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EFFECT OF HEAT TREATMENT ON THE TRIBOLOGICAL PROPERTIES OF TOOL STEEL AND MOLD STEEL

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ABSTRACT

Heat treatment is one of the most common processes done to metals due to its versatility. It can be used to make a material harder or more machinable according to the type of treatment done. Tool steel and mold steel are usually required to be machinable and need to be hard during operation. Which makes them some of the most commonly heat-treated materials. This study investigates the tribological properties of Hot-work tool steel W302, cold-work tool steel K110, and plastic mold steel M303.

It was found that annealing all 3 metals caused the metal to have the highest values of material loss due to wear and the highest friction coefficient. The lowest value for the coefficient of friction for the cold-work tool steel K110 was for the hardened-tempered sample and was the as-received sample for the M303 steel. Hardened-tempered samples across the three tested metals had the highest values of hardness, increasing the hardness of the W302, K110, and M303 by 43.81 %, 126.6 %, and 70.78 % respectively and thus had the lowest values of weight loss due to wear.

KEYWORDS

Heat-treatment, tool steel, mold steel, hardness, wear.

INTRODUCTION

Metallic materials are some of the most used engineering materials due to their favorable mechanical and thermal properties. One of the most commonly used metallic materials are ferrous alloys which are alloys which have Iron as the main component. A wide range of ferrous metals exist, each possessing different properties to serve a wide range of applications. One of those ferrous alloys is steel, which is a ferrous alloy with a carbon content ranging from 0.05 to 1.4 wt. %. Other elements can be added to steel in order to create alloy steels, [1].

Heat treatment is a process which aims at altering the mechanical properties of a metallic material or even polymers by heating and cooling of the material at different

rates [2-8]. Heat treatment has many types, one of which is annealing, which softens a metal and improves its machinability, [9, 10]. Another one is hardening that can be used to improve the hardness of a metal either on the surface or throughout the entire heat-treated piece, [11]. A third type of heat treatment is tempering, [12, 13], which can be done after hardening a metal to decrease its brittleness.

Tool steel is any steel used in making cutting tools. Usually a type of alloy steel. It has to have a set of mechanical properties, such as a high hardness after being quenched and a high machinability in its annealed state, [14, 16]. Tool steel can be divided into cold-work steels and hot-work steel. The main difference is that hot-work steel can retain its hardness under high temperatures.

The effect of chromium content in alloy steel on the wear resistance of the alloy was investigated and it was found that the addition of 12 wt. % chromium maximized the alloy's hardness and wear resistance, [17]. The effect of heat treatment on the wear rate of low alloy wear-resistant steel was tested and it was found that quenching at 900–920 °C and tempering at 350 - 370 °C was optimal for wear rate, [18]. Tempering for 30-60 minutes at 600 °C was found to enhance the wear resistance of AISI H13 tool steel, [19].

In cold-work tool steel, the optimal hardness, highest coefficient of friction and the least wear was achieved when specimens were quenched in oil and normalized in air, [20]. In hot-work steel, the highest values of hardness and coefficient of friction were seen at specimens which were heat treated at brine at 250 °C, quenched then normalized. while minimum wear was inhibited by specimens that were treated in brine at 500 °C, quenched then normalized, [21]. Ductile iron specimens were also heat treated then had their tribological properties tested. The highest hardness was achieved in specimens quenched in water and air. Samples quenched in oil and water had the lowest friction coefficient. Minimum wear was shown by specimens quenched in oil, [22]. In this study. The effect of annealing and hardening-tempering heat treatment on the tribological properties of Hot-work tool steel W302, cold-work tool steel K110 and plastic mold steel M303 was investigated.

EXPERIMENTAL

Hot work tool steel X40CrMoV5-1 (W302) with DIN number <1.2344> according to DIN standard, Cold work tool steel X153CrMoV12 (K110) with DIN number <1.2379>, and Plastic mold steel (M303) X38CrMo16 with DIN number < 1.2316 > have been selected as extensively used different chromium content alloy steels in plastics die industry. The supplier of the used materials was BÖHLER company. According to the supplier, Table 1, Table 2, and Table 3 show the chemical composition of as received alloys, respectively. Table 4 presented the chemical composition of the same alloys according to experimental analyses using EDAX analyzer Fig. 1.

