Study of Wear and Life Enhancement of Hot Forging Dies Using Finite Element Analysis

Rachapol Iamtanomchai and Sasithon Bland*

***Abstract*—This work investigates the wear of hot forging dies using finite element analysis. A finite element model of a forging process of a particular automotive product was developed and validated. The influence of process parameters including initial billet temperature, friction and die surface treatment on die wear was examined. It was found that increasing initial billet temperature and reducing friction can reduce the die wear. The case of 0.1 mm-deep nitriding surface hardening was studied. By choosing optimal process conditions and material hardening, the life of the dies can be increased as much as two times that of the current practice.**

***Index Terms*—Hot forging, Die wear, Finite element**

I. INTRODUCTION

Hot metal forming including forging is one of the most important production processes [1]. This is partly due to the benefits of the process in which mass-produced complex parts can be achieved. The production cost to a large extent depends on the tool cost. The main factor influencing the life of tools/dies is the damage caused by wear, fatigue and plastic deformation, in which wear is the predominant factor [2-5]. Increasing the die life can be achieved by a combination of optimal process conditions as well as materials improvement [6-8]. This work is therefore aimed to investigate the hot forging process coupled with parametric study to predict the life of the dies. The forged product is an automotive part from a particular company. The forging process involves two steps: firstly, a cylindrical billet is forged in a set of blocker dies; then the semi-finished workpiece is forged in a set of finishing dies. The workpiece is then trimmed to achieve final product as seen in Fig 1. A set of dies consists of an upper die and a lower die where four products are forged in one cycle. This is shown in Fig 2. It was found that the blocker dies usually suffer more severe damage than the finishing dies and therefore will be the topic of this study.

II. FINITE ELEMENT MODEL AND VALIDATION

A finite element model of the hot forging process involving a set of blocker dies was developed. Because of symmetry, only one half of the workpiece was modeled. This is shown in Fig 3. The materials for the dies and billet were hardened steel SKD61 and SCM440, respectively. Temperature-dependent materials properties were from standard library. The initial temperature of dies and billet were 200°C and 1200°C, respectively. The coefficient of friction between die and billet was 0.3. The model was set as non-isothermal condition which heat transfer is allowed between the dies, billet and surrounding area. The element type was chosen as tetrahedral mesh with maximum element size of 2 mm.

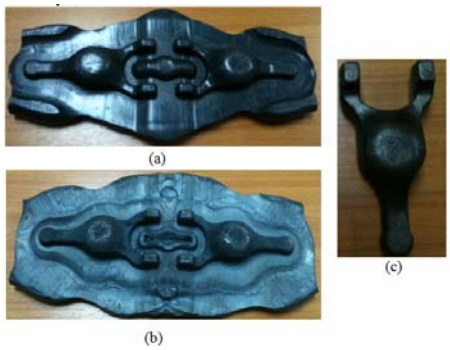

Fig 1 (a) forged workpiece after blocker die; (b) forged workpiece after finishing die and (c) final workpiece

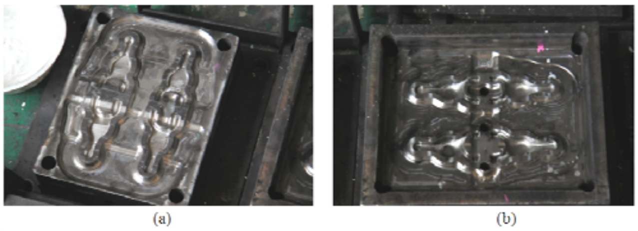

Fig 2 New blocker dies (a) upper die; (b) lower die

The model was validated by comparing the dimensions of the forged workpiece from the model with those of actual product as shown in Fig 4. Four dimensions (labeled as A, B, C and D) were compared and the discrepancies were 5.65%, 8.64%, 3.13% and 1.56%, respectively. Therefore the FE model developed can be used to study the hot forging process of this particular product and will be used for wear analysis and parametric study described in section III.

