Chapter 11
Tribology of Steel–Steel Contact: Comb-Cutter Assembly for Sheep Hair Shearing Device Developed at IIT Delhi

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1 Introduction

The quality of natural wool depends on the quality of hairs received from sheep [1]. The process of sheep hair shearing controls the quality of woolen fleece of a sheep. A sheep shearing machine is extensively used by the wool industries to cut hair from the sheep body as shown in Fig. 1. The machine involves many components which have relative sliding motion involving tribological phenomenon. Comb-cutter is the tribological assembly (Fig. 1a, b) where relative motion is responsible for sheep hair shearing and faces tribological degradation. The blunting and damage of the comb-cutter assembly reduces the yield and needs regrinding. The similar types of machines are also supplied by international vendors and face similar kind of degradations. The comb and cutter used in imported machine are also made of steels. In a similar way, the steels was used in RuTAG machine too but needs frequent grinding and have low wear resistance. The present work is planned to explore the steels which can be utilized for manufacturing of comb-cutter tribo-pair.

The literature is explored to find the available wear resistant steels. However, Engineering Handbook technical information [2] was used to list the steel such as W1, D2, M2, EN31, and A2 steels. As a first approach, wear resistant materials can be selected using the Archard equation [3] and develop quantitative understanding of the wear process. Bourithis et al. [4] compared the wear response of tool steels, AISI D2

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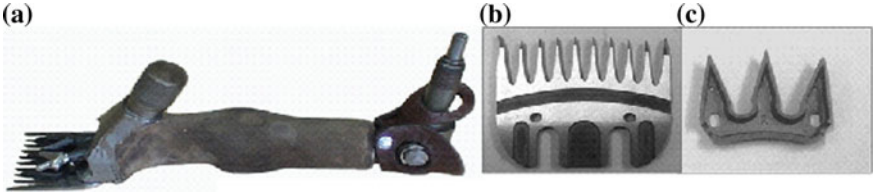

Fig. 1 Photographic view of **a** sheep hair shearing machine assembled at IIT Delhi and tribological components of sheep hair shearing machine; **b** Comb, and **c** Cutter

and O1, with the same hardness (60 HRC) and tested in three different modes of wear; adhesion, three-body and two-body abrasion. They proposed that microstructures of different steels control the wear response. In three-body abrasive wear, the wear rate of D2 steel is almost half than that of O1 steel and this was attributed to the presence of the plate-like hard carbides in its microstructure. In two-body abrasive wear also, D2 steel is better than O1 tool steel. Verma et al. [5] suggested that heat treatment of EN-31, EN-8, and D3 steels can help in improving the hardness from 10 to 55 HRC, 13 to 48 HRC and 18 to 56 HRC, respectively. Kumar et al. [6] studied the tribo-interaction of EN 31 against EN 19 steel under dry sliding for a range of loads and speeds. At low load, wear resistance and coefficient of friction (COF) increases with sliding velocity. At higher load, wear increases initially followed by stable value while the COF first increases followed by considerable decreases with sliding velocity.

Further, the Archard's wear model is suggested as valid. Chengwei et al. [7] studied the plasticity index has been widely applied in studying the contact of rough surfaces given by Greenwood and Williamson. A general expression for the plasticity index (Ψ) suitable for both isotropic and anisotropic rough surfaces. When $\Psi \gg 1$, minimal plastic deformation of asperities occur even at minimal contact pressure $\Psi \ll 0.6$, deformation is largely plastic. Zhang et al. [8] studied the indentation plasticity and radial crack length. Indentation plasticity is defined as the ratio of the plastic displacement divided by the total displacement in the load–displacement curve of a micro-indentation measurement and microhardness dissipation parameter (MDP) measured by micro-indentation test. The literature suggests that the controlled microstructure and suitable heat treatment of different grades of steels can help in improving the wear resistance. The involvement of different wear modes at different speeds and loads and Archard equation suggests that tribo-pair should have different hardness and microstructure. These basic principles can be helpful to identify the suitable materials for Comb and Cutter tribo-pair.

From field testing done in past, it has been realized that the combs and cutters are the most critical parts of the sheep hair shearing machine. They are susceptible to damage and require frequent maintenance. The material being used in the RuTAG machine's comb and the cutter was inferior to the Lister material. The frequent grind during field trials suggests that RuTAG machine's comb and cutter failed due to improper selection of material.

