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## A case study for improving tool life in cold forging: Carbon fiber composite reinforced dies

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### Abstract

Tool life affects the cost of the production significantly and it highly depends on shrink fitting conditions of die components in cold forging operations. The tensile strength of stress ring and shrink fitting rate of die insert are the most effective parameters on tool life. In this study, tool life of dies consisting of H13 steel stress ring were compared to dies with carbon fiber composite reinforced stress rings. Initially, two different composite dies were produced using Tenax-E IMS65 E23 24K 830tex and Tenax-J UMS40 F23 24K 800tex S carbon fibers by filament winding method. In order to determine the proper fiber orientation, numerical analysis of cold forging process was carried out on ABAQUS and SIMUFACT finite element softwares. According to numerical results,  $[90/\pm 45/\pm 15/90]_n$  fiber orientation was chosen for industrial application. It was found that the die made of Tenax-J UMS40 F23 24K 800tex S carbon fiber composite reinforced stress ring has the highest tool life and showed 25% higher tool life compared to conventional steel dies.

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### Introduction

Composite materials have become valuable structural materials in engineering due to their remarkable physical and mechanical behaviors [1]. Due to the recent improvements, composites have become highly preferred materials in automotive, aerospace, space and defense industries. Fiber reinforced polymer matrix composites are mostly used in engineering applications due to their good mechanical properties, high energy absorption capacity, fatigue strength, corrosion resistance, and high rigidity. Researches are mostly focused on usage of new materials as composite components and improving their mechanical properties. As a summary of these researches, fiber orientation was found to be most effective parameter on mechanical strength of fiber-reinforced composites [2]. Finite element simulations are extensively used to predict damage in the work piece during forming and tool life in metal forming operations. Numerical simulations are also efficient tools to determine the tool life of dies which greatly affect cost of forging operations. Input parameters to simulations like flow stress of work-piece material, forging velocity, friction conditions, mechanical properties of die materials and etc. have significant effects on the numerical results. Limiting parameters of shrink-fit method are compressive yield stress of insert material and tensile yield stress of stress ring. Forging companies have to utilize modern techniques that increases profitability to remain competitive in a global market. In the prediction of tool life, mathematical models are based on effective stress or strain [3]. E-glass and carbon fiber composite stress rings are used in different applications such as fixing oil pipes, building beams, and even mechanical parts of printing presses [4]. There are studies in the literature concerning the mechanical properties of composite tubes produced via filament winding method and the usage of these composites in design

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applications. Blast strength of composites consisted of carbon fibers were found to be higher than the composites with E-glass fibers and maximum blast strength was found in  $[\pm 54]_3[90]_1$  fiber orientation. In addition to that, stress-strain curves and elastic modulus along circumferential direction were determined [5]. Fatigue tests were performed on die material and results were used to predict the tool life of the dies and the experimental results were coupled with finite element simulations [6]. In a study, a rotating bending fatigue test and a three bending fatigue tests were carried out on a fine grained WC/Co cemented carbide to estimate WC/Co fatigue crack growth behavior and fatigue lifetime. As a result of these experiments, S-N curves were determined at different stress ratios. Also it was seen that calculated S-N curves at different stress ratio values and results calculated using modified linear elastic fracture mechanics were seen to be in good agreement with the experimental curves [7]. In another study, tool life of cold forging dies with WC/Co die inserts were determined by using finite element simulations. Material flow, effective stress and strains were used to predict the tool life. As an extraction of these experiments, one of the most important modern technique is finite element method that determined the tool life and expedite the production process [8]. Numerical stress distribution was found to be comparable to experimental stress distributions and principle stress was predicted by using haigh diagrams. It was also seen that increasing the pre-stress pressure led to increase in tool life.

Prediction of cold forging tool life used in the production of fasteners is very crucial to decrease the production costs. Appropriate tool design for high tool life which is based on experience is very difficult for the first time production of a complex shaped fastener. Low cycle die damage occurs when forging of complex shaped products having high added value and this leads high costs and production with low efficiency. At this point, it is crucial to increase tool life to lower the production costs of complex shaped products. Motivated by these facts, Tenax-E IMS65 E23 24K 830tex (IMS65) and Tenax-J UMS40 F23 24K 800tex S (UMS40) carbon fiber composites were used in stress rings instead of conventional tool steel to create higher compressive stress on the die insert surface in this study. Therefore, tool life of the cold forging dies were aimed to increase significantly. For this purpose, cold forging operation of a bolt was performed using both composite and conventional steel dies then tool life was compared.

