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Wear Characterization of Advanced High Strength Steel with Cr Content under Dry Sliding Condition

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Abstract: This paper describes the application of experimental design techniques to characterize the wear behavior of two medium carbon steels designing with suitable alloying elements, Mn, Si, Al, and Cr. Application of experimental design technique enabled us to confirm the significance of the factors affecting the wear behavior with a minimum number of experiments. Attempt was to find out the dominant parameter on the wear behaviour. The experiments of sliding wear were performed under pressure range of 0.71- 1.98 MPa and sliding velocity range of 3.43-10.43 m/s. the wear specimens were obtained through hot forging process with ~ 92% reduction on the investigated alloys at a temperature of 1100 ^{0}C followed by air cooling. Microstructural investigations on the worn surfaces were undertaken. The morphology results and the general wear formulas reveal that applied pressure was found to be the most significant parameter.

Keywords: Sliding Wear, Advanced High Strength Steel, Forging Process, Wear Parameter, and experimental Design.

INTRODUCTION

In recent years, reducing the weight of a vehicle to improve fuel economy and the increasing client demand for crash safety standards [1-3] have led to the superior usage of advanced high strength steels (AHSS) in the vehicle industry. High strength and hardness levels make the AHSS suitable for applications where high strength and enhanced safety are major design goals [4-5].

However, producing AHSS with high strength level is increasingly practicable but strength alone is insufficient for engineering components if the steel does not provide sufficient wear resistance.

It is a general observation that the wear resistance of metals and alloys have significant effects on the serviceability of the components [6]. Furthermore, wear resistance is one of most key mechanical property governing the applicability of the steel alloys as per various requirements in order to evaluate their potential for use as engineering components [7]. Moreover, wear of metals and alloys causes huge economic loss. To study the wear behavior of the materials, the influence of independent wear parameters such as applied pressure, sliding velocity, time and other input parameters on sliding wear of different material has been studied by a number of researchers [8-12].

In this work, two medium-carbon steel alloys with Cr content to obtain carbide-free bainite, which results in a good combination of mechanical properties [13-14] were used to investigate the wear behavior and worn surface of these two steel alloys. The main aim of this work is to investigate the relationship between the wear parameters such as pressure and velocity on the wear behavior of the investigated steels and to develop an empirical formula for the wear behavior of advanced strength steel during wear test under dry sliding.

Experimental procedure

The experiments of the dry sliding wear tests have been conducted using specimens of two medium carbon steel alloys prepared by melting steel scraps of plain carbon steel (0.2C-0.9Si-1.5Mn-0.04Al). The chemical compositions of the investigated steels are listed in Table 3.1 that analyzed by using spectro-analytical instruments. Cr has been added to alloy 2 to increase the tensile strength.

The ingots of the steel alloys have been hot forged with 92% % total reduction that is started at 1100 ºC and finished at 900ºC using a 250-kg capacity down stroke power hammer machine. Finally, both alloys are cooled in air. Fig 1 shows a schematic illustration of forging process.

Table-1: Chemical composition of the investigated alloys

	C	**Si**	**Mn**	**Cr**	**Al**	**Fe**
Alloy 1	0.303	2.45	2.15	0.045	0.23	94.8
Alloy 2	0.296	2.39	2.07	0.560	0.31	94.3

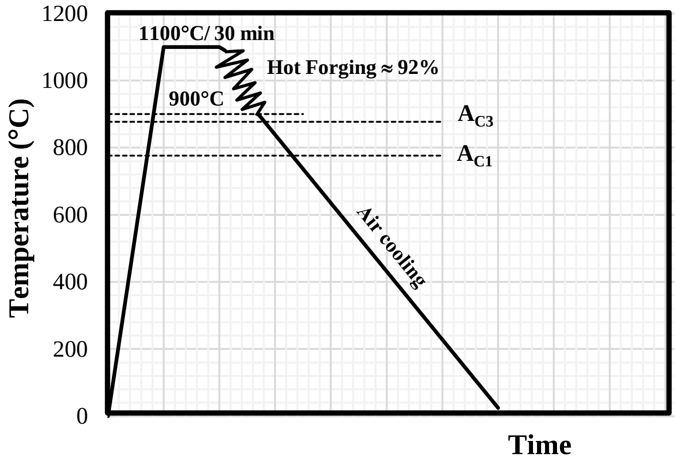

Fig-1: Schematic diagram of the hot forging process

Dry sliding wear testing was carried out at three different sliding velocities (3.43, 6.74, and 10.43 m/s) and at three different pressures (0.71, 1.41, and 1.98 MPa). The wear specimens with 6 mm diameter were machined from the investigated hot forged air cooled alloys (HF1 & HF2).

The experiments were designed according to the experimental design technique (Expert Design – software program). The complete design layout for experiments is summarized in Table 2, which shows the experimental combinations of applied pressure and sliding velocity.

