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EVALUATION OF WEAR IN DIE MATERIAL FOR WARM FORGING PROCESS +

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Abstract :

In this work the methodology to evaluation the abrasive wear in closed warm forging die blocks material were manufactured from hot work tool steel H13 in two conditions; unquenched and quenched and tempered (QT). Two hundred flat countersunk head rivet are produced by warm forging operation, 100 forging (rivet) in each die block material.

The wear in die is evaluated by implementing a methodology of measuring the used (worn) dies profile by a coordinate measurement machine CMM, then compensate the predicted plastic deformation die surface by using FEM-simulation code DEFORM^{TM}-2D to separate the captured wear depth in die surface profile. The measured (separated) wear depth is used in Archad's wear model to estimate the experimental wear coefficient (K) in order to comparing it with the predicted (numerical) wear coefficient (K) from simulation of forging operation. The suggestion of a new wear coefficient (K) to optimizing the forging process, gives the designer a possibility of forecasting the reached wear level.

The numerical results showed a good agreement with experimental where the maximum differences are (12 % and 12.6 %) for unquenched and quenched and tempered die material respectively.

حساب البلى لمادة القالب في عملية التشكيل الدافئ

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المستخلص :

في هذا البحث تم دراسة كيفية حساب البلى التآكلي لوحدة القالب (Die Blocks) لقالب الطرق الدافئ المغلق مصنعة من فولاذ العدد المقاوم للحرارة H13 بحالتيه الغير مصلد والمصلد والمراجع. استخدمت تلك القوالب لإنتاج 200 برشام ذو رأس مسطح مخفي بواسطة عملية الطرق الدافئ ، 100 مطروقة (برشام) بكل قالب.

يتم حساب البلى التآكلي من خلال تطبيق منهجية (آلية) تتضمن قياس المقطع الجانبي للقوالب المستخدمة (المبلاة) بواسطة ماكنة قياس الأبعاد الثلاثية (CMM) بعد تعويض التشويه المرن لسطح القالب المتوقع من استخدام برنامج محاكاة بطريقة العناصر المحددة FEA(DEFORM 2D^{TM}) لفصله عن عمق البلى.

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تم استخدام عمق البلى المقاس في نموذج ارجرد الرياضي (Archard's Model) لحساب معامل البلى (K) الثابت عملياً ومقارنته بمعامل البلى (KPred.) المتوقع (النظري) بطريقة العناصر المحددة FEA لتحسين عملية الطرق من خلال اقتراح معامل بلى تآكلي (K) جديد.
أظهرت النتائج النظرية توافق كبير مع النتائج العملية حيث أن أكبر فرق كان (12%) و (12.6%)لكل من القالب الغير مقسى و والقالب المقسى والمراجع على التوالي.

1. Introduction :

Metal forming is a widely used manufacturing process known for its minimum wastage, high-dimensional precision, and improved mechanical properties of the formed part [1]. For a given weight, parts produced by forging exhibit better mechanical and metallurgical properties and reliability than do those manufactured by casting or machining [2]. The temperature range of steel warm forging processes is approximately 300–600℃. Only low carbon steel can already be forging between 260 and 600℃. The biggest benefit of warm forming compared to hot forming is the higher achievable accuracy [3]. Die life in warm forging is affected by wear in over 70%, the die wear is faster than those of hot forging and cold forging [4]. Die wear is mostly influenced by the hardness of the die material and other material properties such as toughness and ductility. The amounts of wear are proportional to the wear coefficient between the die and the work piece and inverse the hardness of the die [5].
[Tulsyan, 1993][6] And [Painter et al, 1995] [7] investigated the use of the finite element code, DEFORM, together with a post-processing code (written by the authors) to predict die wear in extrusion of automotive exhaust valves. Coefficients in the equation were then determine by regression to approximate the wear profiles observed in experiment. Die and work piece hardness was determined by hardness-temperature polynomials input by Painter et al [7] and Changhyok et al. [8] The abrasive and adhesive models used by Painter et al, are giving in Equation 1 & 2 respectively:

$$Z_{AB} = \int K_{abr} \frac{P^{a1}.v^{b1}.dt}{H_d^{c1}} \quad \ldots\ldots\ldots\ldots\ldots (1)$$

$$Z_{AD} = \int K_{adh} \frac{P^{a2}.v^{b2}.dt}{H_d^{c2}} \quad \ldots\ldots\ldots\ldots\ldots (2)$$

Where:
Z_{AB}: Abrasive wears depth in (mm),
Z_{AD}: Adhesive wears depthin (mm),
P: Local pressure in (N/mm^2),
v: Local sliding velocity in (mm/s),
H_d: Tool hardness in (N/mm^2), and
a_1, b_1, a_2, b_2: Experimental constants, taken as 1.

For abrasive wear on steel dies, c_1 = two and for adhesive wear c_2 =one, although according to some literature the hardness coefficients may vary between 0.5 and 2.5. The theoretical die wear is predicting by FEM and applying wear models, and then the theoretical predicted profile is compare and improved with the experimental die profile [9].

R.S. Lee and J.L. Jou (2003) [4], studied the combinations between the experimental techniques, wear model and numerical simulation method to predict the wear of warm forging die, and estimate the friction coefficient in different temperatures. The wear coefficients in different temperatures acquired from high temperature wear experiment. Finally, the Archard wear theory and DEFORM with FEM code, were used to analyze the warm forging of automotive transmission outer-race and predict the die wear condition.