## 2. Materials and Method

Schematic representation and the picture of a cold forging die are shown in Fig. 1(a) and (b). Here,  $\delta$ ,  $R_{ISR}$  and  $R_I$  are interference value of shrink fitting, inner radius of stress ring and radius of insert, respectively. A typical forging die consists of insert and stress ring as depicted in the figure. Inserts and stress rings of cold forging dies were assembled to each other by shrink-fitting method. In this method, insert is cooled down and the stress ring is heated up. The aim of the shrink-fit method is to create compressive stresses on the insert surface to get higher fatigue resistance.

Die inserts used in this study were made of WC/Co (also called as G materials). Compressive yield stress of these materials ranges between 3100 and 3400 MPa. Mechanical properties of G55 (WC/27Co) are given in Table 1. Inserts were machined to achieve better surface condition and tight dimensional tolerance for shrink-fit operation. Insert material is shown in Fig. 2 for raw and machined conditions respectively.

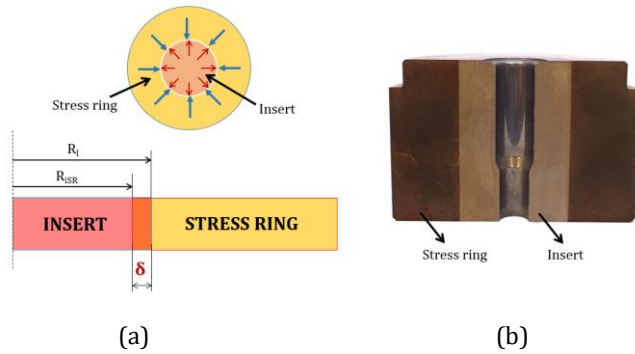


Fig. 1 (a) Schematic representation and (b) cross-sectional picture of a cold forging die  
 Stress rings of conventional cold forging dies are made from H13 (DIN 1.2344) steel having tensile yield stress of 1300 MPa, approximately. Chemical composition and mechanical properties of H13 steel are given in Table 2 and Table 3, respectively.

Table 1 Mechanical properties of G55 [9]

Chemical composition (Co % weight)	27
Density (g/cm <sup>3</sup> )	12.95
Compressive strength (MPa)	3000
Young modulus (GPa)	440
Thermal conductivity (Wm <sup>-1</sup> K <sup>-1</sup> )	90
The average coefficient of thermal expansion (10 <sup>-6</sup> K <sup>-1</sup> )	6.9

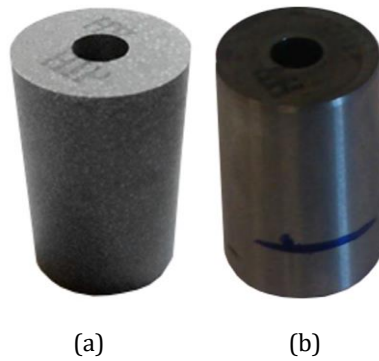


Fig. 2 G55 insert; (a) raw and (b) machined

Table 2 Chemical composition of H13 [10]

C	Si	Mn	Cr	Mo	V
0.39	1.0	0.4	5.3	1.3	0.9

Table 3 Physical and mechanical properties of H13 [10]

Density (kg/m <sup>3</sup> )	Young modulus (GPa)	Yield strength (MPa)		Tensile strength (MPa)	
		45 HRC	52 HRC	45 HRC	52 HRC
7.8	210	1280	1520	1420	1820

Filament winding method is based on fiber winding on a mandrel in which fibers are sunk into heated resin. Desired mechanical properties of fiber reinforced composite materials can be achieved by changing winding angle and production process is completed by winding enough number of fibers. In the following part, drying/curing process is carried out at room temperature or high temperatures in furnaces. Filament winding method is a fast and economically efficient method in which amount of resin can be controlled easily. In this method, orientation of fibers can be changed for each layer during winding process which gives mechanical strength to material in desired directions [11, 12]. Schematic representation of filament winding method is given in Fig. 3.