Hardness was measured using a Vickers hardness (HV) tester shown in Fig. 2. The Vickers hardness measurements of the tested materials were performed under 100 Kgf load and 15 seconds loading time. The specimens were smoothed and polished

before testing to avoid the scratch effect on the measurement of the indentation's diagonals.

Annealing and hardening-tempering heat treatment processes have been applied to all three tested materials in order to study the effect of heat-treatment on microstructure, mechanical and tribological behavior using furnace shown in Fig. 3. In order to clarify the steps of heat treatment process table 5, table 6, and 7 show temperature, resistance time, and cooling method used in annealing process of M 303, W 302, and K 110 alloy steels, respectively. Additionally, table 8, table 9, and table 10 show temperature, resistance time, and cooling method used in hardening followed by tempering process of M 303, W 302, and K 110 alloy steels, respectively.

Pin-on-disc was performed to evaluate the frictional behavior of tested steels and to specify their optimum usage according to comparing their friction coefficients and generated wear rate. Pin-on-disc test rig shown in Fig. 4 was employed to execute the friction comparison between the utilized steels. Steel samples with 10 mm diameter and 18 mm height were used as samples of the pin-on-disc test, sliding velocity was kept constant at 1.3 m/s as the samples were rotated at a 35 mm radius using electrical motor rotates with 350 r.p.m. A silicon carbide paper (Al_2O_3 emery paper) 120 grit was mounted as the counter-face. The load and sliding distance under consideration were recorded in table 11.

Table 1, Chemical composition of steel W 302, [23].

Elements	Cr	Si	Mn	C	Mo	V	Fe
Percentage (%)	5.20	1.10	0.4	0.39	1.40	0.95	Balance

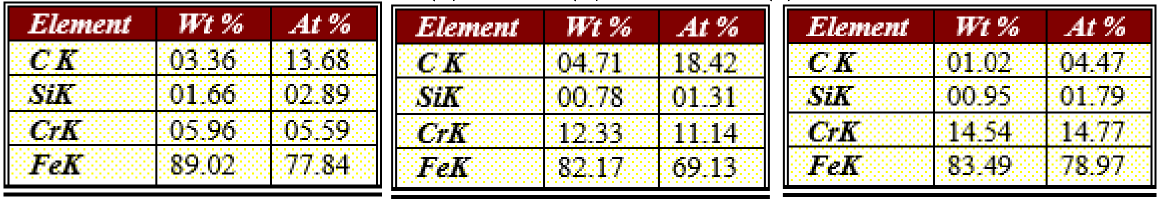
Table 2, Chemical composition of steel K 110, [24].

Elements	Cr	Si	Mn	C	Mo	V	Fe
Percentage (%)	11.30	0.30	0.30	1.55	0.75	0.75	Balance

Table 3, Chemical composition of steel M 303, [25].

Elements	Cr	Si	Mn	C	Mo	Ni	Fe
Percentage (%)	14.50	0.30	0.65	0.27	1.00	0.85	Balance

Table 4, EDAX Quantification (a) W302, (b) K110, and (c) M303.



Element	Wt %	At %
C K	03.36	13.68
SiK	01.66	02.89
CrK	05.96	05.59
FeK	89.02	77.84

(a)

Element	Wt %	At %
C K	04.71	18.42
SiK	00.78	01.31
CrK	12.33	11.14
FeK	82.17	69.13

(b)

Element	Wt %	At %
C K	01.02	04.47
SiK	00.95	01.79
CrK	14.54	14.77
FeK	83.49	78.97

(c)