The main objective is to improve the life of comb and cutter of the machine developed at IIT Delhi. As a starting point, the main focuses on material selection which will be followed by study of Mechanical and Tribological characteristics, respectively.

2 Experimental

2.1 Material

The material being used in the RuTAG machine's comb and cutter was procured from JTC, Rajkot which has a composition almost similar to the imported machine (Lister) but the wear resistance was not so good. After analyzing the chemical composition, some grade of steels (EN31, A2, M2, and D2 steel) were selected which have composition almost similar to the imported machine's material.

2.2 Sample Preparation

To conduct the tribological experiments, the samples were cut by CNC wire cut EDM machine with dimensions 19.5 mm × 40 mm × 5 mm (Disc) and 10 mm × 10 mm × 5 mm (Pin). The samples were surface polished by 80, 150, 220, 400, 600, 800, 1200 grit SiC papers, respectively. Further, these samples were cloth polished using aluminum powder.

2.3 Chemical Characterization

The chemical compositions of standard material and selected steels were analyzed using the Optical Emission Spectrometer and shown in Table 1.

2.4 Heat Treatment

The steels were heat treated under the different parameters. The purpose of heat treatment was to relieve any stress, make material homogenize and improve mechanical properties. The heat treatment schedule for different steels is shown in Table 2.

Table 1 Chemical composition of different materials

Material	Fe (%)	C (%)	Mn (%)	S (%)	Cr (%)	Mo (%)	Ni (%)	V (%)	W (%)
Lister	97.41	1.105	0.340	0.011	0.530	0.012	0.100	0.094	0.026
RuTAG	97.55	0.362	0.651	0.026	0.655	0.137	0.085	0.011	0.036
D2 steel	90.45	1.599	0.601	0.042	>5.50	0.433	0.257	0.189	0.081
M2 steel	91.20	>1.60	0.279	0.054	>5.50	0.236	0.213	0.052	0.088
A2 steel	98.17	0.832	1.105	0.020	4.83	0.020	0.91	0.031	0.035
EN31 steel	96.84	0.970	0.468	0.042	1.150	0.016	0.077	0.010	0.030

Table 2 Parameters for heat treatment of steels

Material	Preheating temp. (°C)	Soaking time	Hardening temp. (°C)	Soaking time	Quenching temp. (medium)	Tempering temp.	Soaking time (h)
A2 steel	760	1 h	954	½ hour	66–51 °C (Interrupted Oil)	200 °C Double tempering required	1
M2 steel	844	1 h	1204	½ hour	66–51 °C (warm Oil)	593 °C Double tempering is required	2
EN31 steel	650	1 h	850	½ hour	60–70 °C (Oil)	200 °C Double tempering is required	1
D2 steel	650	30 min	1010	1 h	65 °C Gas quenching up to 6 bars	515 °C (1st tempering) 480 °C (2nd Tempering)	2

2.5 Tribology Study

Wear tests were conducted on UMT-3 Tribometer using pin-on-disc configuration under reciprocating sliding module. The input parameters (Load = 50 N, sliding Velocity = 0.2 m/s, Stroke length 15 mm, Counter surface size 19.5 × 40 × 5 mm and Pin size 10 × 10 × 5 mm) were selected to simulate the running conditions of the comb-cutter in the sheep shearing machine. On the basis of hardness, steel tribo-pairs were finalized.

2.6 Micro-Indentation Test

Micro-indentation tests were performed using ZWICK ROELLZ 2.5 automated microhardness tester. Indenter used for micro-indentation was Berkovich shaped. The parameters used in controlling the indentation test were: approach load- 49.1 N, holding time-12 s and loading rate-1 N/s.

3 Result and Discussion

3.1 Hardness

Figure 2 shows the comparative mapping of hardness of different as-cast and heat-treated steels. In general, it can be seen that heat treatment results increase in hardness. The increases in hardness of D2 and M2 steels can be attributed to the formation of vanadium carbides, as they have vanadium more than 0.05%. On the other hand, A2 and EN31 steels have less doping of hard carbide forming elements.