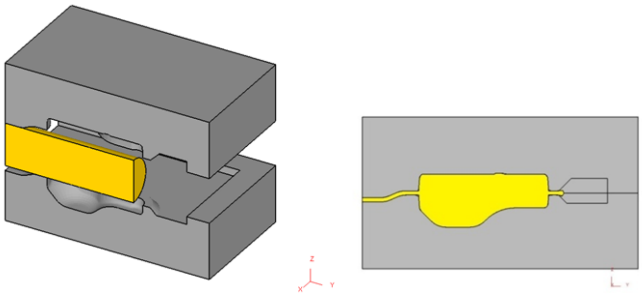
Fig 3 Finite element model of forging process

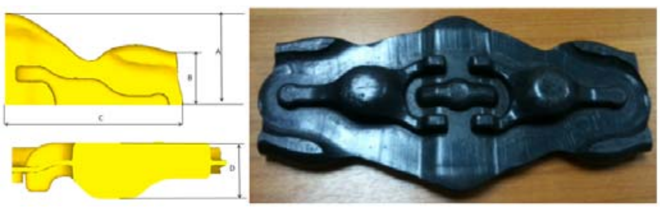
Fig 4 FE results and actual forged part with dimensional comparison

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III. DIE WEAR ANALYSIS AND COMPUTATIONAL PARAMETRIC STUDIES

A. *Die wear analysis*

To analyze the wear mechanism of the dies, inspection of actual dies as well as results from FE simulation were considered. The damaged upper and lower dies are shown in Fig 5. Three areas on each die are of particular interest since they show substantial wear. These are labeled as UD1, UD2 and UD3 for upper die and LD1, LD2 and LD3 for lower die. Effective stress, temperature distribution and normal stress on die obtained from FE model are shown in Fig 6-Fig 8.

It can be seen that high effective stress occurs along the perimeter of the die cavity especially in the area UD1 and UD3 and the stresses are greater than the yield stress at elevated temperature. Hence, the dies suffer from plastic deformation which can be seen on the actual dies. The area of high temperature is around UD2 and LD2 where the both dies can undergo thermal fatigue during forging and cooling down processes. This corresponds to material spallation observed in this area of the actual dies. Normal pressure is high in the area UD2 and LD2 compared to inside the die cavities.

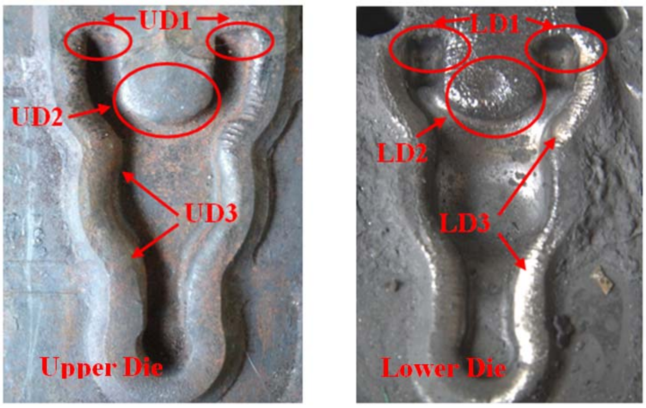

Fig 5 Inspection of damage on the actual blocker dies (a) upper die and (b) lower die

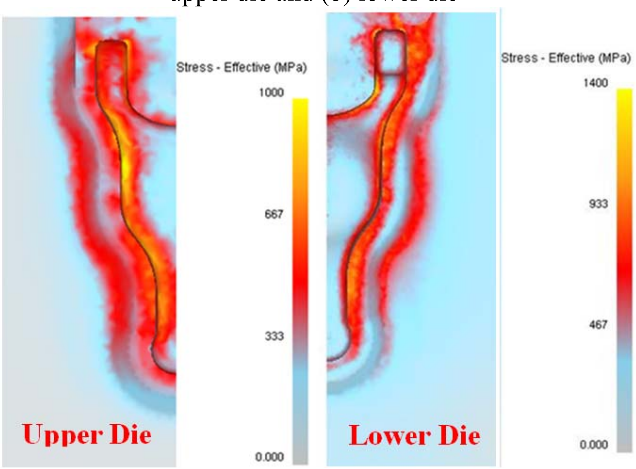

Fig 6 Effective stresses on upper and lower dies

To calculate wear depth of the dies, Archard's equation [9] was used;

$$W = \frac{kPl}{H} \qquad (eq.1)$$

Where W is wear depth (in mm.), k is wear coefficient determined from an experiment, P is normal stress on the die in MPa, l is the sliding distance in mm. and H is a temperature-dependent hardness (MPa)

The temperature-dependent hardness of the material was calculated according to the work of Kang *et al.* [10, 11] where Archard's equation was modified as

$$W = \sum_{1}^{n_{fin}} \frac{kP(Vs)}{H_0} \times \frac{H_0}{H(T,t)} \qquad (eq.2)$$

Where H_0 is hardness at ambient temperature (MPa), H(T,t) is the time- and temperature-dependent function of hardness according to the tempering parameter M [10,11] as shown in Fig 9. The total wear depth was a sum of 'n' incremental wear calculated using values from finite element analysis.