B.A. Behrens et al., (2008) [10] developed a warm forming process sequence of production a long flat pieces (steering link) by selecting the best suitable hot performing technology to obtain the desired mass distribution and offset and adapt the technology to the specific requirements of warm forming. The FE-simulations were performed with the 3D-software Forge3 is used.

S. Abachi et al., (2010) [3] presented the wear analysis of a closed hot forging die used at the final stage of a component has been realized. The simulation of forging process was carried out by commercially available software (MSc. Super Forge.) based on finite volume method and the depth of wear was evaluated with a constant wear coefficient. By comparing the numerical results with the measurement taken from the worn die, the wear coefficient has been evaluate for different points of the die surface and finally a value of wear coefficient is suggested.

C. Choi et al., (2012) [11] estimated the abrasive die wear and plastic deformation in a warm forging operation, using a tempering parameter. This methodology consists of the determination of the steady state dies temperatures using multiple FE simulations. The calculated temperatures is used to predict the plastic deformation of the dies, while, measuring the surface profile of the worn dies by Coordinate Measuring Machine (CMM), identifying the wear profiles caused by abrasive wear and plastic deformation. Determinations of the abrasive wear parameters leads to estimation of die wear for future warm forging.

Warm forming of steel is an economic and ecologic alternative to the conventional hot forging technology. It offers several advantages like reduced energy input, no scale formation and reduced decarburization, and reduced surface roughness and closer tolerances [3]. Wear effected Over 70% of die life in warm forging [4]. This kind of failure affected not only the cost but also the tolerances of forging [5].

2. Methodology of Estimations :

The used methodology for estimating plastic deformation and abrasive wear is outline below [5]:

- Conduct finite element analysis of the steady state temperature distribution of the dies, using multiple operations using DEFORM- 2D, a commercial FE software package.
- Estimate the plastic deformation from the results of the steady state temperature distribution of the dies.
- Extract the wear profile from the measured die surface profile (obtained by CMM) by separating the plastic deformation from abrasive wear.
- Determine the abrasive wear parameter (K), in order to predict abrasive wear on the die surface.

A commercial code DEFORM-2D is using to predict the abrasive wear and plastic deformation. Constant die hardness assumed constant at a steady state temperature of die, and then compute the amount of wear applying the Archard's wear model. Finally the wear parameter (K) is mathematically optimized (to give the minimum difference between the predicted and actual worn die profile), and then verified by comparing the predictions with the experimental results.

3. Experiments :

3.1 Material Properties :

A flat produced countersunk head rivet was select in this research by warm forging of the circular billet of low carbon steel (AISI 1015). The chemical composition and required mechanical properties of AISI 1015 steel are listing in tables 1 and 2 respectively.
The die used in present work was manufactured from a hot work tool steel (AISI H13) in two conditions as received from supplier (hot rolled–annealed) and the second condition quenched and tempered. The chemical composition and required mechanical properties are list in tables 3 and 4 respectively:

3.2 Pin on Disc Wear Test :

The specimens (pin) were make from H13 tool steel (die block material) which is used in present work according to ASTM G-99 specification. The (62 HRC) hardened tool steel disc was used. The relative motion between the two is such that a circumferential wear path on the moved disc surface is generate. The experiment conditions are listing in table 5 below.

4. Finite Element Modeling :

Finite element analysis code DEFORM was used to simulate the warm forging processes of flat countersunk head rivet and geometric representation of the punch, workpiece with its mesh structure and dies in **DEFORM 2D V10** shown in Fig. 2. Note that instead of a 3D model an axisymmetric model is use, since use of an axisymmetric model greatly reduces the modeling and analysis time compared to that of an equivalent 3D model without compromising the accuracy.
By assuming the punch and die are rigid (do not undergo plastic deformation) and their elastic deformation have a negligible effect on deformation of the workpiece to predict the forming load and temperature distribution of billet and die. Then, second step was a die stress analysis by assuming the punch and die as elasto-plastic body. The applied force was interpolate from the final step of load prediction stage, to predicting the wear and plastic deformation of die. The flow stress and material properties are obtained from DEFORM 2D material library.

4.1 Temperature Analysis of Forging Operation :

4.1.1 Billet Temperature Distribution :

A cylindrical (Ø12 X 38 mm) AISI steel (1015) billet was initially heating in the induction furnace to a uniform working temperature about (465 ^{o}C). The billet lose some of heat when exposed to environment for several seconds (8-12 sec) while transfer it from furnace to place it in forging die. Based on case studies conducted by [12], the used heat convection coefficient was 0.02 kW/m^2-K to account for heat loss to the environment of temperature 25°C. This results in a non-uniform temperature distribution in the billet as shown in Fig. 3.

Table (1): Chemical Composition of AISI 1015 Steel.