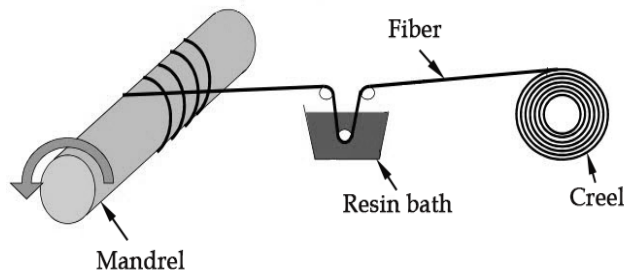


Fig. 3 Schematic representation of filament winding process

In the design of composite stress rings, fiber orientations should be the same though the directions in which maximum tensile stresses are generated. Mechanical properties of UMS40 and IMS65 carbon fibers that were used as reinforcement elements of stress rings in cold forging process are given in Table 4.

In this study, Huntsman Araldite MY740 and Aradur HY 918 having low viscosity and high mechanical properties were used as adhesive and hardener, respectively. Physical and chemical properties of adhesive and hardener are given in Table 5. After combining of carbon fibers and resin in winding method, curing process was applied to composite rings at 80 °C for 2 hours firstly and 120 °C for 8 hours as follows. Photographs of carbon fibers and composite tubes are shown in Fig. 4.

Table 4 Mechanical properties of carbon fibers [13]

Mechanical properties	Tenax-E IMS65 E23 24K 830tex	Tenax-J UMS40 F23 24K 800tex S
Tensile strength (MPa)	6000	4700
Tensile modulus (GPa)	290	395
Elongation (%)	1.9	1.2
Density (g/cm <sup>3</sup> )	1.78	1.79
Filament diameter (µm)	5	4.8

Determination of ratio between fiber and matrix materials in a composite is so essential to achieve desired mechanical properties. At this point, mechanical behavior of composite material is improved by increasing the volume of fibers while fiber holding ability of matrix material is decreased with increasing fiber content in the composite. By considering this fact, fiber content in stress rings was selected as 55% in the study.

Table 5 Physical and chemical properties of adhesive and hardener [14]

Physical properties	Araldite adhesive	MY740	Aradur hardener	HY918
Viscosity (25°C)-(mPa.s)	10,000-14,500 ISO 12058		50-80 ISO 12058	
Density (25°C)-(g/cm <sup>3</sup> )	1.15-1.20		1.18-1.24	
Mixing ratio (weight)	100		80	
Flash point (°C)	>200		159	



Fig. 4 UMS 40-IMS 65 carbon fiber rolls (a) and composite tubes with fiber orientation of  $[90/\pm 45/\pm 15/90]_n$  (b)

### 3. Design of Forging Dies and Stations

In the design process of cold forging of fasteners, the highly required facts are experience and usage of modern design tools like CAD and CAE. The fastener (bolt) which was formed by using carbon fiber composite reinforced dies has four forging stations; i) pre-taper, ii) taper, iii) pre-heading and iv) heading steps. Bolt shapes in all forging stations are shown in Fig. 5. Considering the whole forging process of the shown bolt, carbon fiber composite stress ring was used in the 4<sup>th</sup> forging station (stationary heading die) as shown in Fig. 6.