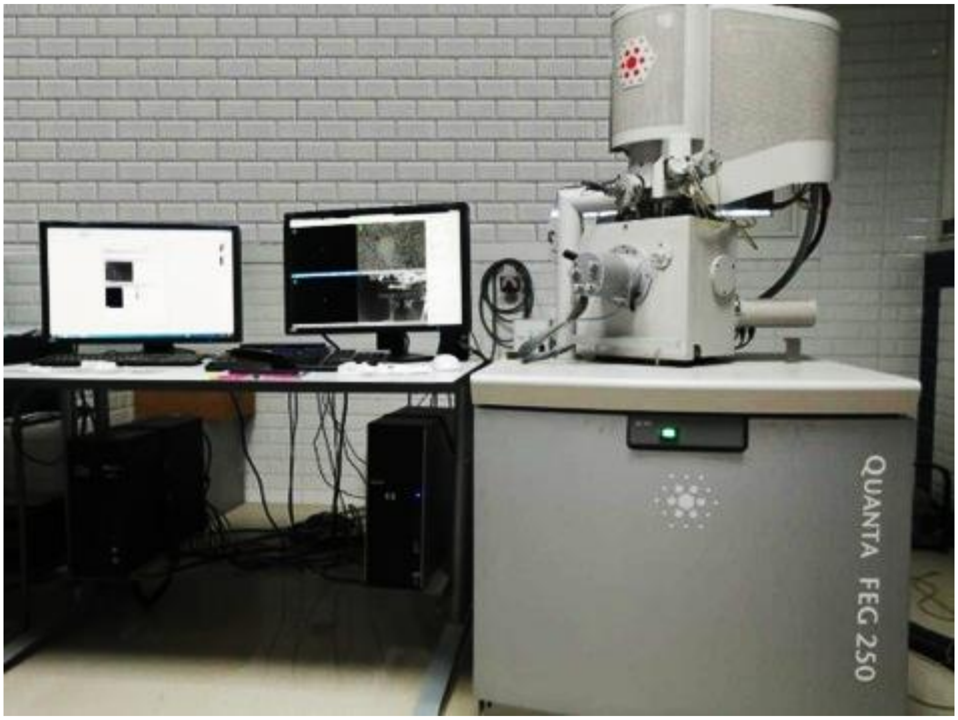


Fig. 1 EDAX analyzer.

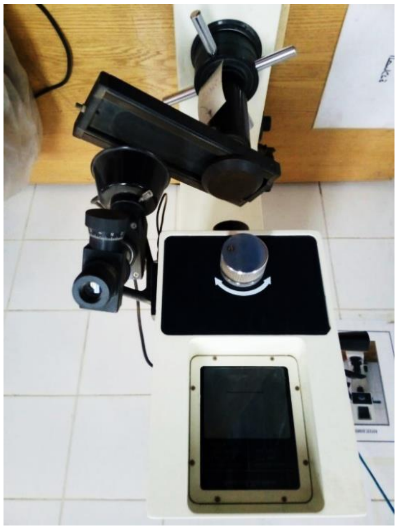


Fig. 2 Vickers hardness tester.

Fig. 3 Heat-Treatment furnace.

Table 5, Annealing process of M 303 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**cooling**
Annealing	**20 → 725**	**45**	**In furnace**

Table 6, Hardening followed by tempering process of M 303 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**cooling**
Hardening	**20 → 610**	**45**	**-**
	610 → 840	**45**	**-**
	840 → 1020	**45**	**Oil**
Tempering	**20 → 200**	**120**	**Air**

Table 7, Annealing process of W 302 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**cooling**
Annealing	**20 → 800**	**45**	**In furnace (slow cooling rate)**

Table 8, Hardening followed by tempering process of W 302 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**cooling**
Hardening	**20 → 610**	**45**	**-**
	610 → 840	**45**	**-**
	840 → 1050	**45**	**Oil**
Tempering	**20 → 500**	**60**	**Air**

Table 9, Annealing process of K 110 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**Cooling**
Annealing	**20 → 850**	**45**	**In furnace**

Table 10, Hardening followed by tempering process of K 110 alloy steel.

Heat-treatment	**Temperature, ˚C**	**Resistance time, min**	**Cooling**
Hardening	**20 → 610**	**45**	**-**
	610 → 840	**45**	**-**
	840 → 1030	**45**	**Oil**
Tempering	**20 → 200**	**60**	**Air**

Table 11, Tribological test Parameters and condition.

