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Wear Mechanism of Hot Forging Die from the Viewpoint of Diffusion

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The occurrence of plastic flow, the formation of the re-quenched zone and heat cracks, etc. have been considered as the reasons for the wear of hot forging die. Besides, the diffusion of the alloying elements within the die steel into works also can be considered to be one reason, because the work contacts the die surface under high pressure and flows over the die surface developing a new surface per each forging stroke and it is repeated many times. In this study, it is assumed that a depleted zone is formed on the die surface as a result of diffusion of alloying elements within the die into the work, the depleted zone breaks away at the critical thickness, and the break-away thickness is equal to the diffusion distances of elements. From these assumptions, the wear rates were calculated. The results of calculation show the remarkable dependence of the wear rate on the temperature on the die surface, and this coincides well with the existent experimental results.

Keywords die surface temperature, die wear, diffusion, friction, hot forging

1. Introduction

In the hot forging of metals, the die contacts the work and the work slips on the surface of the die under high pressure, so the friction heat is generated on the boundary between the die and the work. It can be considered that the friction heat is large enough to heat the surface of the die to higher temperatures. There, the die surface is heated not only by the heat of the work, but also by the friction heat resulting from the slip between die and work. The temperature increase can be described quantitatively by the following equation (1) (Ref 1).

$$\Delta\theta = \frac{1}{2b}\frac{m\sigma_0}{\sqrt{2}}\frac{\lambda_g}{\sqrt{\Delta t}} \quad \text{(Eq 1)}$$

where $\Delta\theta$ is temperature increase, b is heat flux, m is Tresca's friction coefficient, σ_0 is flow stress of the work, λ_g is slip length of the work, and Δt is slip time.

Thus, the temperature increase $\Delta\theta$ is proportional to the friction coefficient, flow stress and slip length, but in inverse proportion to the slip time.

The die surface is heated beyond the A_1 transformation temperature ($\alpha \rightarrow \gamma$ transformation temperature, approximately 1123 K in Fe-5% Cr binary system) by this friction heat.

As a result, the following phenomena are considered to occur (Ref 1):

(1) The high temperature strength of the die is lowered and plastic flow is caused and wear takes place.
(2) The re-quenched layer is formed on the die surface during the cooling, it breaks away at the boundary with the substrate, and wear takes place.
(3) Heat cracks develop during the cooling, break-away occurs, and wear takes place.

But at the die surface, besides these phenomena, diffusion of alloying elements from the die to the work can possibly occur. If diffusion occurs, the high temperature strength is lowered more, and the thickness of the re-quenched layer increases due to the lowering of the A_1 transformation temperature. As a result, wear is suggested to increase more than can be expected by the present theory.

Therefore, here first, the thickness of the diffusion layer was calculated, and then the wear rate was calculated under some simple assumptions, e.g., when the depleted zone caused on the die by the diffusion of the elements from die to works reaches some critical value, break-away occurs and wear takes place.

2. Diffusion Distances of Major Alloying Elements within SKD 61 into the Work

The chemical composition of die steel JIS SKD 61(AISI H13) is, for instance, 0.36C-1.0Mn-5.21Cr-1.25Mo-0.85V (Ref 2). Assume that these alloying elements diffuse into carbon steel work, for example, S45C. Diffusion data of these elements are shown in Table 1 (Ref 3). Here it was assumed for the convenience of calculation that both surfaces of the die and work are at the same temperature after being heated by the friction heat. Specifically temperatures at the boundary were assumed to be 973, 1173, 1273, 1373, 1473, 1573, and 1623 K, respectively. Matrices are thought to be α-Fe at 973 K, and γ-Fe at 1173, 1273, 1373, 1473, 1573, and

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Table 1 Diffusion data of alloying elements of the die steel into Fe

Diffusion element	Matrix metal	Frequency factor D_0, $m^2\ s^{-1}$	Activation energy Q, kJ mol^{-1}
Cr	α-Fe	2.3×10^{-4}	239
	γ-Fe	1.69×10^{-5}	264
Mn	α-Fe	1.49×10^{-4}	233
	γ-Fe	1.78×10^{-5}	264
Mo	α-Fe	4.6×10^{-3}	285
	γ-Fe	3.6×10^{-6}	240
V	α-Fe	3.1×10^{-4}	239
	γ-Fe	2.8×10^{-5}	264

1623 K, respectively, because the α-γ transformation temperature is suspected to be 1053 K and γ-δ 1723 K in S45C, respectively.