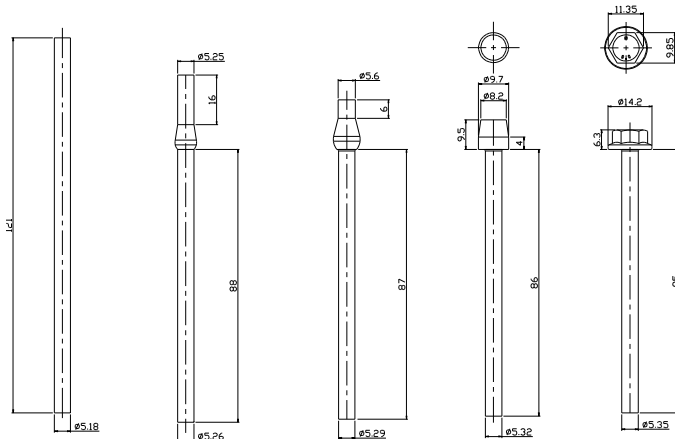


Fig. 5 Preformed shapes of the bolt in four forging stations

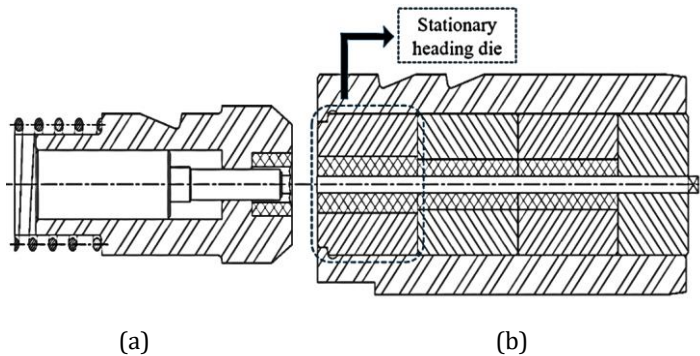


Fig. 6 4<sup>th</sup> forging station; (a) moving and (b) stationary dies

## 4. Results and Discussions

### 4.1. Analysis of Shrink Fitting

There are analytically developed methods available in the literature for optimization of shrink fitting of dies. However, these methods give poor predictions for dies having complex geometries. For any forging condition, certain shrink fitting ratios are prescribed when dies with complex geometries are present to carry out operations safely. Numerical simulations are also useful tools to determine these specific shrink fitting values. Conventional shrink fitting ratio is generally taken as 0.5%. Usage of carbon fiber composite reinforced stress rings allow us to use higher shrink fitting ratios than 0.5% due to high tensile yield strength of carbon fiber composites. Numerical simulations showed that shrink fitting ratio of 2.857% for UMS40 and 3.429% for IMS65 carbon fiber stress rings can be achieved. By using these shrink fitting ratios, numerical stress analyses of

press fit operation were carried out with ABAQUS finite element software. Distributions of minimum principle stress on dies for different ring material are shown in Fig. 7. When these shrink fitting ratios were applied, compressive residual stresses were seen to increase approximately 18% in contrast to shrink fitting ratio of 0.5% for both cases. This leads to decrease in tensile strains which results a significant increase in tool life.

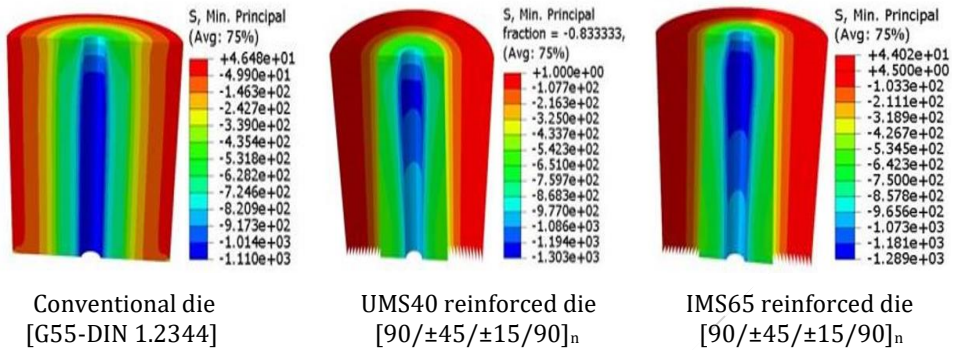


Fig. 7 Distributions of minimum principal stress in dies after shrink fitting

#### 4.2. Prediction of Tool Life

In this part of the study, increased shrink fitting ratios were applied to the 4<sup>th</sup> stationary heading die to determine tool life. Morrow equations [15] were used for tool life calculations of WC/Co die insert material. In the models, materials for insert and stress ring were taken as G55 and H13, respectively and they were modeled as linear elastic. Work piece material was selected as 20MnB4 steel alloy. Three stations were modeled in 2D axisymmetric while the 4<sup>th</sup> station was modeled in 3D. In the simulations, calculated stresses in the work piece in previous stations were transferred to next stations to consider the pre-forming effects. In these analysis, shrink fit ratios are higher than the conventional ones. Here, approximately 7‰ shrink fitting ratio was used

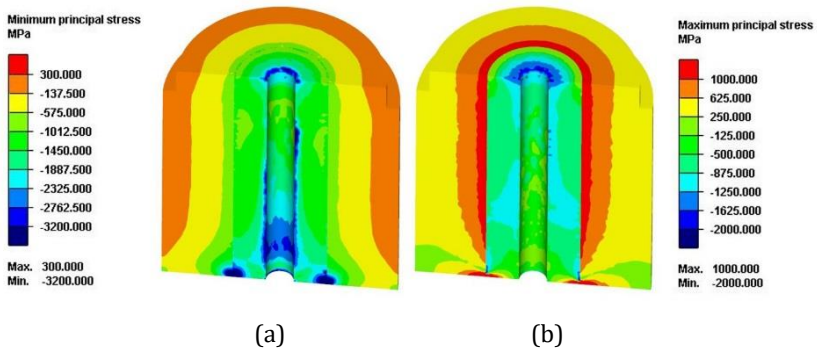


Fig. 8 Distribution of (a) minimum and (b) maximum principal stresses

Forging was conducted with 7‰ shrink fitting ratio numerically and distributions of minimum and maximum principle stresses on the stress ring and insert are shown in Fig. 8(a) and (b), respectively. As depicted in the figure, both principal stresses were found to be lower than yield stress of insert and stress ring materials. When the results were



compared to generated stresses on dies having 5% shrink fitting ratio, it was found that die stresses decreased approximately 18%.