Parameter or condition	**Values**
Applied load (N)	**10, 14, 18, 22**
Sliding distance (m)	**155**
Sliding velocity (m/s)	**1.3**
Radius of rotation (mm)	**35**
Rotary speed (r.p.m)	**350**
Abrasive counter-face	**120 grits (Al_2O_3 emery paper)**

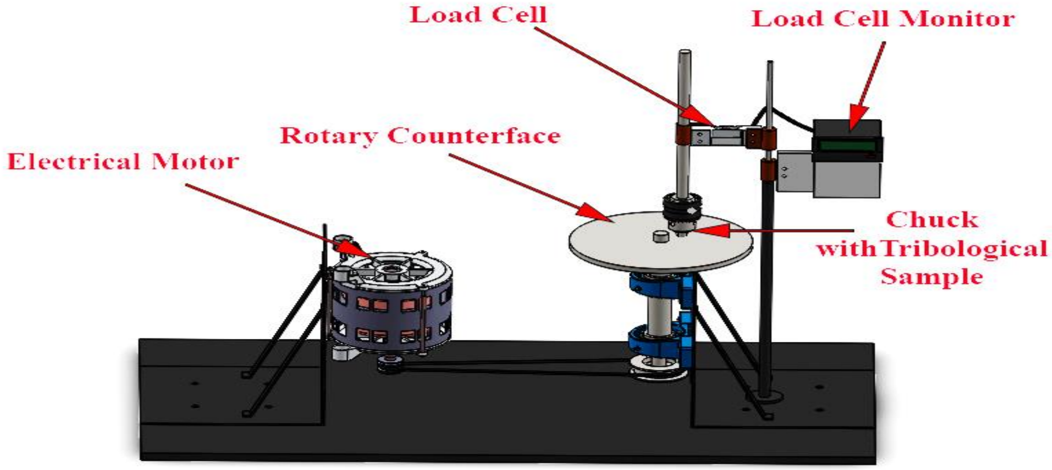


Fig. 4 Pin on disc tester.

RESULTS AND DISCUSSION

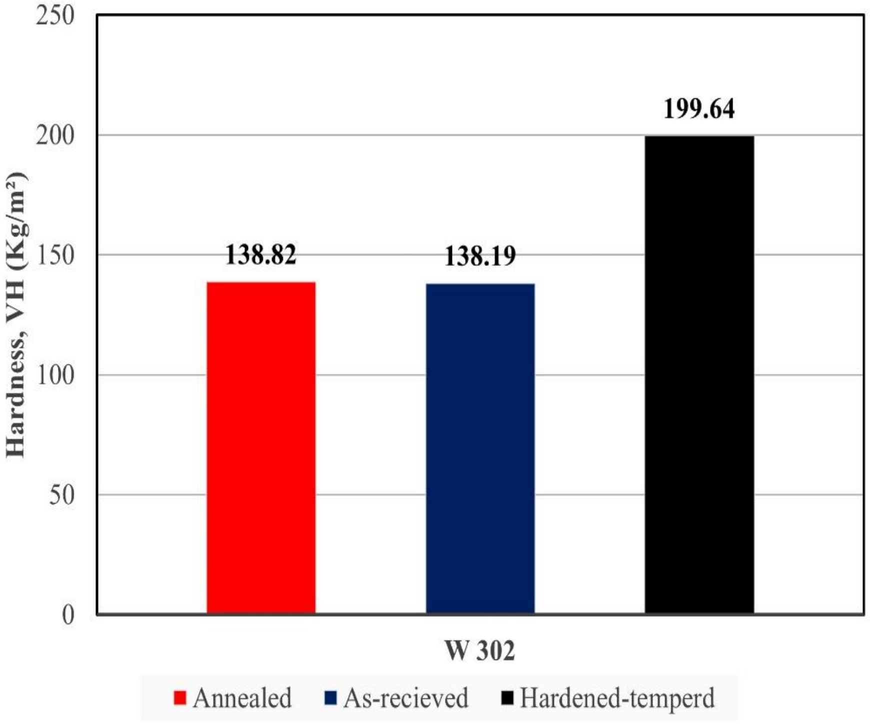


Fig. 5 Hardness of W 302 alloy steel.