$$M = T(20 + \log t) \qquad (eq.3)$$

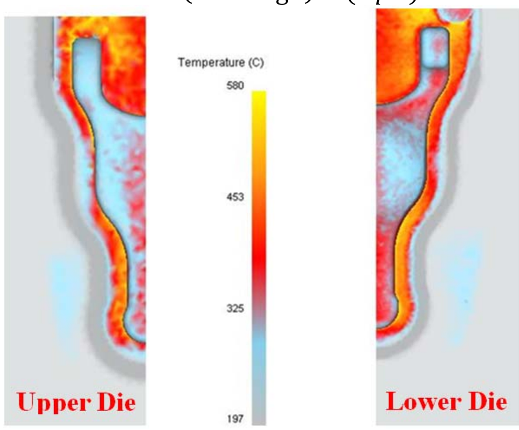

Fig 7 Temperature distribution on upper and lower dies

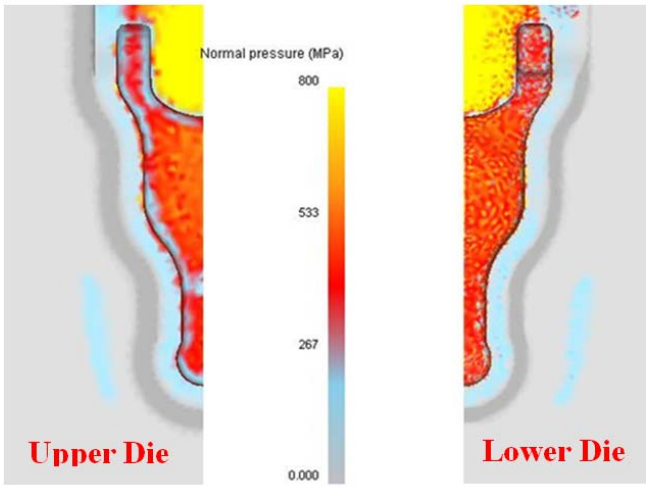

Fig 8 Normal pressure on upper and lower dies

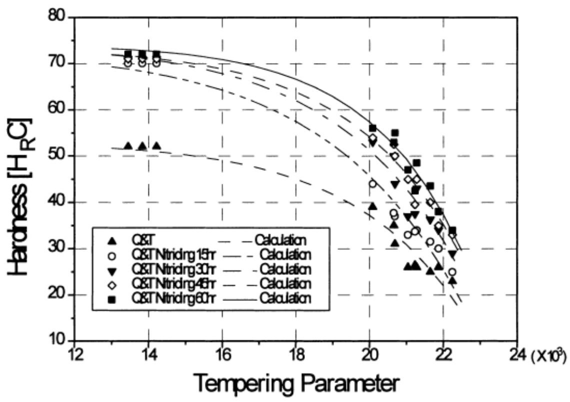

Fig 9 Material hardness as a function of tempering parameter [10,11]

The wear depth after 10,000 cycles at 4 locations labeled as U1, U2 on the upper die and L1 and L2 on the lower die (see Fig 10) were calculated according to Eq. 2 and shown together with measured wear in Table I. The values of normal stress, velocity and sliding distance were obtained from each increment of the FE simulation. The wear coefficient was obtained from an experiment and equals to 3.54×10^{-4}.

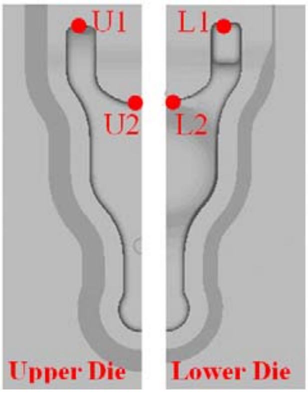

Fig 10 Locations where wear is calculated and measured

Table I Comparison of calculated wear depth and measured wear depth at 4 locations on the upper and lower dies

Location	Calculated wear depth after 10,000 cycles (mm)	Measured wear depth of damaged die (after approximately 10,000 cycles) (mm)	Discrepancy
U1	2.96	3.76	21%
U2	1.55	Not available	n/a
L1	2.35	2.89	19%
L2	0.95	Not available	n/a

It can be seen that wear is the most severe at location U1 on the upper die, and location L1 on the lower die. The discrepancies of 21% and 19% at those two locations, respectively, can be accounted for as follows: firstly, the wear measurement was carried out on the damaged die which has been in service for approximately 10,000 cycles. No exact data was available. Secondly, the calculate wear does not take into account other wear mechanism such as thermal fatigue wear, hence it results in the wear which is less than the actual measurement. However, the model can be used to study the effects of parameters such as initial billet temperature, die friction and material surface treatment on wear and provide comparative results. Only location U1 and L1 will be considered since they are the critical locations that determine the life of the die.