### 4.3. Preparation of Dies and Forging Trials

Technical drawings of die insert and stress ring designed to be used in numerical calculations are shown in Fig. 9. In the machining process of composites, proper cutting tools were selected and used. Inner diameters of carbon fiber composite reinforced stress rings are given in Table 6.

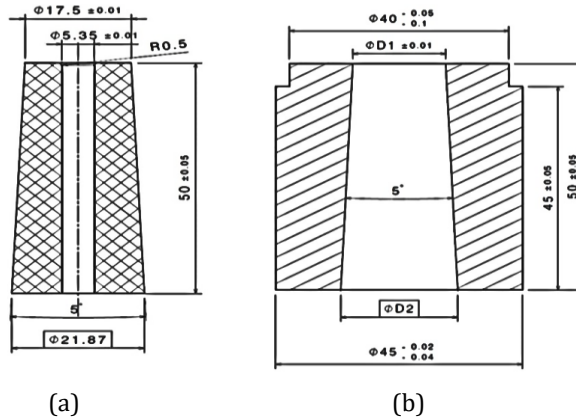


Fig. 9 Technical drawings of (a) die insert and (b) stress ring of 4<sup>th</sup> station heading die

Table 6 Geometric values of stress ring drawing

	UMS40	IMS65
$\phi D1$	$\phi 17.00$	$\phi 16.90$
$\phi D2$	$\phi 21.37$	$\phi 21.27$

After shrink fitting process at press machine, the surfaces of dies were polished as shown in Fig. 10. Polished dies were then assembled to forging machine for trial applications.

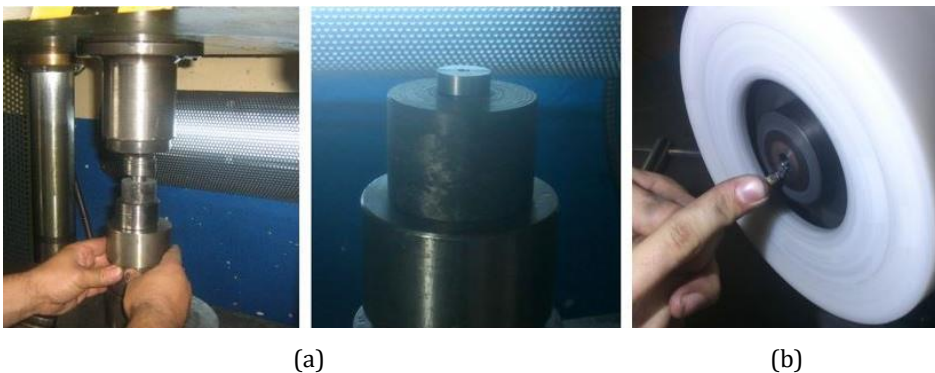


Fig. 10 (a) Press fitting and (b) surface polishing

Conventional die having H13 stress ring, UMS40 and IMS65 carbon fiber composite stress rings having  $[90/\pm45/\pm15/90]_n$  fiber orientation with G55 die insert are shown in Fig. 11(a), (b) and (c), respectively.