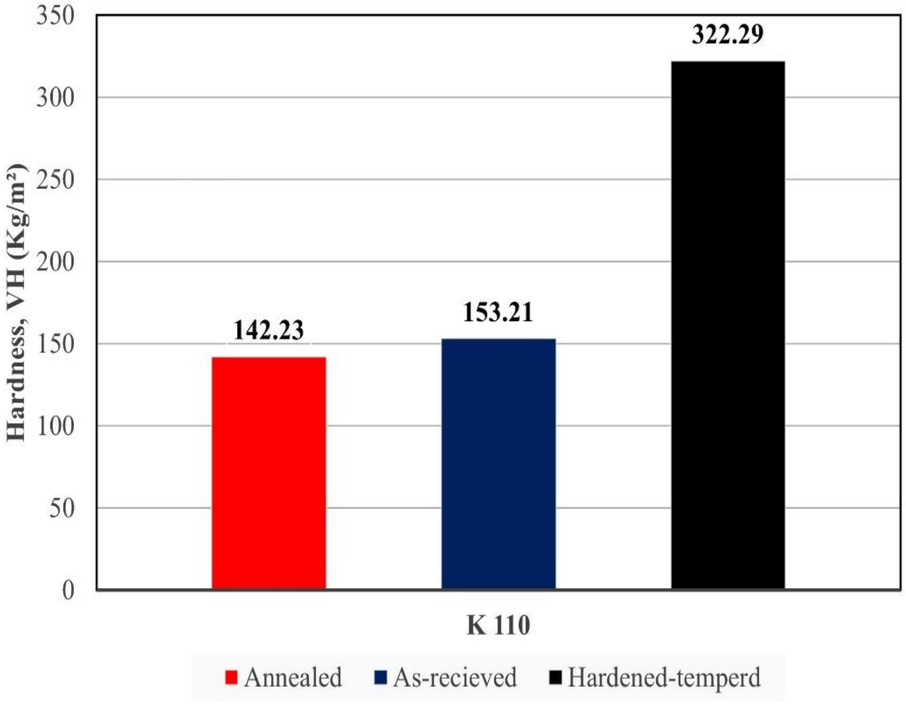


Fig. 6 Hardness of K110 alloy steel.

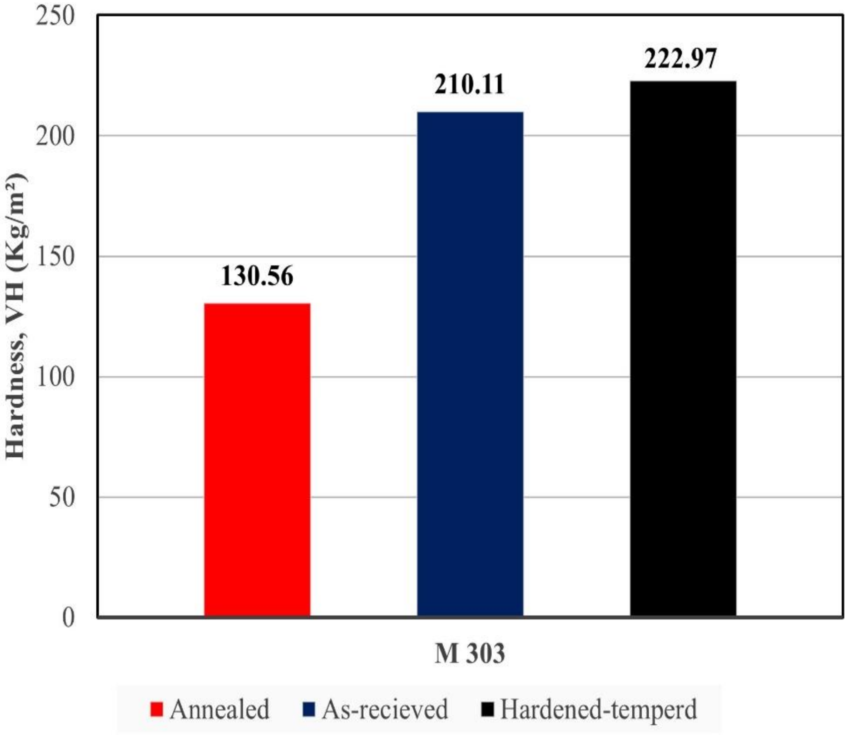


Fig. 7 Hardness of M 303 alloy steel.