Each wear sample was weighed before and after the test using a four digital microbalance. For each condition, three wear samples were tested and the average was used for calculation of the wear rate. The worn surfaces of the wear samples were examined.

Table-2: Wear parameters and their levels

Level	Velocity (m/s)	Pressure (MPa)		
		P_1 = 0.71	P_2 = 1.41	P_3 = 1.98
1	V_1 =3.43	P_1V_1	P_2V_1	P_3V_1
2	V_2 = 6.74	P_1V_2	P_2V_2	P_3V_2
3	V_3 = 10.43	P_1V_3	P_3V_2	P_3V_2

RESULTS AND DISCUSSIONS

Fig. 2 illustrates the typical morphology of the worn surfaces for the hot forged alloy 1 (HF1) after sliding wear at various wear conditions (different pressure and different sliding velocity). It can be found from the images that many adhesive traces, scratch marks, and debris, typically parallel to the sliding direction, are obvious on all the worn surfaces. The topographies are characteristics of abrasion causing wear by the removal of small crumbs. The wear rate in the fragmented area increases steadily as the wear parameters increases.

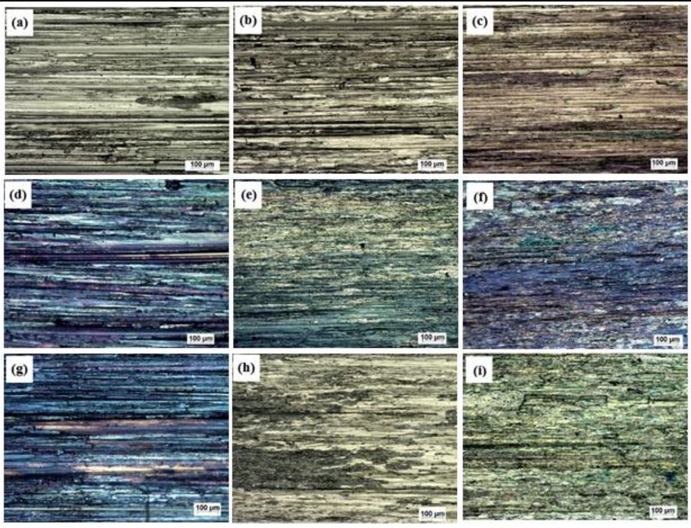

Fig-2: Micrographs of HF1 worn surface after sliding wear at different wear conditions
(a) 3.43 m/s – 0.71 MPa, (b) 6.74 m/s – 0.71 MPa, (c) 10.43 m/s – 0.71 MPa
(d) 3.43 m/s – 1.41 MPa, (e) 6.74 m/s – 1.41 MPa, (f) 10.43 m/s – 1.41 MPa
(g) 3.43 m/s – 1.98 MPa, (h) 6.74 m/s – 1.98 MPa, (i) 10.43 m/s – 1.98 MPa

The HF1 behavior at different parameters of wear (different levels of sliding velocity and pressure) is illustrated in Fig. 3. It is clear that the maximum wear rate is approximately 84 mg/min at the maximum pressure and minimum velocity. Meanwhile, at the medium velocity (6.74 m/s) the wear rate is constant till 1.41 MPa, and then the wear rate decreases. The relationship between the wear parameters, sliding velocity (V), applied pressure (P), and the output response, wear rate for HF2 is obtained by nonlinear regression analysis.

$$\text{Wear Rate}_{HF1} = -584.62 + 1051.62\,(P) + 110.85\,(V) - 330.84\,(P^2) - 4.11\,(V^2) - 173.61\,(P \times V) + 42.24\,(P^2 \times V) + 4.82\,(P \times V^2)$$

Fig-**4:** shows the most severe conditions of wear testing is the pressure that has a pronounced effect (deep lines of plastic deformation) on the worn surface with blue color due to Oxygen absorption (at right hand). On the other hand, the velocity has a lower effect (at left hand) with superficial plastic deformation line (not deep lines). The final conclusion can be derived as; the pressure is the dominant parameter for controlling the wear process.