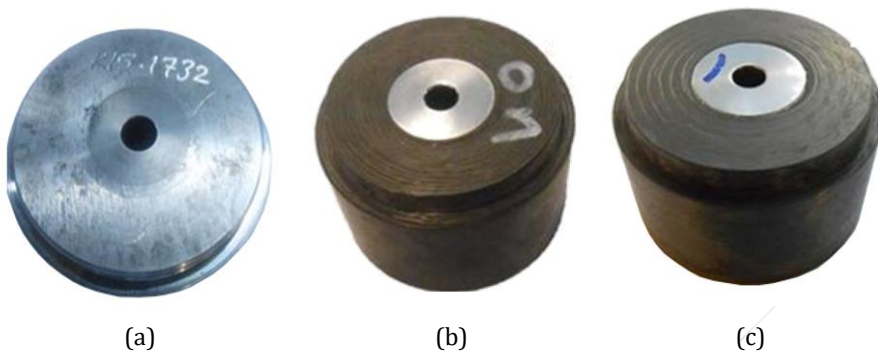


Fig. 11 (a) Conventional, (b) UMS40 and (c) IMS65 composite dies

Before application of composite dies, tool life of conventional dies was determined and estimated as 500.000 ppd (parts per die). First application was conducted with die having  $[90/\pm45/\pm15/90]_n$  fiber oriented UMS40 carbon fiber composite. Tool life of this die was determined as 625.000 ppd (approximately 25% higher production value). However, fiber abrasion which leads to loosening of shrink fitting between stress ring and die insert was observed. Due to this situation, deviation of die insert led to complete die failure. Lastly, IMS65 composite die was used in the forging application and the die experienced failure after completing 125.000 ppd. Tool life of dies are given in Fig. 12.

Stereo zoom microscope images of failed composite stress rings are given in Fig. 13. During the forging of the work-piece in each station, a part of plastic deformation energy is converted to heat which leads to increase the material temperature. Because of that, abrasion occurred on the carbon fiber composite reinforced die stress ring surface due to exceeding the resin glass transition temperature during cold forming process. Therefore, shrink fit ratio between die insert and stress ring was decreased and flexure began on the die leading to out of distortion tolerance. As a result, dies having carbon fiber composite reinforced stress ring failed. According to the productions trials conducted with UMS40 carbon fibers showed better strength and resistance than IMS65 carbon fibers. Tool life of die with UMS 40 carbon fiber composite was determined to be approximately 5 times longer production value.

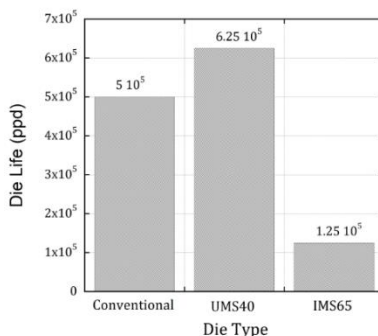


Fig. 12 Tool life of metal and composite dies

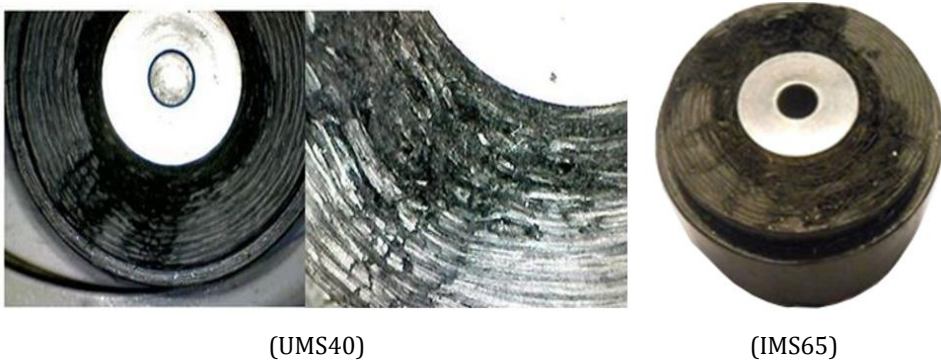


Fig. 13 Stereo zoom microscope images of composite dies

## 5. Conclusions

In the cold forging process of fasteners, tool life can be very low due to complexity of forged parts. This leads to significant increase in production costs. In recent years, composite materials become popular in engineering applications due to their mechanical properties such as high strength to density ratios. In this study, composite tubes have chosen and produced by using IMS65 and UMS40 carbon fibers due to the high strength and high Young modulus. These were then used as stress rings in cold forging dies and tool life were compared to conventional H13 dies. Stress and forming analysis were carried out with ABAQUS and SIMUFACT finite element softwares. According to investigations, below conclusions were drawn from the study;

- It was found that the proper fiber orientation for this application was determined as  $[90/\pm 45/\pm 15/90]_n$ .
- It was determined that fiber content about 55% is adequate to use in composites for stress ring application.
- By using composites in dies, the minimum compression stress on the die insert was increased approximately 18% compared to conventional steel dies.
- Tool life of UMS40 composite die was 5 times higher than IMS65 composite die.
- It was determined that stress rings with UMS40 and IMS65 have approximately 33% and 14% higher cost than conventional steel dies, respectively.
- Tool life of UMS 40 composite die was found to be approximately 25% higher than conventional die.
- Composites were seen to applicable to forging dies however production cost of composite dies and total die consumption should be considered and compared for industrial application.

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