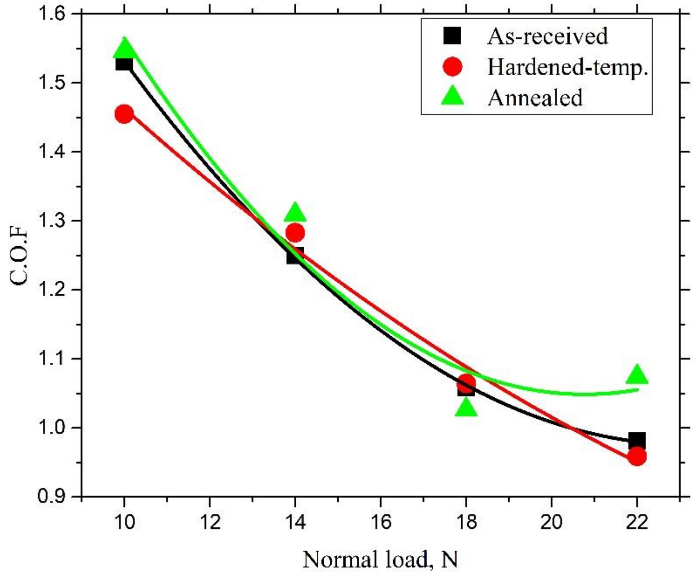


Fig. 8 Effect of normal load on friction coefficient for W302.

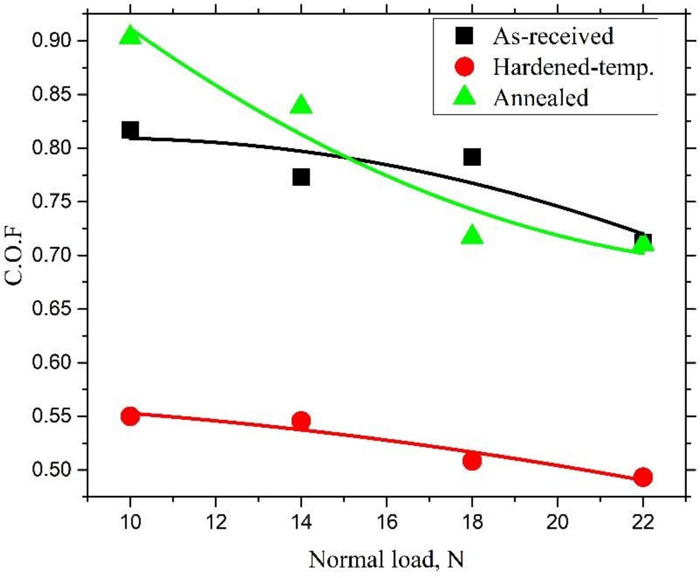


Fig. 9 Effect of normal load on friction coefficient for K110.

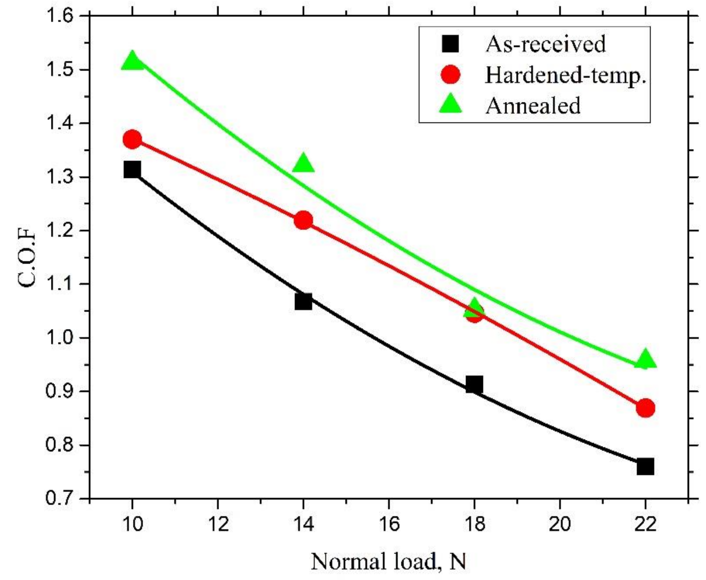


Fig. 10 Effect of normal load on friction coefficient for M 303.

