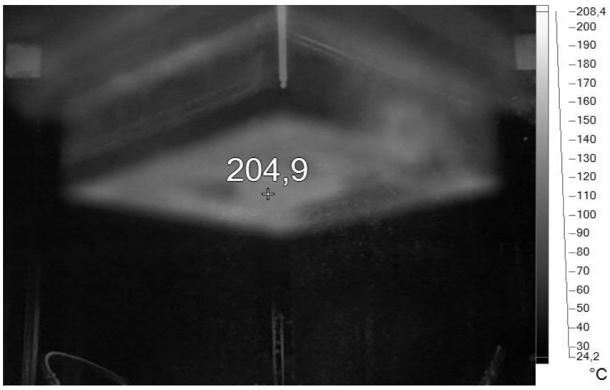

Fig. 9 *Temperature reading before commencing automatic forging for the upper die*

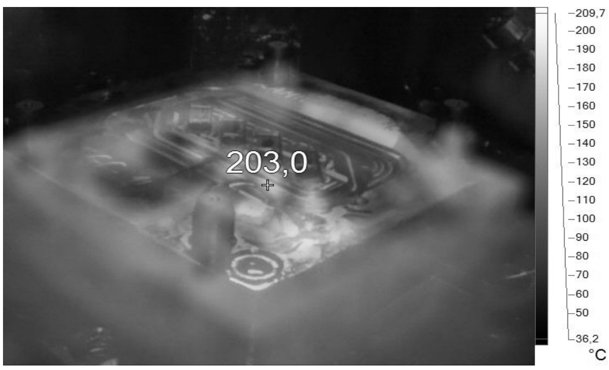

Fig. 10 *Temperature reading before commencing automatic forging for the lower die*

Under these established limits, the initial simulation was carried out to determine the press force needed for die forging during the first forging cycle after heating the tools. The outcomes are shown in Figure 11 for manual forging and in Figure 12 for automated forging.

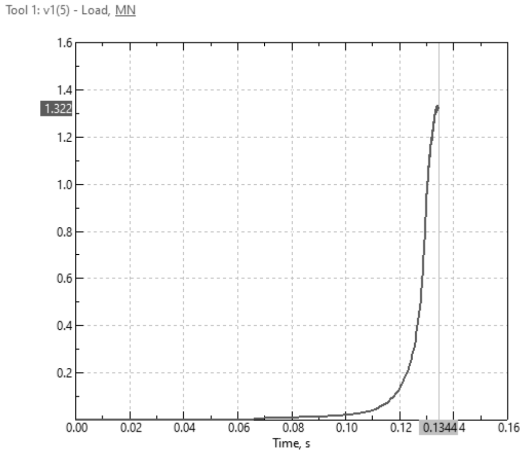

Fig. 11 *The progression of press force required during the initial forging of the brass slide block in the manual forging*

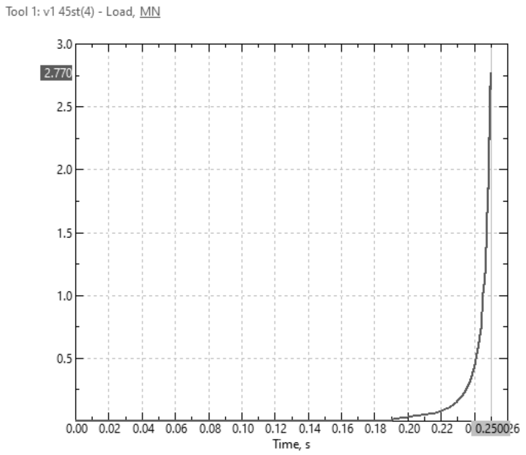

Fig. 12 *The progression of press force required during the initial forging of the brass slide block in the automatic forging*

The findings suggest that the force needed to forge the first piece after tool heating amounts to 1.322 MN in manual forging and 2.770 MN in automatic forging, marking an increase of more than double. However, considering that four forgings are produced at a time during the automatic cycle, the force required to forge a single forging is approximately 0.693 MN, which is nearly half the value required for a single forging during manual cycle, which should positively impact the extension of the life time of the forging dies. The simulation of the forging process aimed to predict the durability of forging tools under conditions closely resembling real-world scenarios necessitated the determination of the cycles required for the tools' temperature to stabilize. This is illustrated in Figure 13 for both manual and automatic forging processes.