3.2 Load-Indentation Depth

Figure 3 shows the variation of indentation depth with load for different heat-treated steels. The slope of unloading curve and recovery in indentation depth indicates the estimates of elastic modulus and contact stiffness, respectively. High the unloading slope, higher the elastic modulus, and smaller the recovery depth, higher the contact stiffness.

EN 31 and A2 steel have almost similar elastic modulus observed in both (as-received and heat-treated) conditions, whereas M2 and D2 steel (heat treated) have maximum elastic modulus to other steels (as-received). After the heat treatment, it was observed that minimum differences in elastic modulus of different steels as shown in Fig. 5. Elastic modulus E of the steels were estimated using Eq. 1.

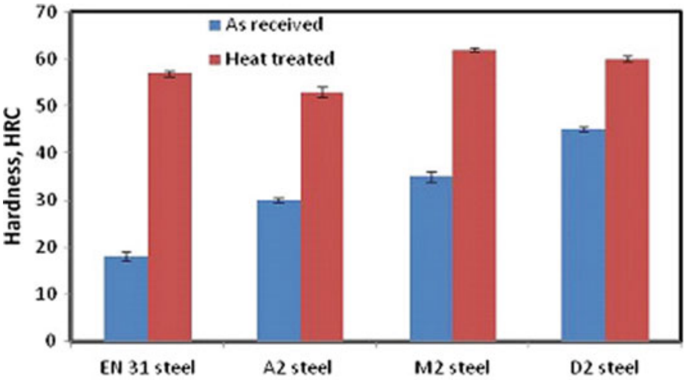

Fig. 2 Hardness variation for different type of steels when they are as-cast and heat treated

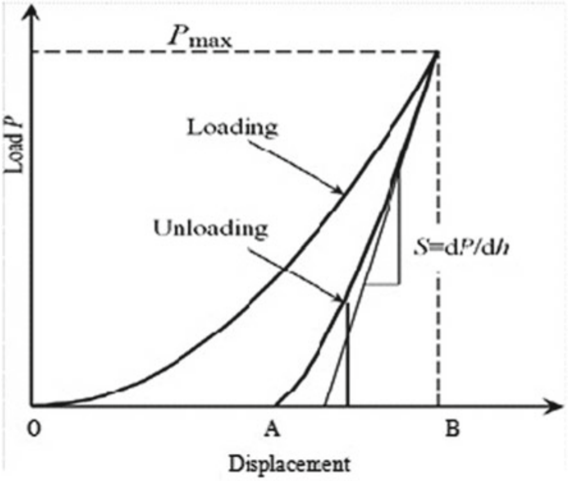

Fig. 3 Schematic representation of a micro-indentation load–displacement curve

$$\frac{1}{E_r} = \frac{1 - \nu^2}{E} + \frac{1 - \nu_i^2}{E_i}, \tag{1}$$

where $E_i = 1140$ GPa and $\upsilon_i = 0.07$ are Young's modulus and Poisson's ratio of the indenter, respectively; ν is Poisson's ratio = 0.3 of the sample; E_r is reduced Young's modulus, which is given by $E_r = S/2\beta\ (\sqrt{\pi}/A_c)$. Where S is the contact stiffness of the material; β is a constant that depends on the geometry of the indenter (β = 1 for a Berkovich indenter with the angle of 65.271 between the tip inclined face and the vertical axis); A_c is the projected area of the indentation. The estimated values of elastic modulus for different steels are shown in Fig. 4. The effect of heat treatment on elastic modulus is not significant, except for M2 steel.

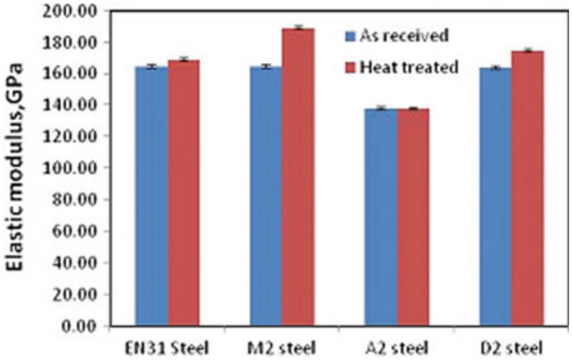

Fig. 4 Effect of heat treatment of steels on Elastic modulus

3.3 *Plasticity and Brittleness*

Indentation plasticity is defined as the ratio of the plastic displacement divided by the total displacement (Eq. 2) in the load–displacement curve of a micro-indentation measurement (Fig. 3).