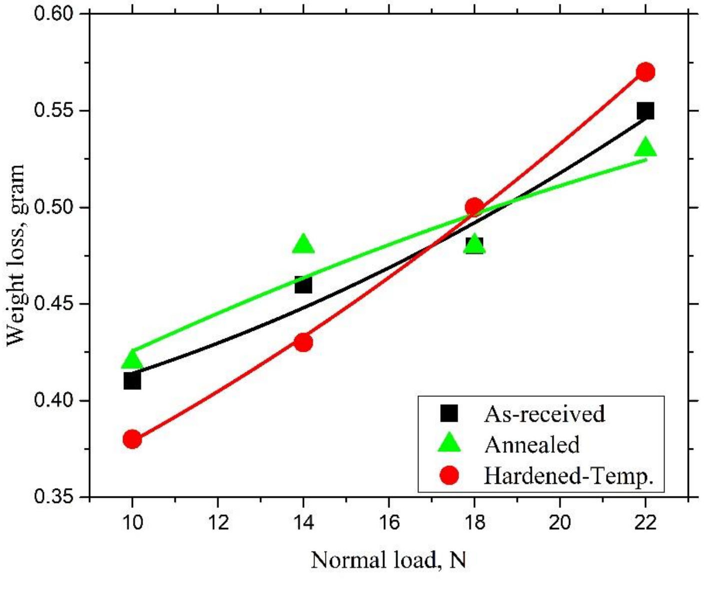


Fig. 11 Effect of normal load on weight loss for W 302.

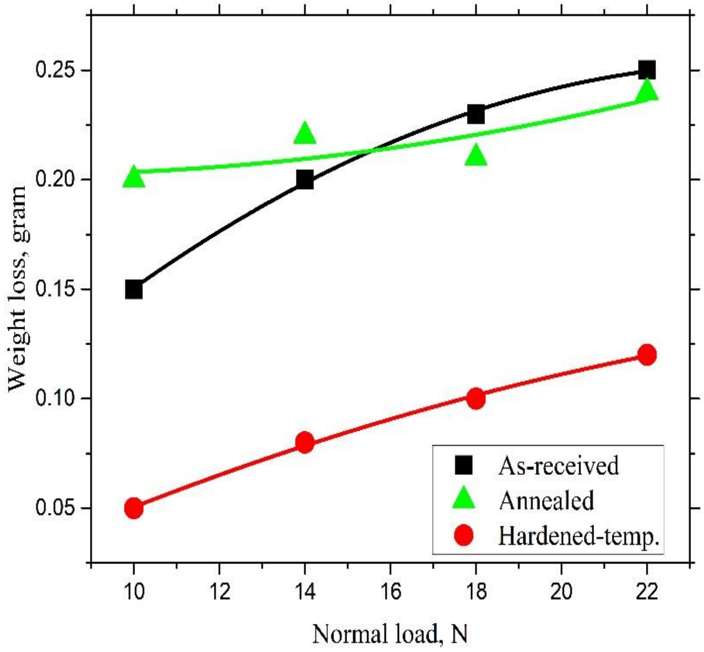


Fig. 12 Effect of normal load on weight loss for K 110.

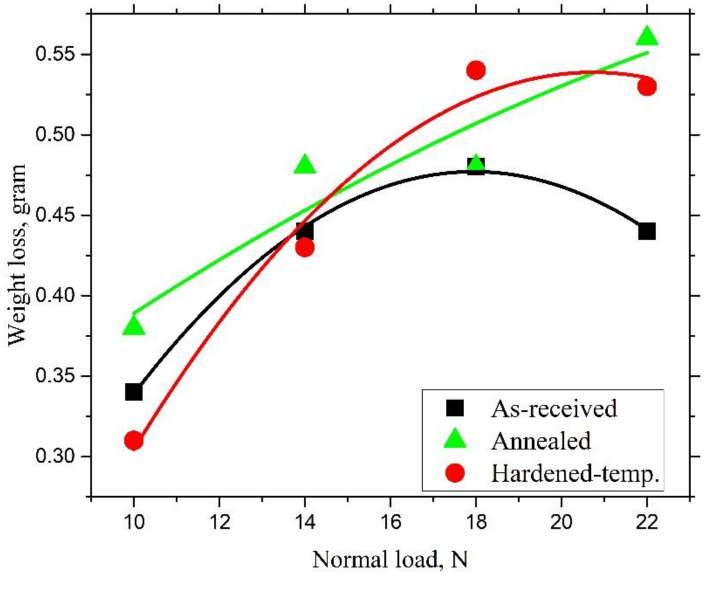


Fig. 13 Effect of normal load on weight loss for M 303.