B. Effects of initial billet temperature on die wear

The effects of initial billet temperature on die wear are investigated by considering the temperature of 1200°C and 1300°C in addition to the current temperature of 1100°C. The contact pressure, sliding velocity, die temperature and wear depth at locations U1 and L1 are shown in Fig 11-14. It can be seen that by increasing the initial billet temperature, contact pressure on the dies can be reduced (Fig 11). The initial billet temperature has negligible effect on the sliding velocity especially on the lower die (Fig 12). Similarly, temperature of both upper and lower dies is hardly affected by initial billet temperature (Fig 13). However, the amount of wear of the upper dies depend greatly on initial billet temperature; in which wear is greatest at 1100°C and is reduced as the temperature increases to 1200°C and 1300°C, respectively. On the contrary, initial billet temperature of 1200°C and 1300°C result in similar amount of wear on the lower die, both being lesser than the case of 1100°C (Fig 14).

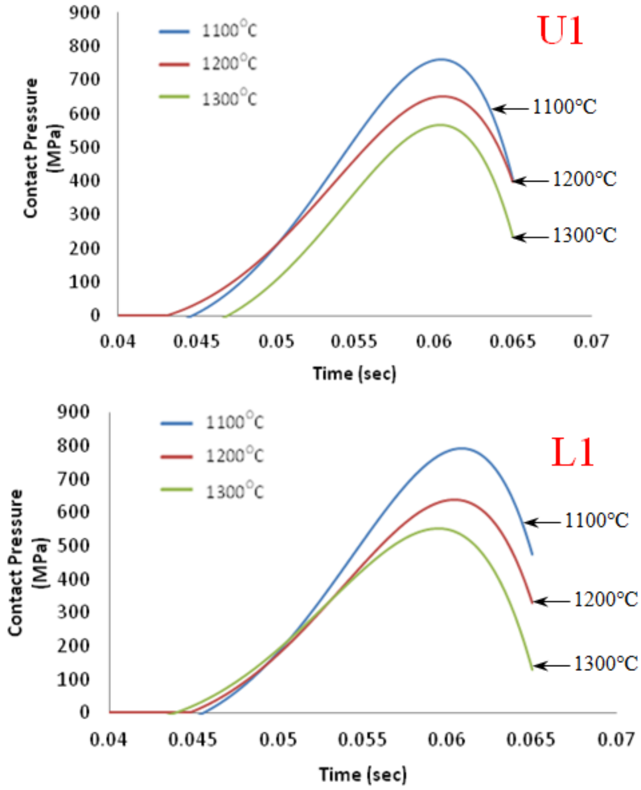

Fig 11 Contact pressure during forging at location U1 and L1; initial billet temperature of 1100°C, 1200°C and 1300°C

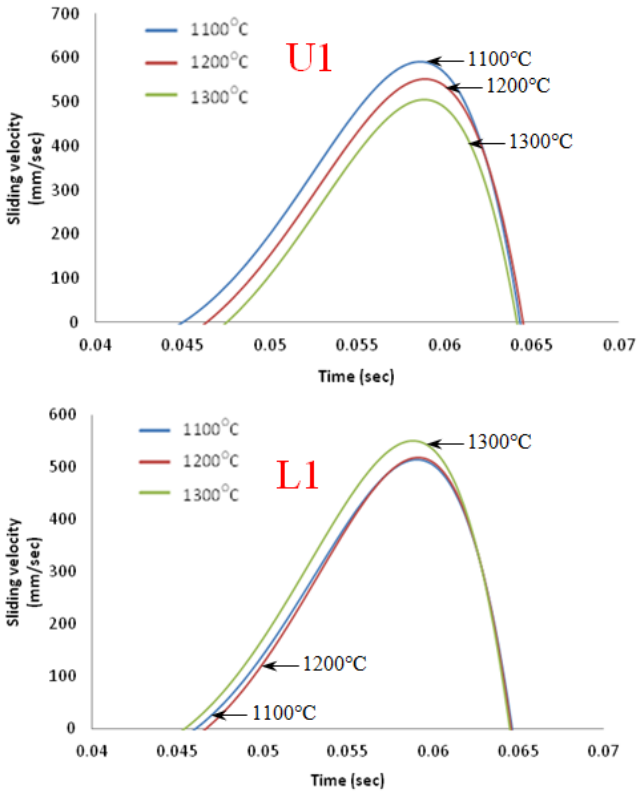

Fig 12 sliding velocity during forging at location U1 and L1; initial billet temperature of 1100°C, 1200°C and 1300°C