Element	C%	Si%	S%	P%	Mn%
Nominal*	0.17	0.300	0.045	0.045	0.40
Actual **	0.176	0.243	0.040	0.030	0.42
Element	Ni%	Cr%	Mo%	Cu%	
Nominal*	—	—	—	—	
Actual **	0.079	0.091	0.050	0.090	

** From Key to Steel Handbook (2001)*
*** Tested by (ALR spectrometer) device.*

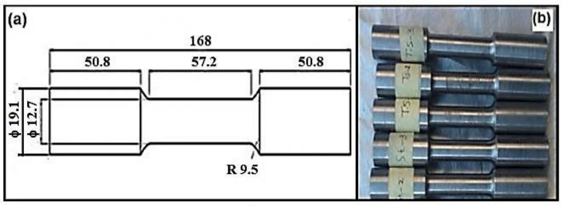


Figure (1): Tensile Specimen
(a) Geometry according ASTM E8. (b) Photo

Table (2); Mechanical Properties of AISI 1015 Steel

Property	UTS (MPa)	Y.P (MPa)	Young Modulus (GPa)
Nominal*	440	350	210
Actual **	480	325.7	216
Property	EL.*** (%)	Hardness (HB)	
Nominal*	25	—	
Actual **	33.5	150	

** From Key to Steel Handbook (2001)*
*** Average of five standard tensile specimens according ASTM E8 (Figure 1). Tested by ((Tenius Olsen) tension test device.*
**** Elongation for gauge length (L_o= 50 mm)*

Table (3): Chemical Composition of (AISI H13) Tool Steel

Element	C%	Si%	S%	P%	Mn%
Nominal*	0.42	1.20	0.02	0.03	050
Actual	0.40	0.93	0.01	0.01	0.40
Element	Ni%	Cr%	Mo%	Cu%	
Nominal*	---	5.50	1.50	---	
Actual	0.06	5.20	1.34	0.05	

** From Key to Steel handbook (2001)*
*** Tested by (ALR spectrometer) device*

Table (4): Mechanical Properties of (AISI H13) Tool Steel at Room Tempearture.

Property	UTS (MPa)	Y.P (MPa)	Young Modulus (GPa)
Nominal**	730 (1960)	649 (1575)	216 ——
Actual***	680	404.33	226
Property	EL.* (%)	Hardness (HRC)	
Nominal**	26.0 ——	22 (52)	
Actual***	25.6	22 (52)	

** Elongation for gauge length (L_o=50 mm)*
*** From Key to Steel Handbook (2001)*
**** Avverage of five tensile specimens according ASTM E8*
( ) For qumche d and tempered AISI H13 from (ASM Metals Handbook Vo.04.

Table 5: Conditions for Wear Test

Disc	Hardened Tool Steel (62 HRC)
Pin	Un-quenched (22 HRC) H13 quenched and tempered (52 HRC)
Temperature (°C)	Room Temperature 25°C
Nominal Force (N)	10, 20, 30, 40 and 50
Sliding Velocity (m/s)	1
Sliding Length (m)	1800
Lubrication	None

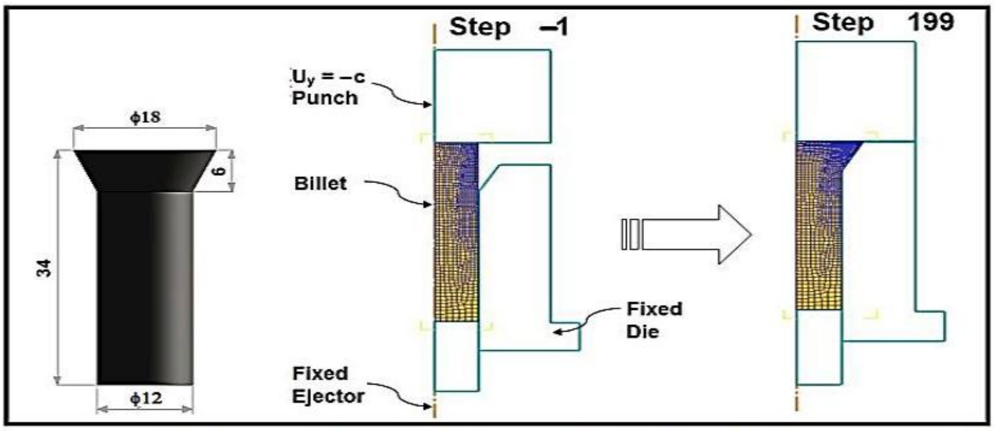


Figure (2) Standard countersunk flat head rivet modeled with the applied boundary conditions.

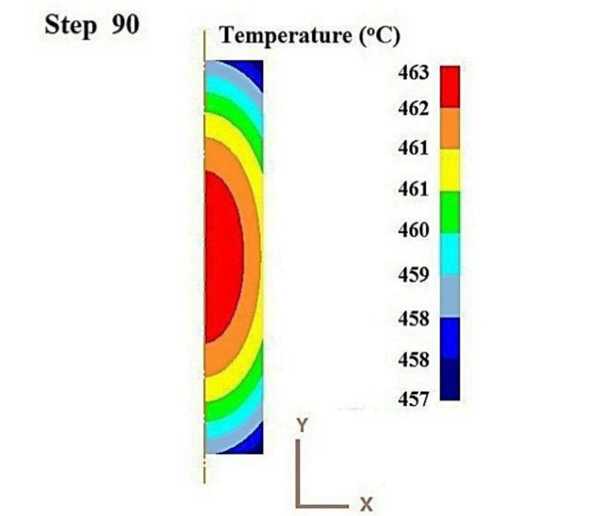


Fig. (3): Billet Temperature After Environment Exposure.