$$\text{Plasticity} = \varepsilon_{\text{p}}/\varepsilon = \text{OA/OB}, \tag{2}$$

where ε_p is the plastic deformation and ε is the total deformation. Microhardness dissipation parameter (MDP) is used to express the plasticity in terms of the mechanical work done during different stages of indentation (Eq. 3).

$$\text{MDP} = \text{Plastic work/(plastic work} + \text{elastic work)} \tag{3}$$

Figure 5 shows that due to heat treatment (except D2 steel) there is increase in MDP. The increase in MDP can be recorded as EN31 > A2 > M2 > D2.

Brittleness index is defined as the ratio of the elastic deformation divided by the total deformation (plastic deformation + elastic deformation) in the load–displacement curve of a micro-indentation measurement (Fig. 3). A high brittleness index exhibits a high Young's modulus (E) and low Poisson's ratio. Brittleness index variation for different steels is shown in Fig. 6. The brittleness index of heat-treated steels was less as compared to that of as-cast steels. After heat treatment, almost all the steels have the same value of brittleness index. However, with careful observation, it can be said that A2 and D2 steel have lower brittleness.

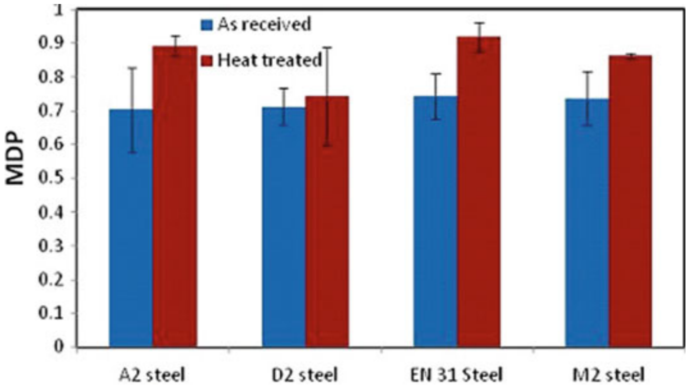

Fig. 5 MDP variation for different steels as-received and heat treated

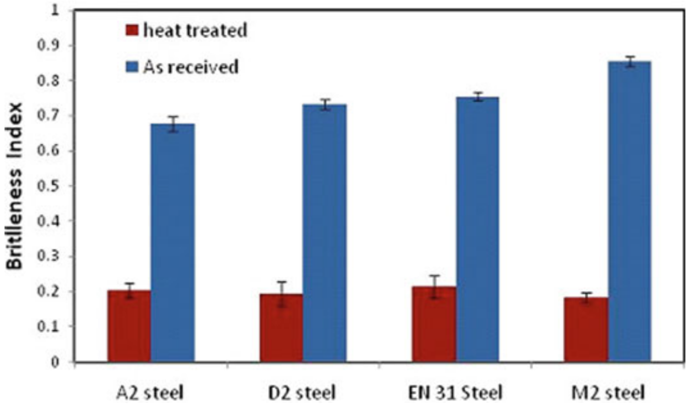

Fig. 6 Brittleness variation for different steels: as-received and heat treated

3.4 H/E Ratio

Hardness (H) and elastic modulus (E), assessed by micro-indentation test were used to estimate H/E ratios. High H/E ratio is associated to surfaces with enhanced wear resistance. Further, high H/E ratio gives lower plasticity index and more elastic contact. The H/E ratios of different conditioned steels are mapped in Fig. 7. Except for A2 steel, there is an increase in H/E ratio due to heat treatment. Based on the above arguments it can be stated, "among the selected steels, D2 steel should be most wear resistant and A2 steel should be least wear resistant".