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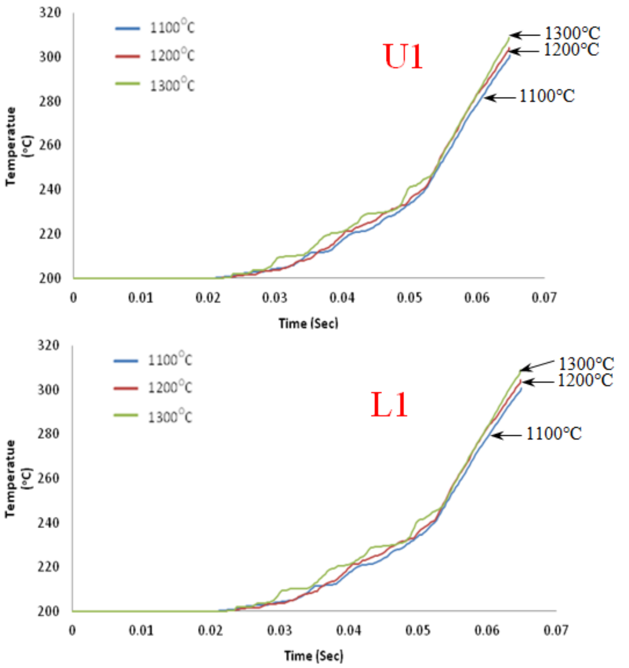

Fig 13 Die temperature during forging at location U1 and L1; initial billet temperature of 1100°C, 1200°C and 1300°C

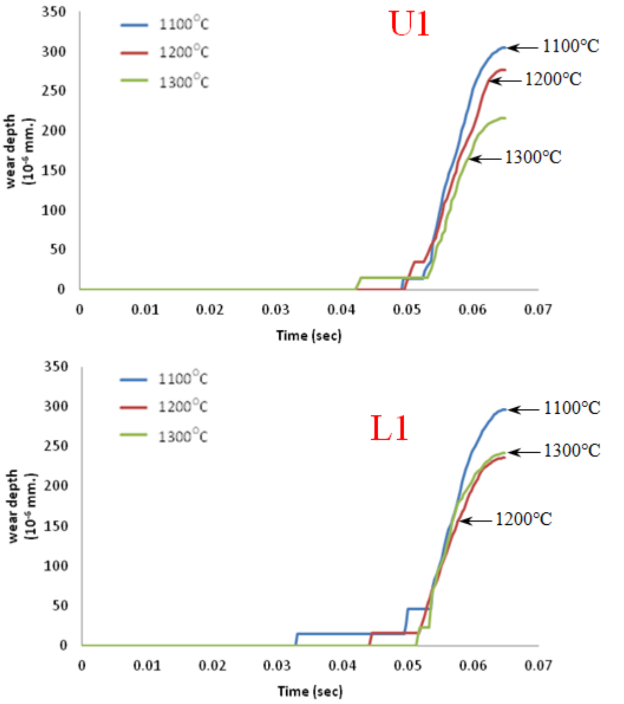

Fig 14 Wear depth per cycle during forging at location U1 and L1; initial billet temperature of 1100°C, 1200°C and 1300°C

Table II. Hardness and wear coefficient of SKD 61 and SKD 61 with nitriding samples obtained experimentally

	Hardness (HRC)	Wear coefficient (k)
SKD 61	52	3.54×10^{-4}
SKD 61+ nitriding (treatment depth 0.1 mm)	69	6.98×10^{-5}