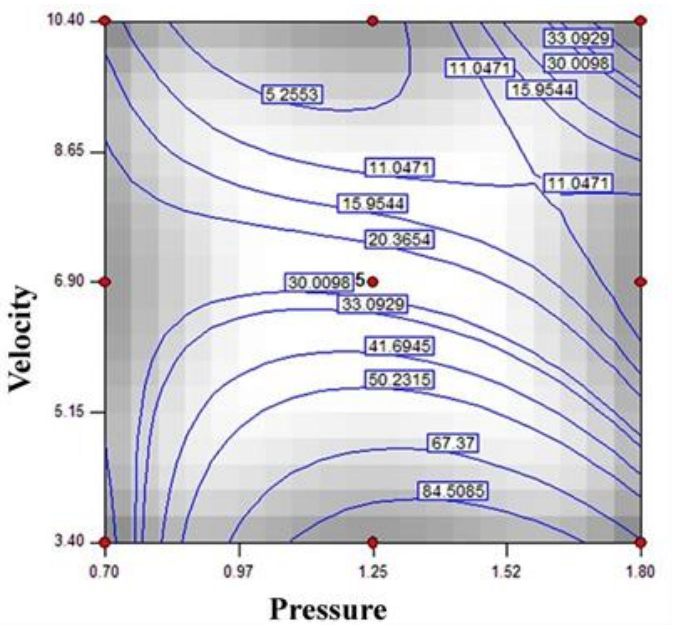

Fig-3: **Illustration of the wear behavior at different wear parameters for HF1**

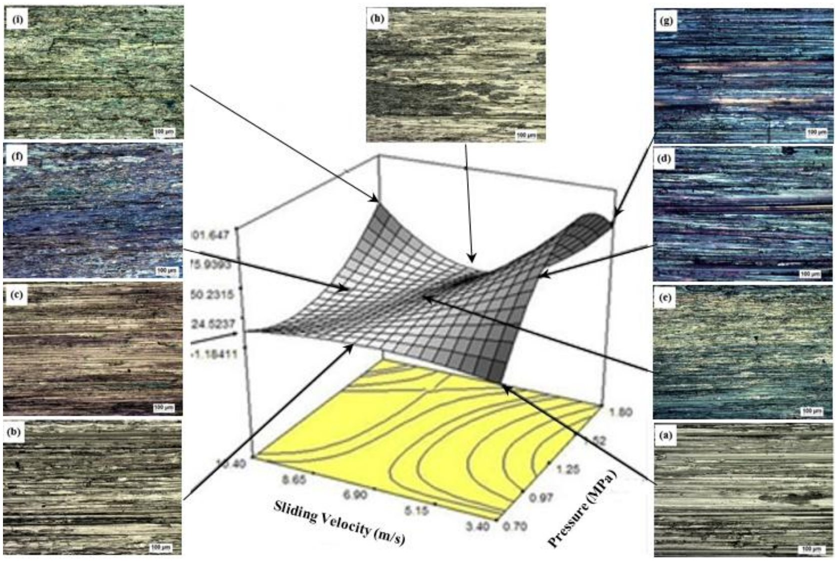

Fig-4: **3D illustration of the wear rate at different wear parameters with worn surfaces for HF1**

Fig-5**:** shows the worn surface morphology of hot forged alloy 2 (HF2) after sliding wear at different sliding wear conditions (different pressure and different sliding velocity). The figure shows the presence of adhesion marks and attached debris to the worn surface under different wear testing conditions. The wear behavior of HF2 at different wear parameters is shown in Fig. 6. It is clear that the maximum wear rate is approximately 65 mg/min. at the maximum pressure and minimum velocity. It is observed that at medium velocity (6.74 m/s) the wear rate is continuous increases with increase the pressure. The formula expressed the relationships between wear rate as response and input parameters pressure and velocity are listed below.

$$\text{Wear Rate}_{HF2} = 55.35 + 108.44\,(P) - 34.46\,(V) - 25.923\,(P^2) + 2.368\,(V^2) - 1.072\,(P \times V)$$