In general, diffusion coefficient D is expressed by

$$D = D_0 \exp(-Q/RT) \quad \text{(Eq 2)}$$

And diffusion distance l is expressed by

$$l = \sqrt{Dt} \quad \text{(Eq 3)}$$

where D is diffusion coefficient (m^2/s), D_0 is frequency factor (m^2/s), Q is activation energy (J/mol), R is gas constant (8.315 J/(mol K)), l is diffusion distance (m), and t is time (s).

Diffusion distance vs. diffusion time curves of each element into the iron matrix are shown in Fig. 1 Carbon was omitted, because carbon is also contained in forged material such as S45C. As shown, diffusion distances are similar for each element at each temperature. Therefore, average values of D of four elements were adopted to calculate the diffusion distance in the following. In general, as the diffusion proceeds, the depleted zone is formed in the higher concentration side and the depth of the depleted zone equals the diffusion distance in the counterpart (Ref 4). In the practical hot forging process, it is considered that alloying elements within the die diffuse into the work. Consequently, the depleted zone will be formed on the surface of the die, and the depleted zone will brake away at a critical thickness. The concentration profile of solute in the depleted zone is shown in Fig. 2. The concentration of solute on the ordinate is normalized by assuming the concentration at the boundary to be 0 and that of full concentration to be 1. The distance x into the material on the abscissa is normalized by the diffusion distance $\sqrt{Dt}$. The concentration of solute is 52% of the matrix at the distance of $\sqrt{Dt}$. It was assumed that the break-away occurs at this place and, moreover, its thickness was assumed to be tentatively 0.2, 1 and 5 μm, respectively. Diffusion times when the thickness of the break-away layer (=the diffusion distance $\sqrt{Dt}$) becomes 0.2, 1 and 5 μm at 1273, 1373, 1473, 1573, and 1623 K were calculated, respectively. Results are shown in Table 2. The value of the quotient, i.e., break-away thickness divided by the diffusion time, was defined as the rate of wear (μm/s). Figure 3 shows this situation. The depleted zone is formed on the die surface as a result of diffusion of the alloying elements within the die into the work with increasing forging number ((a) upper-left). Fracture phenomena such as cracks occur when the value of the diffusion distance in the depleted zone reaches a critical value ((a) upper-right). Consequently, the depleted zone breaks away at the distance of $\sqrt{Dt}$ ((a) lower-left). New depleted zone is formed on the new surface again by diffusion ((a) lower-right). It is repeated afterwards. The break-away thickness is accumulated as shown in Fig. 3(b). The slope of the straight line connecting the origin and break-away point in the figure is wear rate in this study. At that time, precisely, the new surface has already a concentration of 48% lower on the surface than in the matrix. Therefore, diffusion time until next break-away becomes shorter since the second time. For convenience, the diffusion time in this case was estimated to be 52% of the diffusion time to the virgin surface. Therefore, the wear rate was calculated using this revised diffusion time. Here, moreover, for the sake of clarity, wear rates are expressed as the wear after 10^4 s, because it corresponds to the total accumulated time of 1 s dwell time (contact time) and 10,000 forging times, which seems normal in actual forging operations. Figure 4 shows the results graphically. It shows that both increasing temperature on the die surface and decreasing break-away thickness increases the wear rate remarkably.