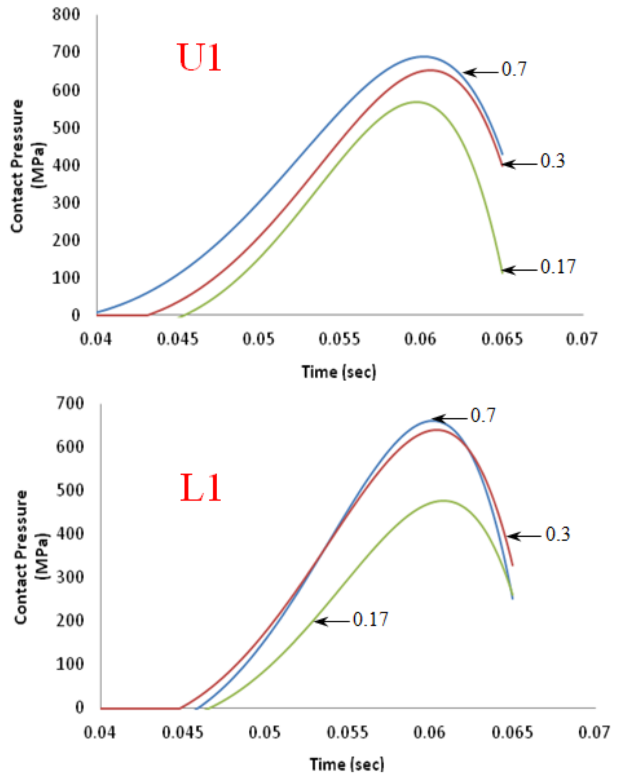

Fig 15 Contact pressure during forging at location U1 and L1; coefficient of friction of 0.17, 0.3 and 0.7

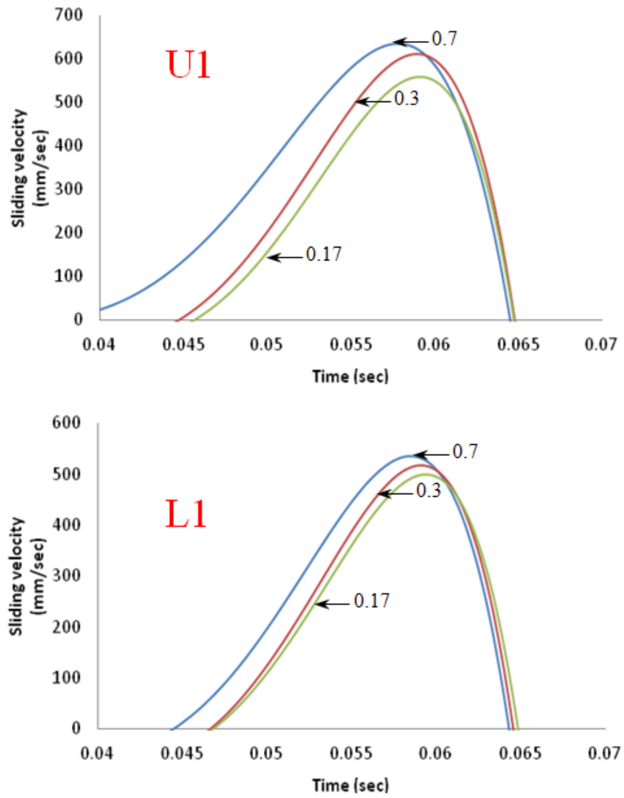

Fig 16 Sliding velocity during forging at location U1 and L1; coefficient of friction of 0.17, 0.3 and 0.7

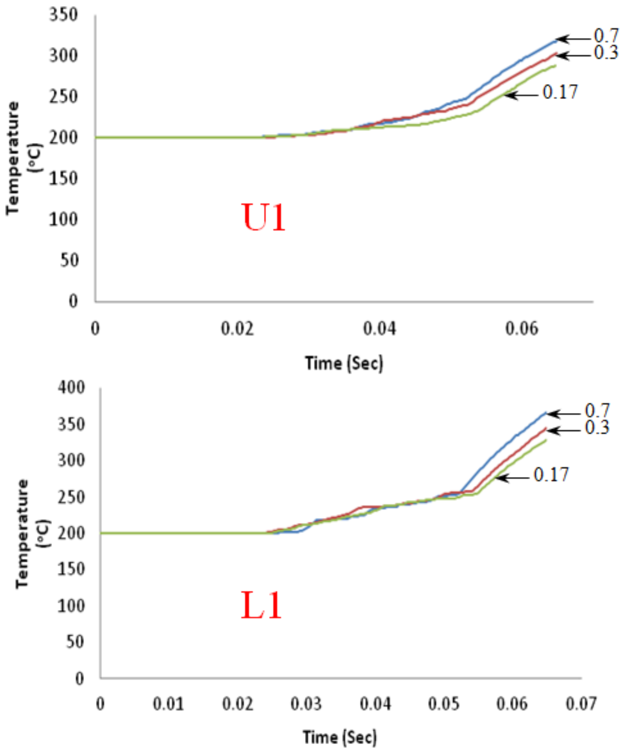

Fig 17 Die temperature during forging at location U1 and L1; coefficient of friction of 0.17, 0.3 and 0.7