For both manual and automatic forging processes, the number of applied forging cycles used to estimate the corresponding average operating temperature of the tools was 100, with their initial temperature set at 200°C according to previous measurements using a thermal imaging camera. The simulation showed a clear downward trend in the average temperature of the tools for manually performed cycles, with the final result being only about 124.5°C. It can be assumed that if further simulation were conducted, including additional manual production cycles, the tool temperature would continue to decrease, which would be significantly too low for proper forging and would primarily negatively affect the durability of the tools. For this reason, in actual manual forging processes, breaks are taken to reheat the forging tools, which unfortunately impacts the productivity in a given time unit. On the other hand, the simulation for the automatic forging process was stopped after obtaining the result for the 29th production cycle, where the average operating temperature of the forging tools was calculated at 192.3°C and showed stabilization at this level. It is clear that the shorter and more consistent cycle of the automatic forging process, combined with the consistent lubrication of the forging tools using oil + graphite, results in only a slight reduction in tool temperature from their initial value after heating and starting the process. Such simulated optimal working conditions of the dies should also contribute to extending their durability.

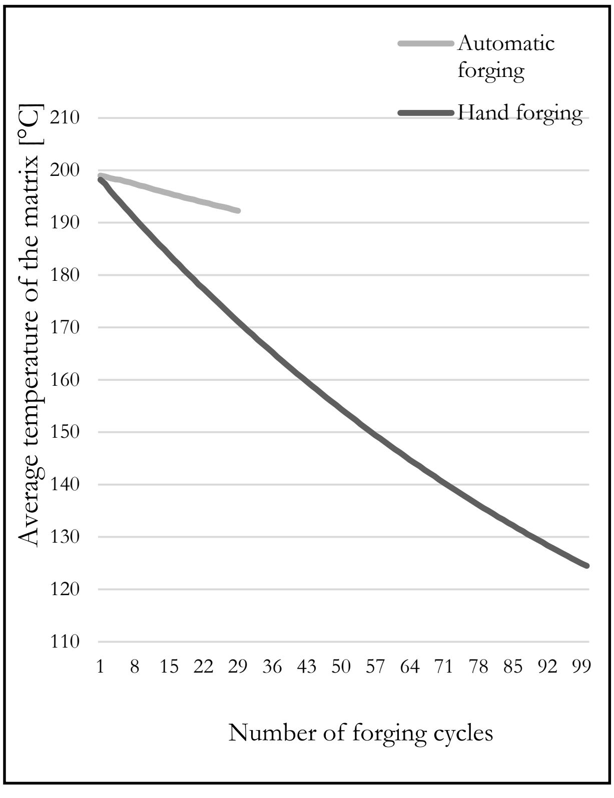

Fig. 13 *The average temperature of the die over a specified number of forging cycles*

By defining the forging process parameters and collecting data on the average die temperature for each cycle, the simulation aimed to predict the die's durability. The QForm UK 10.3.3 software includes integrated tools and algorithms for estimating the number of cycles until the first fatigue crack appears and for calculating the minimum and maximum stress in the tool. Simulation outcomes for manual forging are illustrated in Figure 14 and Figure 15, while those for automated forging are depicted in Figure 16 and Figure 17.

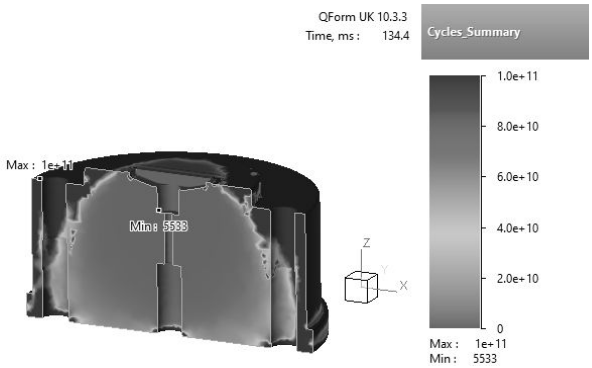

Fig. 14 *The lowest cycle count at which fatigue cracking initiates during manual forging*

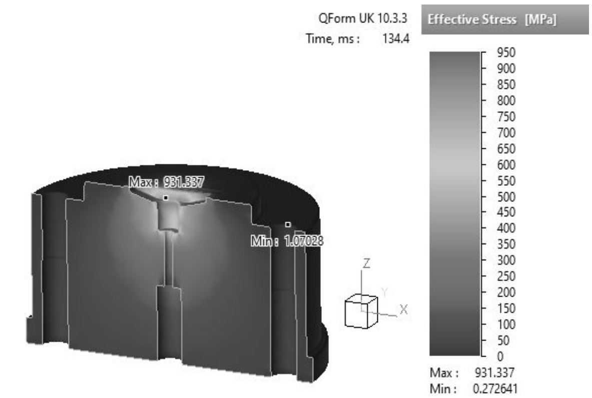

Fig. 15 *The stress levels at which fatigue cracking initiates in the die during manual forging*