The data presented in Fig. 5 demonstrates a notable increase in hardness for hardened-tempered W302 alloy steel, as compared to annealed W302. Specifically, the hardness has risen from 138.82 kg/m^2 to 199.64 kg/m^2, resulting in an improvement percentage of 43.81%. The Vickers hardness number for heat-treated K110 alloy steel is illustrated in Fig. 6. The K110 specimen, after annealing, exhibited a hardness number of 142.23 kg/m^2. In addition, it should be noted that the hardness of hardened-tempered K110 steel is 322.29 kg/m^2, exhibiting an improvement percentage of 126.6 %.

Hardening-tempering treatment accomplished improvement in hardness of M303 by 70.78 % in the comparison to annealing treatment. Hardened tempered M 303 and annealed M303 steels have 222.97 kg/m^2 and 130.56 kg/m^2, respectively. Figure 7presented Vickers hardness numbers of different treated M303 steels.

The oil-quenching process followed by tempering demonstrated the highest levels of hardness due to the rapid cooling rate, resulting in the formation of a martensitic microstructure that explains the high strength of the component. The K110 alloy steel exhibited the most significant enhancement in hardness, with an increase of 126.6 %. This notable gain can be attributed to its high carbon concentration of 1.55 %. A rise in carbon levels is associated with an increased probability of an increase in the proportion of cementite. The annealing procedure, which is utilized to eliminate impurities inside grains, decrease grain size, and enhance ductility, exhibits the most minimal levels of hardness.

It is well known that annealed metals are softer (more ductile) than unannealed metals. This fact causes them to have a higher coefficient of friction when tasted against other metals. This is due to peaks on the surface of the metal, requiring more energy to break-off from the metal due to the increased toughness of the metal. This cause the interlocking of the surface of sandpaper and metal to be harder to break-off and this increase their coefficient of friction as presented in Fig. 8 - 10.

Increasing the contact force between the metal and sandpaper causes better interlocking between peaks and valleys of both surfaces, this causes the parting-off of peaks of the metal to be easier as chance of peaks sliding against one another became less. This decreasing the coefficient of friction. Another reason is the increase in wear, which does two things. Polishes the surface of the metals and causes the metal particles that are shaved off the surface to lag between the metal and sandpaper, on which the surface can roll on. These two effects decrease the coefficient of friction.

The coefficient of friction (C.O.F.) for steel alloy M303 is seen to be lower in its as-received condition compared to its hardened-tempered form. This behavior can be ascribed to the transformation of martensite, a hard element, into relatively troostite, which is tempered martensite.

The evaluation of material wear can be achieved through the measurement of weight loss under certain circumstances. In general, the magnitude of wear has a positive

correlation with the magnitude of the normal force. The annealed alloy exhibited the maximum wear. Hardened-tempered alloy steel, however, showed the least amount of wear. The wear of a material is significantly influenced by its hardness. The inclusion of carbides, such as chromium carbides, has the potential to optimize the ability of a material to withstand wear by introducing rigid particles into the steel matrix. The minimum weight loss peak (0.05 gram) shown in Fig. 11 appears to be consistent with the highest hardness value of hardened tempered K110 alloy steel, which is 322.29 kg/m^2. Similar observations were made in Fig. 12 for alloy steel W302 and Fig. 13 for alloy steel M303.

CONCLUSIONS

The effect of heat treatment on the tribological properties of Hot-work tool steel W302, cold-work tool steel K110 and plastic mold steel M303 were investigated. The following conclusions can be made:

1. Hardened-tempered specimens expectedly had the highest hardness values and thus showed the lowest values of weight loss in general.

2. Coefficient of friction values for K 110 steel were lowest in the hardened-tempered specimen and highest in the annealed specimen.

3. The coefficient of friction for the M 303 steel was lowest in the as-received state and highest in the annealed state.

4. Annealed samples showed the highest values for both coefficient of friction and wear in all 3 tested steels.

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