4.1.2 Die Temperature Distribution :

Based on case studies conducted by [12], the default interface heat-transfer conditions during forging (heat transfer coefficient of (11 kW/m^2-K) and free resting (heat transfer coefficient of (one kW/m^2-K) and the found default interface friction conditions (Shear friction coefficient of 0.25) are from DEFORM™ to give accurate results. The die was assume as rigid, based upon experimental data obtained from ring compression test the friction conditions are [13]. In any forging process, the dies get heating, as the parts are forge one after another. This absorbed heat is lost to the atmosphere, as more parts are forged, the temperature distribution at contact with the workpiece in the dies changes until it reaches a quasi-steady state (no increase in the max. temperature in the dies), and the temperature variation at different points on surface of die is shown in Fig.4 and Fig. 5 respectively.

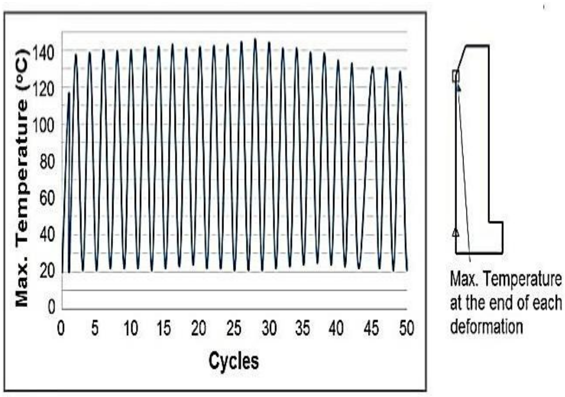
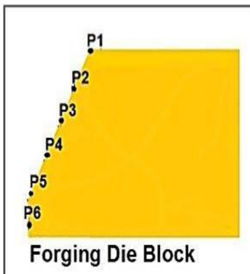


Fig. (4) Variation of Max. Temperature in Forging Die for 50 Forging Cycles



Position	Start of Cycle Temperature (°C)	Max. Temperature (at End of Deformation) (°C)
P1	75	111
P2	86	112
P3	89	115
P4	93	113
P5	125	131
P6	127	140

Fig. (5): Temperature Variation at P1, P2, P3, P4, P5 and P6 at the End 50th Forging Cycle.

4.2 <u>Stress Analysis of Forging Operation :</u>

The elasto-plastic assumed tooling. The maximum effective stress location in forging die block during (deformation) operation of the 100 forging cycles shown in Fig. 6. The yield stress of die material (680 MPa & 1372 MPa) is pass of unquenched, quenched and tempered die block respectively, which is means a die block plastically deformed.

5. <u>Results and Discussion :</u>

5.1 <u>Wear Behavior</u> :

Fig. 7shows the variation of wear rate with load for quenched, tempered, and unquenched tool steel. The wear rate increased rapidly by 75% especially under the load ranging (10 to 20 N) and (30 to 40 N) with subsequent increase by 23% under the load from (20 to 30 N) and (40 to 50 N), the wear rate of low hardness. (22 HRC) H13 still tendency to be increase, because of low hardness and low strength of unquenched H13 lead to plastically deforming of asperities and remove the material from the pin surface. However, the high hardness (52 HRC) H13 tool steel had a relatively a constant slower increasing tendency and lower wear rate than unquenched H13 because the wear rate strongly depended on hardness, where the wear rate increased by 16%.

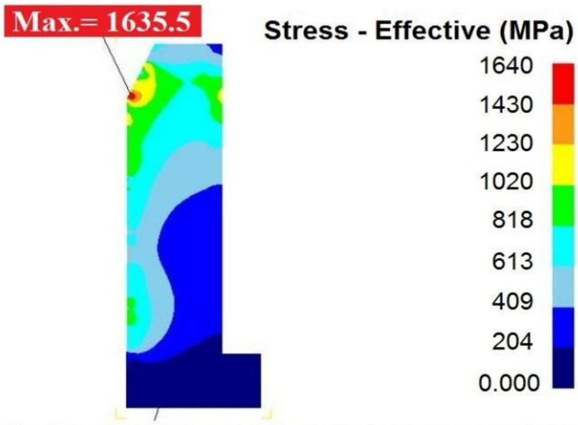


Fig. (6): Max. Effective Stress Location in the Forging Die Block During Forging Operation of 100th Cycle.

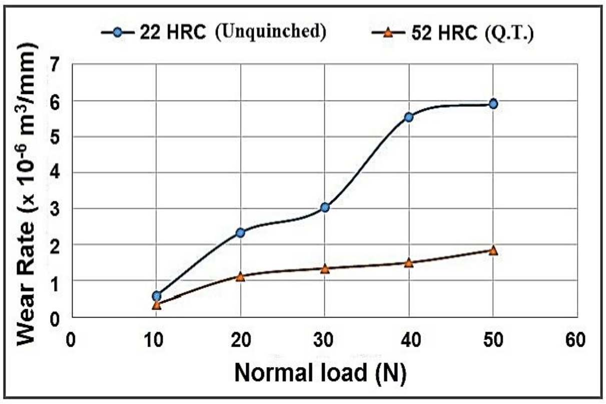


Fig. (7): Variation of Wear Rate with Load for Hot Work Tool Steel (H13) in Two Conditions (Unquenched, and Quenched & Tempered (Q & T)

The wear loss of a material is positively proportional to normal load and sliding distance, but inversely proportional to hardness. The wear rate of unquenched H13 increased 68% compared to quenched and tempered H13. The suggested our results are in agreement with Archrd's wear mode.