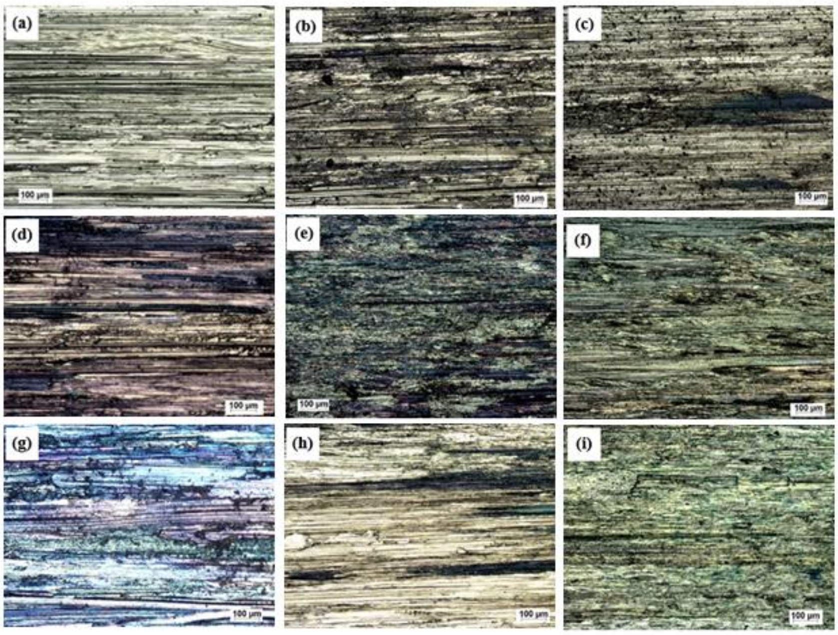

Fig-5: Micrographs of HF1 worn surface after sliding wear at different wear conditions
(a) 3.43 m/s – 0.71 MPa, (b) 6.74 m/s – 0.71 MPa, (c) 10.43 m/s – 0.71 MPa
(d) 3.43 m/s – 1.41 MPa, (e) 6.74 m/s – 1.41 MPa, (f) 10.43 m/s – 1.41 MPa
(g) 3.43 m/s – 1.98 MPa, (h) 6.74 m/s – 1.98 MPa, (i) 10.43 m/s – 1.98 MPa

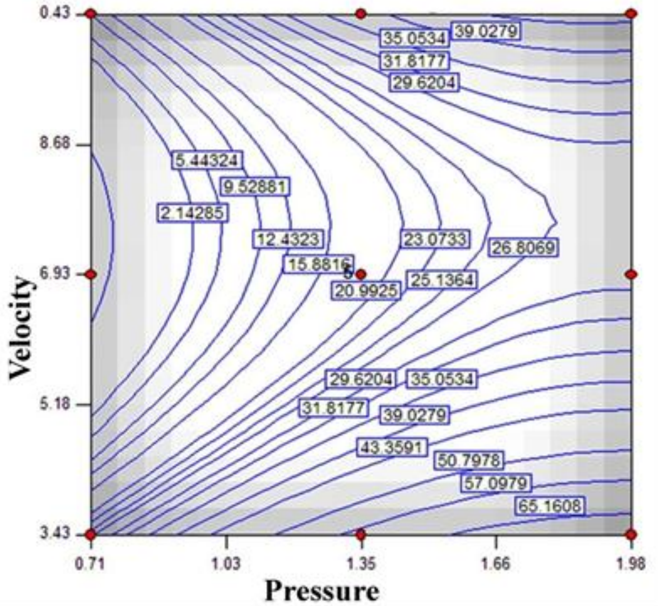

Fig-6: **Illustration of the wear behavior at different wear parameters for HF2**

Fig-7**:** shows the most severe conditions of wear testing where the pressure has a pronounced effect (deep lines of plastic deformation) on the worn surface with red and blue colors due to Oxygen absorption (right hand). On the other hand, the velocity has a lower effect (left hand) with superficial plastic deformation line (not deep lines but shallow). The final conclusion can be derived as; the pressure is the dominant parameter for controlling the wear process. From Fig. 6 and 7, it is apparent that the addition of Cr decreases the wear rate from 84 mg/min to 65 mg/min (24% red.).

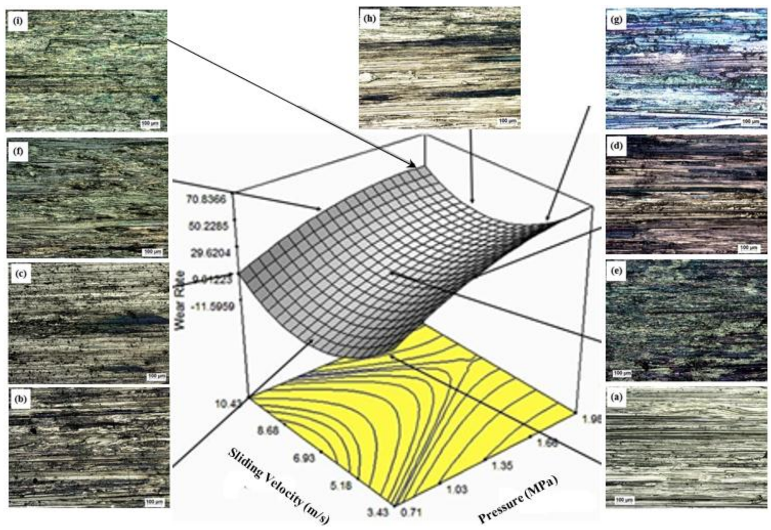

Fig-7: **3D illustration of the wear rate at different wear parameters with worn surfaces for HF2**

CONCLUDING REMARKS

The present work has been carried out to develop the general formulas to express the relatonship between wear rate as response and input parameters namely applied pressure and sliding velocity for two medium steel alloy. The morphology results and the general wear formulas reveal that applied pressure was found to be the most significant parameter. The maximum weight loss due to wear was found to be 65 mg/min when the pressure was 1.98 MPa and the sliding velocity of 6.74 m/s. the addition of Cr decreases the wear rate from 84 mg/min to 65 mg/min (24% red.).

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