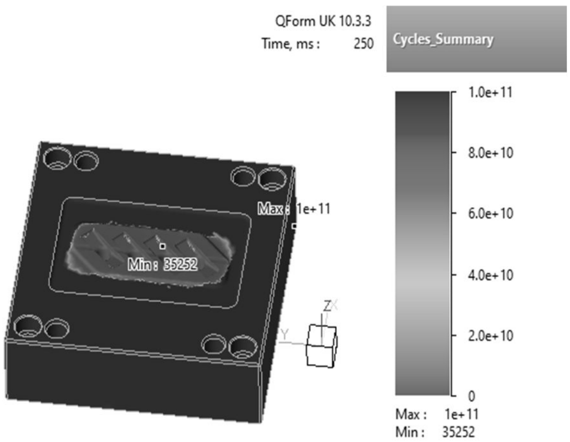

Fig. 16 *The lowest cycle count at which fatigue cracking initiates during automatic forging*

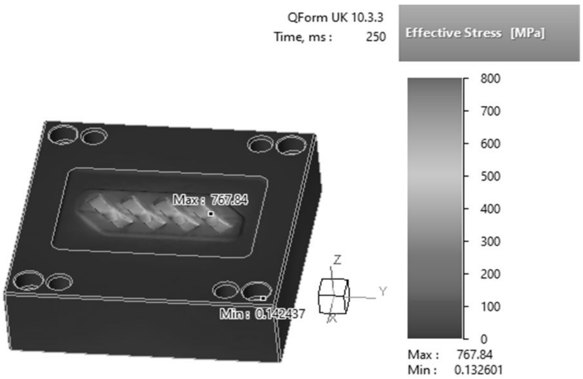

Fig. 17 *The stress levels at which fatigue cracking initiates in the die during automatic forging*

The computer simulation analysis shows that fatigue cracking in the die during manual forging starts approximately at the 5,533rd production cycle, with the die experiencing a peak stress of 931.337 MPa at that point. In contrast, during automatic forging, fatigue crack initiation occurs around the 35,252nd cycle, with the die reaching a maximum stress of 767.84 MPa. This highlights the potential for more than a six-fold increase in die durability with automatic forging, owing to shorter, more consistent production cycles carried out at higher temperatures. Additionally, the lower maximum stresses of 163 MPa observed in automatic forging simulations further support this finding compared to manual forging.

4 Conclusions and perspectives

Automation and robotization of manufacturing processes, including hot die forging, is an irreversible path in the industrial economy. Entrepreneurs seeking to remain competitive see opportunities for developing their technology or machinery by building and purchasing dedicated robotic stations tailored to their needs [33-34]. In many cases, this not only fills the gap caused by the lack of qualified workers in the market but also allows for a significant increase in the number of forgings produced per unit of time while ensuring consistent quality.

In the case of the hot die forging process, the introduction of automation and robotization helps to reduce the physical strain on human workers, who would otherwise have to perform tasks in contact with high temperatures and engage in repetitive, often force-intensive activities. Automation also significantly enhances the consistency of process parameters, which is unattainable in manual forging due to the high complexity of the forging operations, characterized by a large number of parameters that need to be precisely set and monitored in each machine cycle. Stabilizing the forging process parameters, in turn, ensures proper working conditions for the forging tools, leading to an increase in their durability.

Hot forging tools are subjected to intense destructive forces during their operation, including cyclically varying high thermal and mechanical loads. These demanding and complex operational conditions prompt entrepreneurs to seek methods and solutions to reduce tool wear, particularly considering the high costs of purchasing die materials and manufacturing processes. Besides automation and robotization of the process, another way to achieve a higher number of forgings before the tools are deemed unfit for use is the application of multi-cavity dies. These allow for the production of two or more forgings per machine cycle. In the analyzed case, four forgings were produced from a single heated preform. The research focused on simulating the durability of these specially designed dies in automated forging operations. This involved predicting the cycle count until the initial fatigue crack appears and identifying the range of stresses - both minimum and maximum - that occur within the tool under these operational parameters.

The obtained results clearly highlight the advantage of automatic forging over manual forging, achieved through stable process conditions and the performance of forging tools. Referring to the actual manual forging process, where a set of forging tools is deemed unfit for use after approximately 80,000 forgings, compared to the simulated moment of the first fatigue crack occurrence, which amounts to 35,252 forgings in the automatic cycle, and multiplying this by the 4 workpieces obtained during one die cycle, we get a value of 141,008 produced forgings. It is important to note that the initial signs of die wear often do not disqualify it from further use, so the actual die life for the automatic forging process should be significantly higher.

Using company resources efficiently for designing and manufacturing forging tools is crucial. Simulation programs for forging processes and tool durability can lead to significant savings. While these simulations cannot predict every tool failure, they provide valuable insights on potential fatigue cracks, aiding technologists in decision-making. Simulations help verify operational parameters and tool design, ultimately saving time and costs by reducing the need for real production tests and modifications.

Further investigation into the effect of automation on forging tool durability might include analyzing the hot die forging process with a multi-cavity toolset, but unlike the analyzed case where the preform was a single piece of material, each cavity in the die would be supplied with its dedicated preform. This should positively affect the mechanical loads on the die, thereby contributing to increased durability. However, this hypothesis requires confirmation through further testing.

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