5 .2 Experimental Wear Coefficient (K) Evaluation :

The Fig.8 shows the high increasing tendency of wear constant (K) for unquenched with increasing the loading rate. The (K) value is positively proportional with loss of material to normal load ratio (W_v/L) according to Archrd's wear model. However, in Fig. 9 the quenched and temper shows slightly decreasing rate of (K) value. The average wear coefficient (K) values were ($2.02x10^{-3}$) and ($2.25x10^{-4}$) for unquenched, quenched and tempered respectively. These values were used as initial (K) value as input information in FEA simulation software.

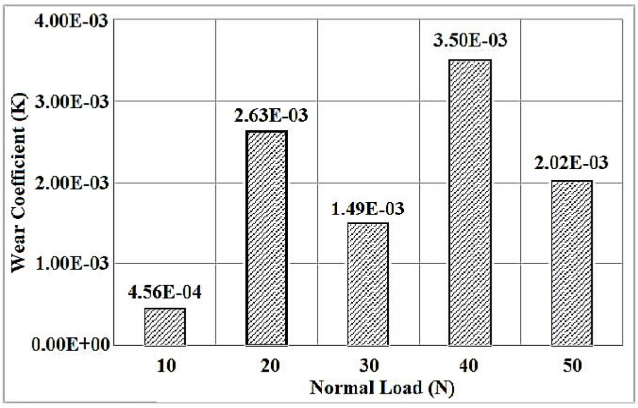


Fig. (8) Wear coefficient (K) for unquenched H13 (22HRC) with load.

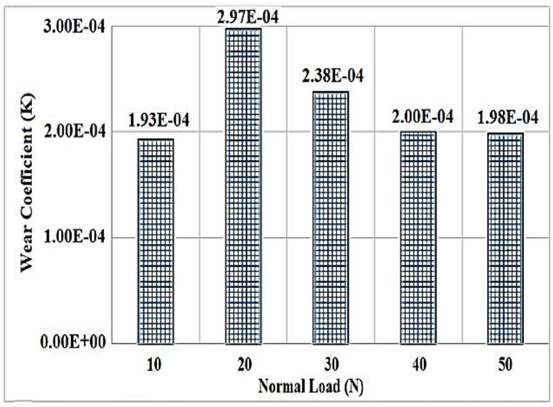


Fig. (9) Wear coefficient (K) for quenched and tempered H13 (52HRC) with load.

5 .3 Plastic Deformation Estimation :

The assumed elasto-plastic forging die block. Simulation results for 100 cycles shows that the plastic and elastic deformation during the forging operation of two set of die block is shown in Fig. 10(a) and 11 (a). The predicted plastic deformation of die is compared to the CMM measurements (measured wear depth) of vertical half sectioned forging die sample after service of 100 cycle in Fig. 10 (b) and 11 (b) the plastic deformation (dashed line) is used as a zero axis to separate the wear which was captured in the measurements from the plastic deformation. Thus any results to the left of zero line are signs of plastic deformation, therefor the 'pure' wear profile of two die set to the right in Fig. 10 (c)and 11 (c), show the wear depth in unquenched die is increase by 75% than in quenched and tempered die

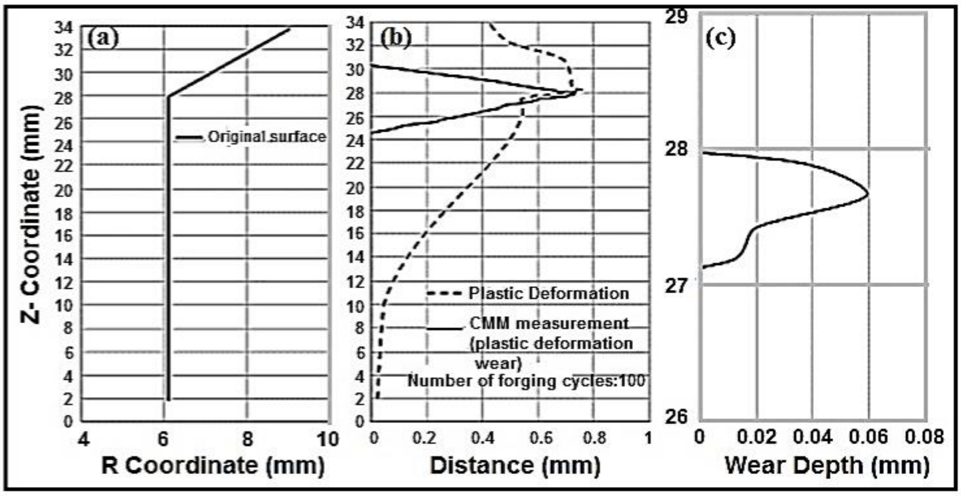


Fig. (10) (Unquinched Die Block): (a) Die geometry, (b) Predicted plastic deformation vs. CMM measurement for forging die block (100 cycles), and (c) Corrected CMM data to account for plastic deformation.