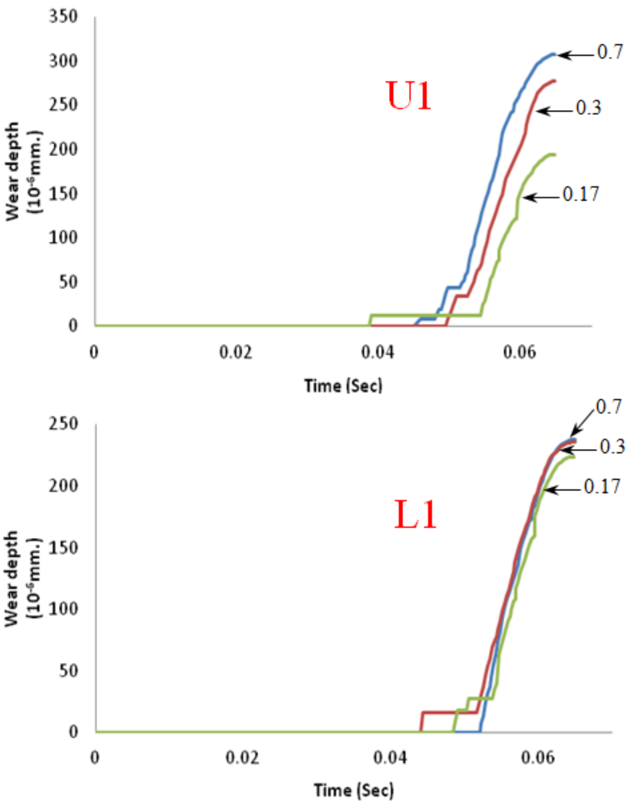

Fig 18 wear depth per cycle during forging at location U1 and L1; coefficient of friction of 0.17, 0.3 and 0.7

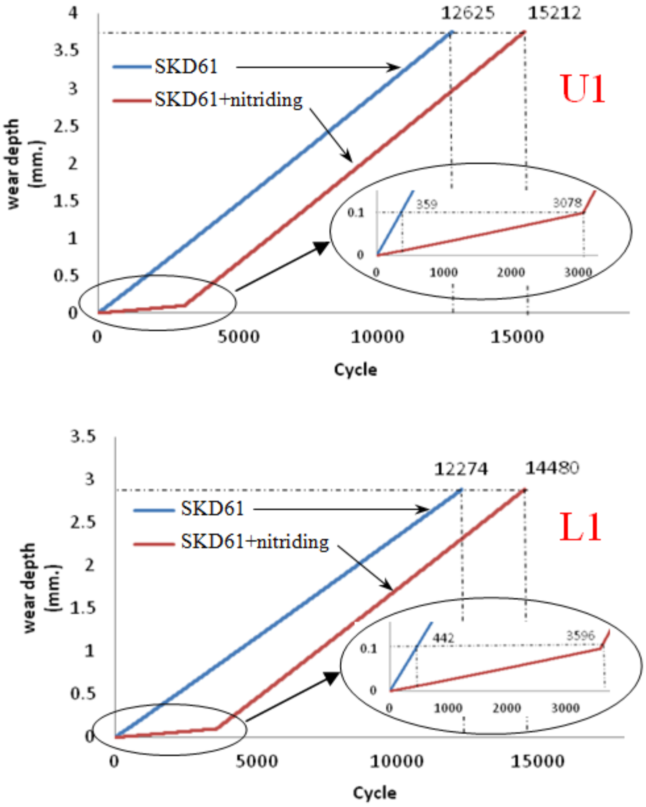

Fig 19 Wear depth variation with no. of cycles for SKD61 compared to SKD61with nitriding treatment