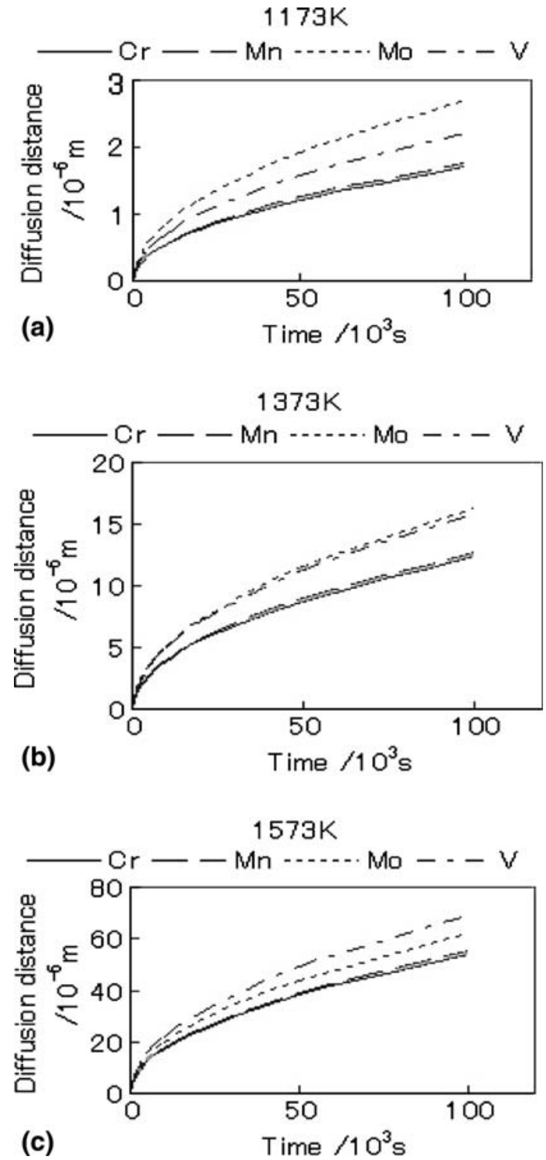

Fig. 1 Diffusion curves of each element in the iron matrix

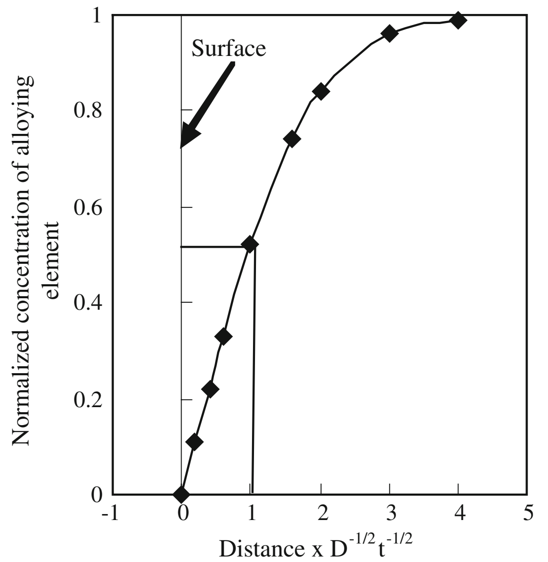

Fig. 2 Concentration profile of solute in the depleted zone

Table 2 Diffusion times (s) at the diffusion distances of 0.2, 1, and 5 μm, respectively, at high temperatures

Diffusion distance ($\sqrt{Dt}$)	1273 K	1373 K	1473 K	1573 K	1623 K
0.2 μm	111	19	4	1	0.6
1 μm	2,786	479	104	27	15
5 μm	69,650	11,974	2,602	684	373

3. Discussion

3.1 Comparison to the Measured Wear Rates

Data on wear rate that correspond to measurement of both forging numbers and dwell time (contact time) are very limited. Therefore, it is not possible to compare Fig. 4 directly to the wear rate in the practical operation. Nevertheless, judging from the region of wear rate up to 1 mm/10^4 s in Fig. 4, wear rates in the conventional forging are considered to be in the temperature range from 1373 to 1573 K and in the range of the break-away thickness from 0.2 to 1 μm in Fig. 4, respectively. On the other hand, in 1960s, high energy-rate forging (h.e.r.f.) techniques were noticed. Their practical barrier was the huge die wear. Figure 5 shows the wear profile of the H.50 (Fe-0.37C-1.0Si-5.0Cr-1.35-Mo-1.10V) die steel after 2000 shots when 1 inch diameter by 1 inch height pellets of En8 (normal forging steel) were high-energy-rate hot forged at 75% reduction by the flat dies (Ref 5). Results of the dwell times of 40 ms and 250 ms per shot are shown in Fig. 5, respectively. From this figure, wear rates at the maximum wear depths of the upper die and the lower die were calculated at the dwell time of 40 and 250 ms, respectively. Calculated wear rates (μm/10^4 s) are 38,100 and 19,050 for the upper and lower die, respectively, at the dwell time of 40 ms. And those are 9652 and 3556 for the upper die and lower die, respectively, at the dwell time of 250 ms. According to these, wear rates at the high energy-rate forging are extremely large. These values are much larger than the maximum value of the wear rate at the break-away thickness of