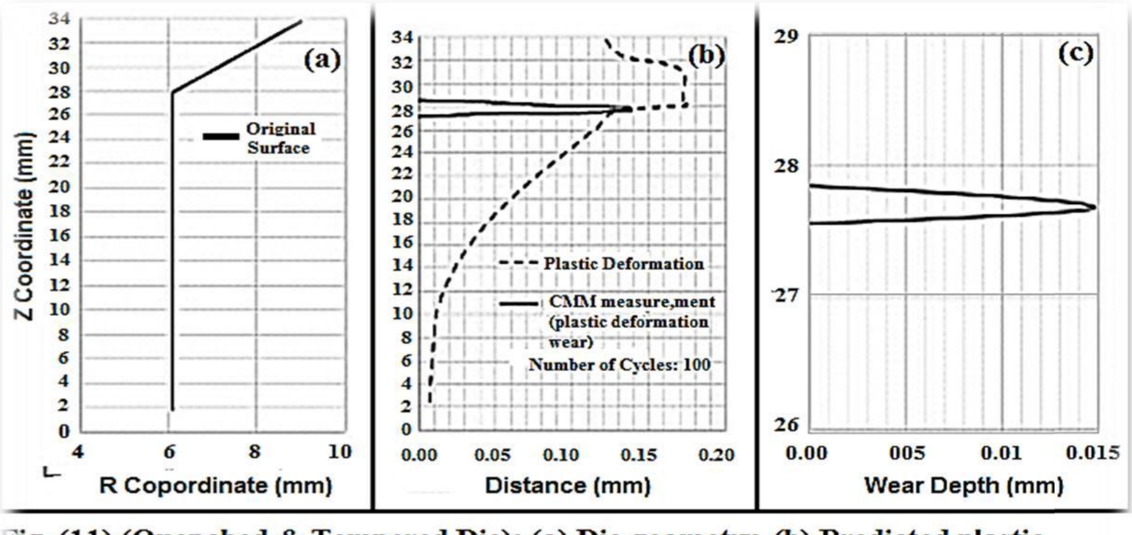


Fig. (11) (Quenched & Tempered Die): (a) Die geometry, (b) Predicted plastic deformation vs. CMM measurement for forging die block (100 cycles), and (c) Corrected CMM data to account for plastic deformation.

5 .4 Worn Dies Surface profile Determination :

The worn die surface (unquenched, quenched and tempered) were measured on each die half (using CMM machine) and analyzed to confirm the FEA simulation results. In reality, the measured profile is a combination of wear and plastic deformation, which is why the plastic deformation needs to be predicted. The measured points on the forging die are shown in Fig. 12 the measurements conditions of the dies are listed in table 6.The average 'worn' profile of three inner profiles for the same die part was obtained. Fig. 13 and 14 show the average measured profile compared with the original die geometry to determine the deviations between them.

Table (6) Measurement Conditions for the Die Profile.

Equipment	Virtual DMIS CMM
Probe radius	1 mm
Measure	
* Inner surface	3 vertical lines (22.5° apart)
* Outer sutrafce	3 vertical lines (45.0° apart)
Distance between measured points (z)	
* Inner profile	0.99 mm
* Outer profile	0.11

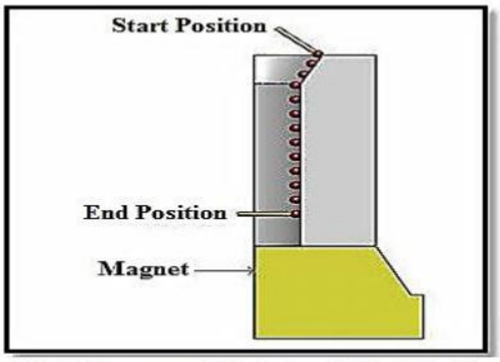


Fig. (12) Measured Points of the Die Profile

5 .5 Abrasive Wear Analysis :

For wear prediction the pressure, sliding velocities are determined using DEFORM 2D. Figures 15 and 16 shows the average normal pressure and sliding velocity of the four points taken at the most worn region of two-die block sets inner surface after 100 forging cycles.

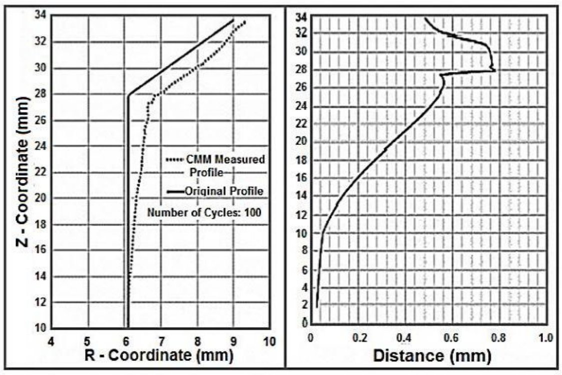


Fig. (13) CMM Measurement results of unquenched forging die after 100 cycle.

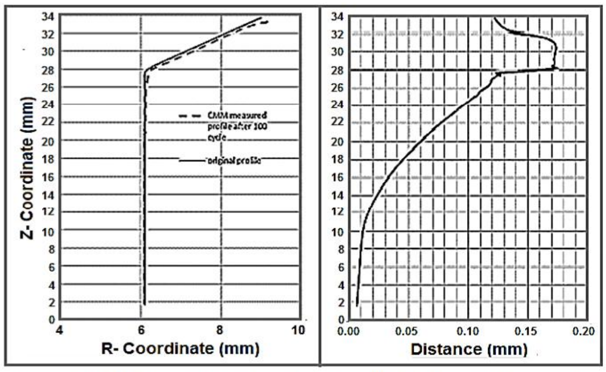


Fig. (14) CMM Measurement results of quenched & tempered forging die after100 cycle.