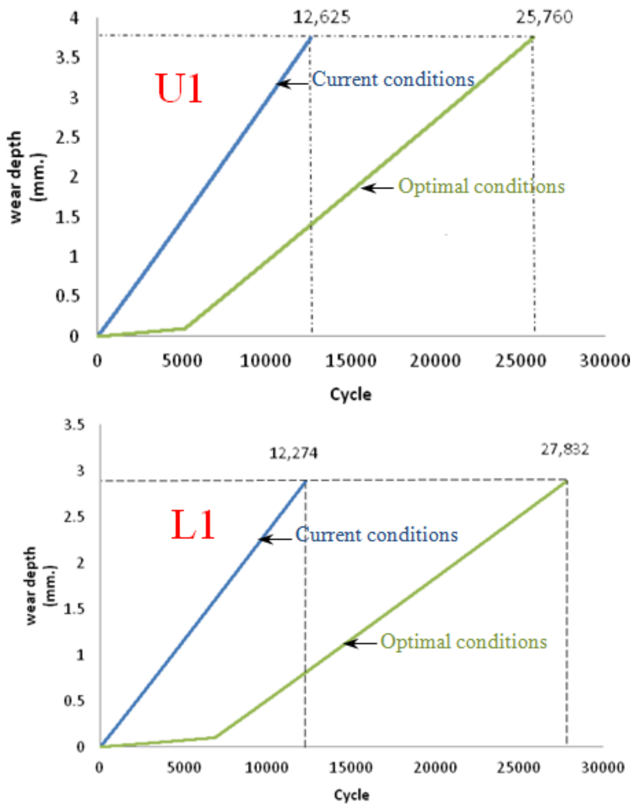

Fig 20 Comparison of die life for current conditions and optimal conditions; (a) upper die and (b) lower die

C Effects of surface friction between die and workpiece on die wear

During hot forging, some form of lubricant is often used to reduce the friction and enhance material flow inside the dies. The case of low, medium and high friction represented by the coefficient of friction of 0.17, 0.30 and 0.70 (no lubrication) will be investigated [12]. Fig 15-18 show the contact pressure, sliding velocity, die temperature and wear depth, respectively, at location U1 and U2 for the various cases of friction. As expected lower friction results in lower contact pressure since the material can flow more easily inside the dies. However in the case of the lower die, the contact pressure at the end of the cycle is insignificantly affected by the level of friction (Fig 15). The sliding velocity at the beginning of the cycle varies with the level of friction. However, towards the end of the cycle, this variation is minimal (Fig 16). When die temperature is concerned, it is slightly affected by the level of friction, in which higher friction (coefficient of friction of 0.7) gives rise to higher die temperature than lower friction (Fig 17). Friction does not seem to have influence on wear level on the lower die, unlike the upper die where high friction results in significantly higher wear (Fig 18).

D Effects of surface treatment on die wear

Additional to finding optimal process conditions, the effect of material surface treatment on wear is also investigated. An experiment to determine the hardness and the wear coefficient was carried out on a sample of SKD61 which has been through nitriding process. The hardness and the wear coefficient of the SKD61 and SKD61 with nitriding samples are shown in Table II.

Using the improved hardness and wear coefficient, the wear of the upper die and lower die was calculated and shown in Fig 19. It can be seen that the nitride-treated upper die can be used for 3078 cycles before the wear reach the base material (SKD61) compared to 359 cycles of the untreated die. Similarly, the nitride-treated lower die can sustain 3596 cycles compared to 442 cycles for the wear to reach 0.1 mm deep. Overall by nitride-treating the die surface, the life of the upper die can increase by about 20%, i.e. from 12625 cycles to 15212 cycles. The life of the lower die can increase by about 18% from 12274 cycles to 14480 cycles.

IV. Discussion and Conclusions

This work developed a finite element model of a particular automotive product undergoing hot forging process. Contact pressure, sliding velocity and temperature distribution were obtained from every time increment of the model and were used to calculate incremental wear of the upper and lower dies. The wear calculation takes into account reduced material hardness at elevated temperature and the total wear per cycle at two critical locations was then obtained. The influence of forging process parameters on die wear was examined in order to determine the optimal process conditions. Higher initial billet temperature can reduce the die wear for both upper die and lower die as a result of lower contact pressure. Lower friction substantially reduces the die wear of the upper die but has negligible effect on the lower die. Surface treatment of the die material by nitriding process can also improve the die life by about 20%. By choosing optimal process conditions and nitride-treated die, the die life can increase as much as 126% and 108% on the lower die and upper die, respectively.

V. Die Life Enhancement Using Optimal Process Conditions

Using results from parametric studies in Section III, the optimal process conditions were chosen. The life of the upper and lower dies are then calculated based on the critical wear depth of 3.76 mm and 2.89 mm for the upper and lower die, respectively. The die life can double, e.g. from 12,625 cycles to 25,760 cycles for the upper die and from 12,274 cycles to 27,832 cycles for the lower die (Fig 20). This is summarized in Table III.

Table III. Optimal process conditions compared to current process

Conditions	Current	Optimal process
Billet initial temperature(^{o}C)	1200	1300
Die temperature (^{o}C)	200	200
Coefficient of friction	0.3	0.17
Die Material	SKD 61	SKD 61+Nitriding
Life cycle (Upper die)	12,625	25,760
Life cycle (Lower die)	12,274	27,832
Life enhancement (Upper die)	-	104%
Life enhancement (Lower die)	-	126%

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