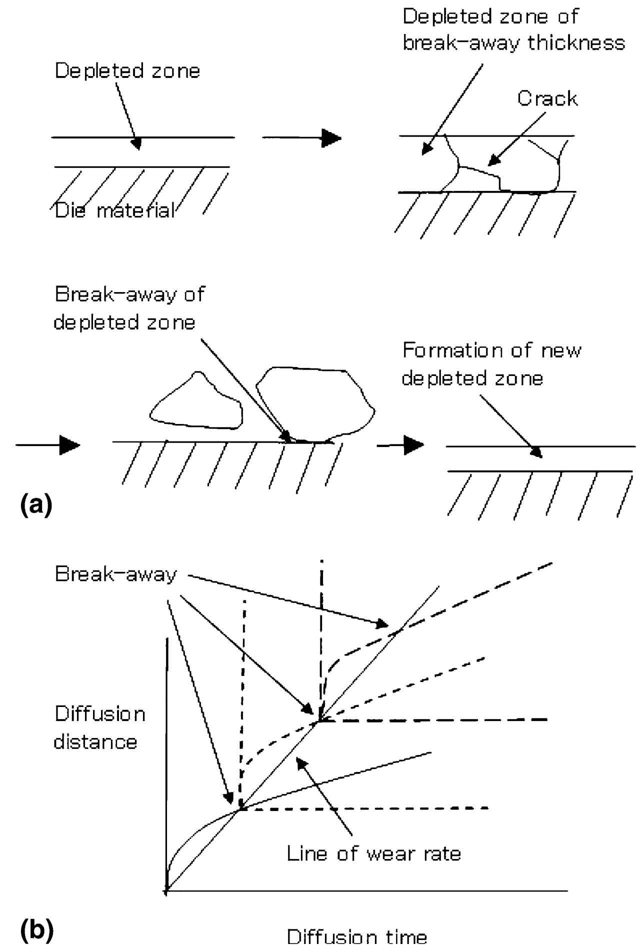

Fig. 3 The formation of depleted zone, its break-away (a), and the wear rate obtained from accumulated diffusion distance vs. diffusion time curves (b)

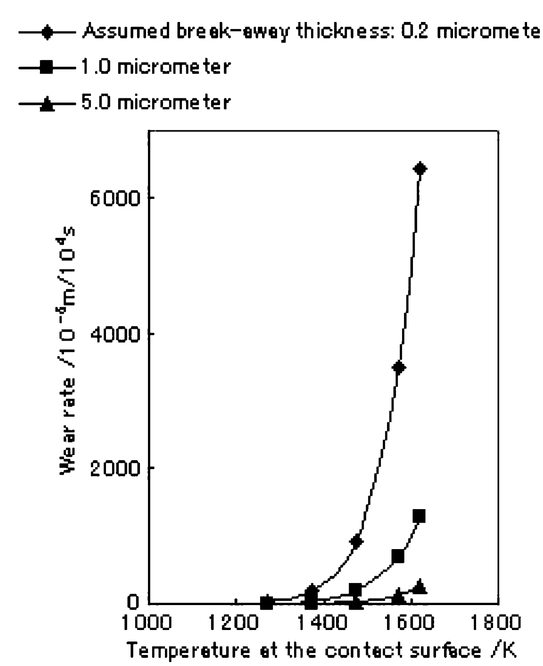

Fig. 4 Relationship between the wear rate and the temperature at the contact surface as a parameter of the assumed break-away thickness

0.2 μm and the contact surface temperature of 1623 K in Fig. 4. Thus, both much larger temperature increase on the die surface and much thinner break-away thickness at the high energy-rate forging can be expected, since the flow stress is very large and the slip speed is very high there.