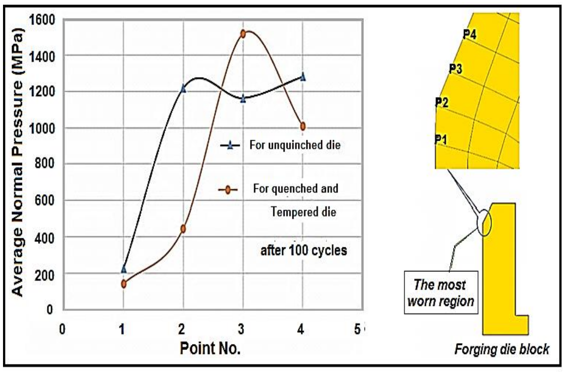


Fig. (15) Normal pressure at points 1, 2, 3 and 4

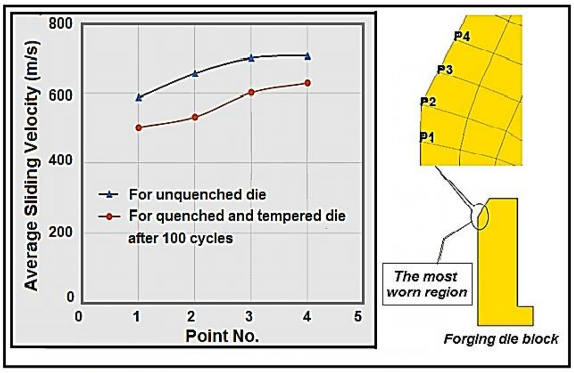


Fig. (16) Sliding velocity at points 1, 2, 3 and 4

Archrd's model used to estimate the wear depth. From the FEA simulation of 100 forging cycles use the (pressure, sliding velocity, time and wear depth) at the most worn region are listed in table 7 and 8. For two die sets, to predict the wear coefficient value (K), then use the same parameters above pressure, sliding velocity, time and wear depth which captured from CMM measurements to estimate the (K) value to comparison it with that predicted (K) value from FEA simulation results.

Table (7) Wear amount of the last step of 100th cycle and 5000 forgings of unquenched die block.

Final step for each forging (step 1037) /cycle 100						(FEA) Simulation Wear (10^{-2}) after 100 cycle	5000 forge wear
Point	H_r (MPa)	K (10^{-3})	P (MPa)	V (mm/s)	t (sec)		
1	2423	2.71	228	587	0.078	1.18	0.59
2	2423	0.786	1220	657	0.078	2.05	1.025
3	2423	2.27	1160	701	0.078	6.02	3.01
4	2423	2.21	1280	707	0.078	6.52	3.26
Avg.		**1.99**	**974**	**663**		**3.94**	**1.97**
						CMM measured wear (10^{-3}) after 100 cycle	
1	2423	2.42	228	587	0.078	1.05431	0.527
2	2423	0.759	1220	657	0.078	1.9785	0.9893
3	2423	2.24	1160	701	0.078	5.9431	2.971
4	2423	1.58	1280	707	0.078	4.6718	2.335
Avg.		**1.75**				**3.4119**	**1.705**

where
H_v is Vickers hardness, **P** is normal pressure,
V is sliding velocity and **t** is time

Table (8): wear amount of the last step of 100th cycle and 5000 forgings of quenched and tempered die bloc

Final step for each forging (step 1037) /cycle 100						(FEA)simulation Wear (10^{-3}) after 100 cycle	5000 forge wear
Point	H_V (MPa)	K (10^{-3})	P (MPa)	V (mm/s)	T (sec)		
1	5366	1.39	144	501	0.079	1.49	0.0745
2	5366	1.67	449	531	0.079	5.89	0.2945
3	5366	1.10	1520	601	0.079	14.9	0.745
4	5366	1.24	1010	629	0.079	11.7	0.585
Avg.		**1.35**	**781**	**566**		**8.48**	**0.4247**
						CMM measured wear (10^{-3}) after 100 cycle	
1	5366	4.77	144	501	0.079	**1.32**	0.066
2	5366	0.0167	449	531	0.079	**5.25**	0.262
3	5366	0.00438	1520	601	0.079	**11.52**	0.576
4	5366	0.00582	1010	629	0.079	**11.09**	0.547
Avg.		**1.20**	**781**	**566**		**7.26**	**0.3627**

where
H_v is Vickers hardness, **P** is normal pressure,
V is sliding velocity and **τ** is time

5 .6 Results Comparison :

After estimation the optimized wear coefficients (K) by taking the average value to minimize the error between the predicted wear coefficient (by FEA), and the actual wear coefficient (from CMM measurements data compensated for plastic deformation). The comparison shows that the predicted and actual measured wear coefficient are very closed to each other and to input information of FEA simulation (as it should be) as shown in Table 9.

Table (9) Comparison between predicted and actual wear coefficient.

	Forging die block	
(K) value	Unquenched	Quenched and Tempered
Predicted	1.99×10^{-3}	1.35×10^{-3}
Actual	1.75×10^{-3}	1.20×10^{-3}
Difference	12 %	11.11 %
Average (K) value	1.87×10^{-3}	1.275×10^{-3}

The results show a significant difference between the wear depth of unquenched die and quenched and tempered die block because of inversely proportional of hardness with wear depth, farthermore the quenched and tempered die block possess high tensile strength which resist the tensile stress applied to the die surface due to friction shear force generated during forming operation. Therefore, the average (K) value listed in table above as a new input information to FEA simulation to minimize the predicted and measured profile as shown in fig. 17 and 18. The investigated constant wear coefficient 'k' parameter can be used for future estimation of die wear in warm forging.

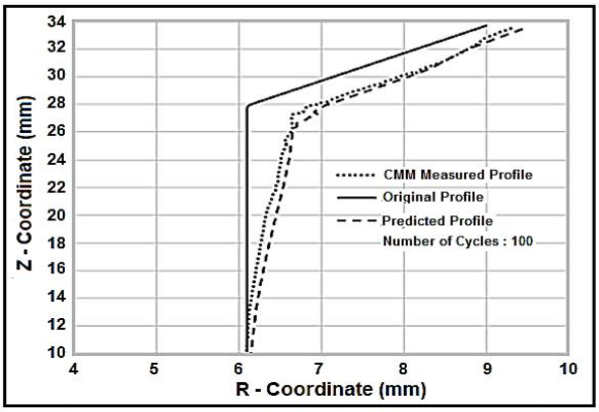


Fig. (17) The original, Predicted and CMM Measured profiles of unquenched forging die block.

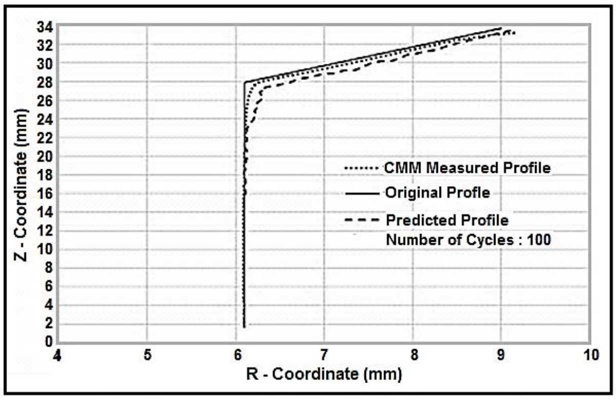


Fig. (18) The Original, Predicted and CMM Measured Profiles of Quenched & Tempered Forging Die Block.

5 .7 <u>The Products Dimensions Accuracy :</u>

For experiments, 200 workpieces have been forged 100 workpiece by each die block. The die geometry primarily defined the dimensions. Wear and plastic deformation of the die influenced the dimensional accuracy of the forged parts.

The observed deviation in rivet is by measuring the forgings; this deviation opposes the wear and plastic deformation in die material. The maximum amount of deviation was (0.725 mm and 0.1 mm) for each 100 unquenched forged parts, quenched and tempered die block respectively as shown in Fig. 19, these results agree with measured die displacement results shown in Figs. 13 and 14.

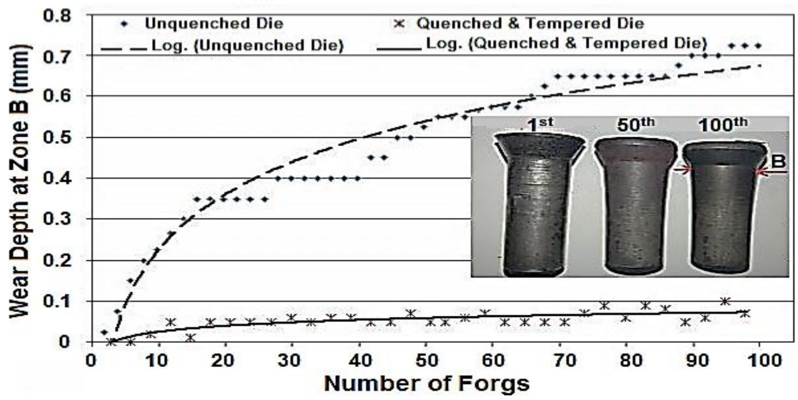


Fig. (19) The maximum wear depth vs. the number of forged

6. Conclusions :

From the present work, the conclusion can be:

1. In wear analysis of dies, at the regions where there are high effective stresses wear may occur. Therefore, the interface pressure, sliding velocity, contact time and hardness, which are affected by high temperatures, have greater effects on the wear depth.
2. The wear coefficients of (1.87×10^{-3} and 1.275×10^{-3}) for unquenched, quenched and tempered die blocks respectively, can be used as a good approximation for warm forging dies, under the same conditions.
3. Costly experimental work and die tryouts can be minimized with use of FEM simulation to predict die life. This is important for the die design and gives the designer the possibility of forecasting quit correctly, to minimizing the maintenance operations on the dies.
4. The modified wear model and experimental results combine with finite element analysis to predict wear amounts of the countersunk head rivet in warm forging die in the design stage. After 5000 forging, the most worn depth is near 1.97 mm and 0.42 mm for unquenched, quenched and tempered die block respectively. If the maximum dimension variable is 1.0 mm the dies life is only about 2500 forging and 12000 forging by unquenched, quenched and tempered die respectively.

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