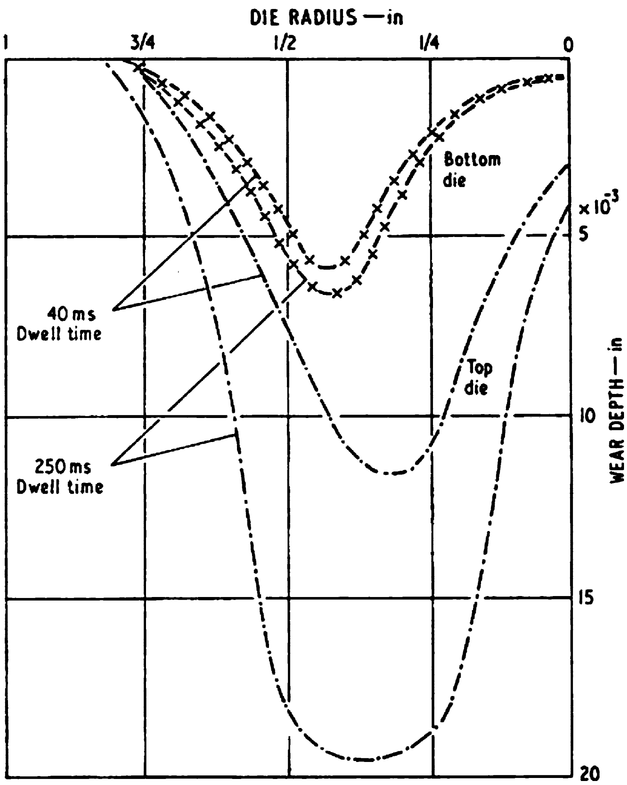

Fig. 5 Wear profiles of H.50 dies after 2000 forgings for short and long dwell times at the high-energy-rate hot forging (Ref 5)

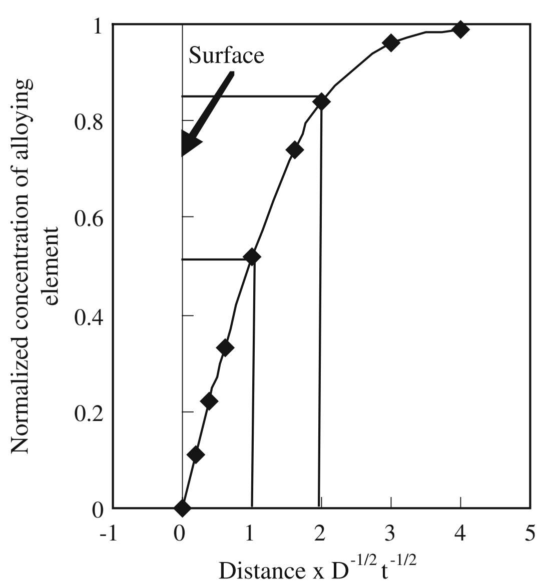

Fig. 6 Concentration profile and concentrations of the elements in the die at the diffusion boundary when the break-away thickness equals $\sqrt{Dt}$ and $2\sqrt{Dt}$, respectively

3.2 The Case in Which the Break-Away Thickness is Estimated to be Equal to $2\sqrt{Dt}$

From above mentioned, the surface temperatures of the die were estimated to be around 1473 K at the normal forging and over 1573 K at the high energy-rate forging, respectively, though the surface temperature mentioned here is originally an average and simplified one. At a glance, these values may be

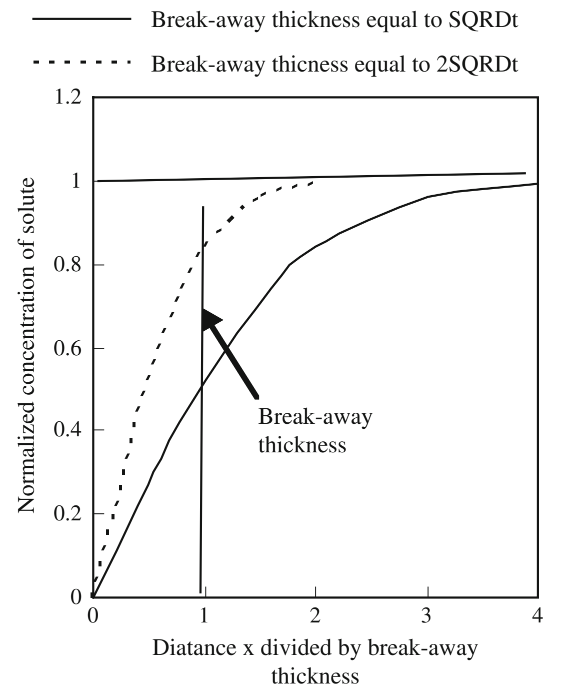

Fig. 7 Concentration profiles at the same break-away thickness when the break-away thickness equals $\sqrt{Dt}$ and $2\sqrt{Dt}$, respectively

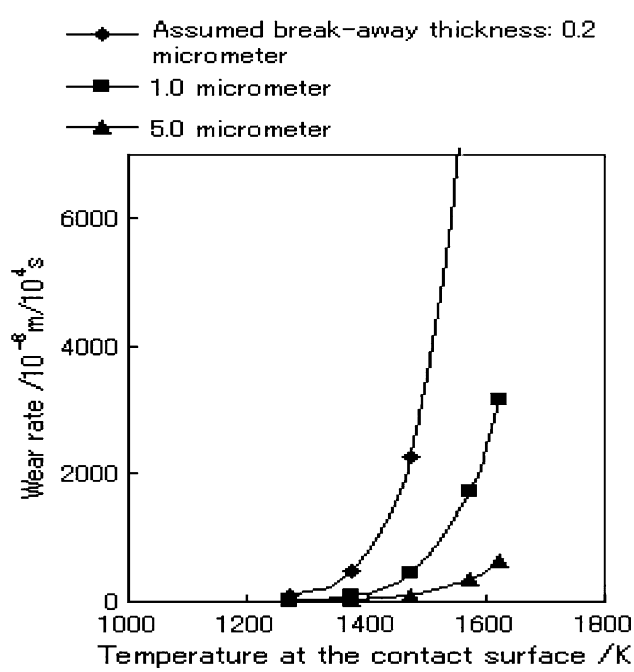

Fig. 8 Wear rates when the break-away thickness is estimated to be equal to $2\sqrt{Dt}$

considerably larger than one would normally expect. Then, wear rates were calculated for the case in which the break-away thickness is estimated to be equal to the diffusion distance $2\sqrt{Dt}$. Figure 6 shows the concentration of the elements in the die at the diffusion boundary when the break-away thickness equals $\sqrt{Dt}$ and $2\sqrt{Dt}$, respectively. In this figure, the distance on the abscissa is expressed by the unit of length x divided by $\sqrt{Dt}$ as same as in Fig. 2.

At the distance of $2\sqrt{Dt}$, the concentration of the alloying elements is about 85% of the original concentration, while at the distance of $\sqrt{Dt}$, that is about 52% of the original concentration. As the mechanical properties of the alloy degrade even at the small reduction of the concentration of the alloying elements, the case when the break-away thickness is assumed to equal $2\sqrt{Dt}$ seems more realistic. Figure 7 shows the concentration profile of solute when the diffusion distance is equal to $\sqrt{Dt}$ and $2\sqrt{Dt}$ at the same break-away thickness, respectively. As known from this figure, the diffusion time until the break-away at the diffusion distance of $2\sqrt{Dt}$ is 1/4 at the diffusion distance of $\sqrt{Dt}$, which leads to an increased wear rate. As the concentration of solute on the new surface after break-away is lowered to 85% of the matrix at the break-away at $2\sqrt{Dt}$, it was assumed for the convenience that the diffusion time is 85% of the virgin material. Figure 8 shows the wear rate calculated by this revised diffusion time. Estimated diffusion temperatures are lowered considerably. Therefore, this figure seems more reasonable than Fig. 4. From this figure, the most possible die surface temperature which shows reasonable wear rate experienced in the conventional hot forging seems to be around 1400 K. In the real forging process, the die is previously heated to several hundred degrees K. And moreover, the die surface is heated by the work but it is little, because it is due to the static heat transfer. Once the metal flow occurs, the die surface is greatly heated to the higher temperature, because the heat is generated by the friction at the contact surface locally and dynamically as shown in Eq 1. If the wear of the die can be assumed to be governed even partially by the diffusion of the alloying elements inside the die, as Fig. 8 shows, the wear of the die increases remarkably as the surface temperature increases. And it is also governed by the thickness of the break-away layer. The wear increases also remarkably as the thickness of the break-away layer decreases. Since the temperature increase of the die is caused by the friction heat, the reduction of friction heat is the key factor. On the other hand, the prevention of the diffusion of elements in the die is also effective. For that purpose, the surface treatment to form thermally stable compound can be effective.

4. Conclusions

In hot forging, alloying elements inside the die can be considered to diffuse into works by the temperature increase at the contact surface due to the friction heat. It was assumed that when the thickness of the depleted zone which has been formed on the die surface as a result of diffusion of the allying elements into works reaches the critical thickness, the break-away occurs and wear takes place. From the calculation results of the diffusion distances of the elements, it is recognized that the die surface temperature is the most important key factor in die wear and the thickness of the break-away layer is the next most important factor. Increasing temperature on the die surface increases the die wear and decreasing the thickness of the break-away layer increases the die wear. The lowering of friction heat and prevention of diffusion of alloying elements are important for the reduction of die wear. The wear phenomena such as heat crack, break-away, re-quenched layer and plastic flow, etc. seem to be accompanying phenomena which occur at the break-away of the depleted zone.

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