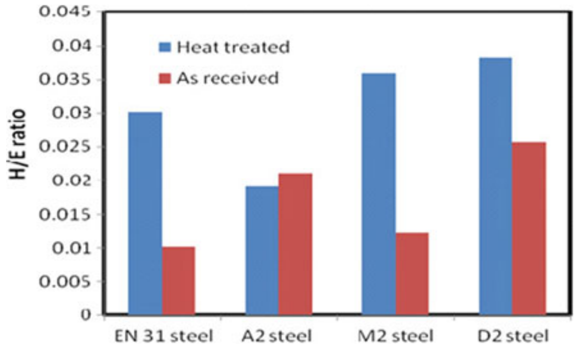

Fig. 7 Effect of heat treatment on H/E ratio of different steels

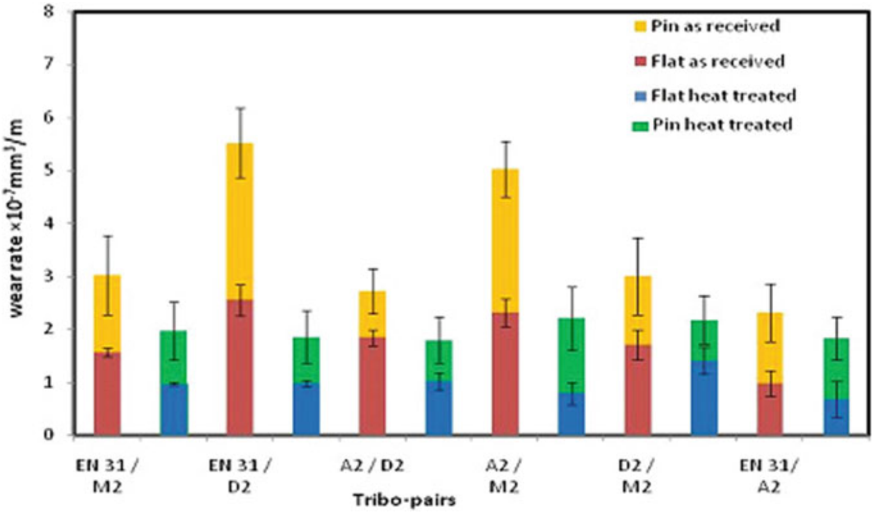

Fig. 8 Wear rate variation for different steel tribo-pairs: as-received and heat treated

3.5 *Wear*

Specific wear rate is used to indicate the wear response of different tribo-pairs. The summary of wear responses is presented in Fig. 8. The specific wear rates of the materials were obtained by using Eq. 4.

$$\mathrm{W} = \Delta W/\rho * \mathrm{F} * \mathrm{S}\,, \tag{4}$$

where W denotes specific wear rates in mm^3/Nm. ΔW is the weight loss measured in grams, ρ is density of the worn material in g/mm^3, and F is the applied load in N and S is sliding distance (m).

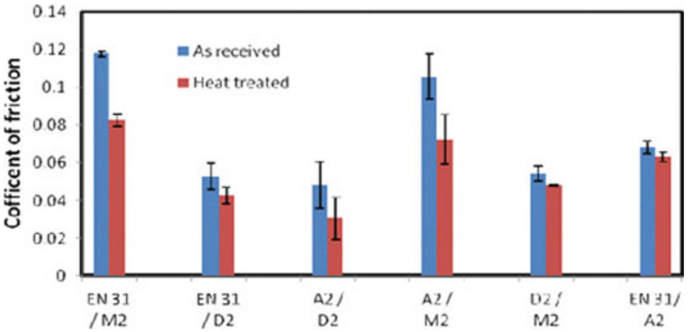

Fig. 9 Coefficient of friction for different steels; as-received and heat-treated tribo-pairs

Figure 8 shows the wear rates for as-received and heat treated steels under minimal lubricated condition. It is clear that heat treatment has resulted in reduction of wear rates. Considering the wear of complete tribo-pair, it can be noticed that A2/D2 and EN31/A2 tribo-pairs show the lowest wear. Further, careful observation of these two combinations indicates that wear of A2 steel is minimum for both the cases. Now considering the manufacturing complexity of comb and cutter in sheep hair shearing machine, it may be desirable to opt A2 steel for comb and EN31 or D2 steel for cutter.

3.6 *Friction*

The other complementary parameter in tribo-pair performance monitoring is level of friction. The variation in coefficient of friction for different tribo-pairs is shown in Fig. 9. It is clear, for all the tribo-pairs, the heat treatment resulted reduction in friction too. The lowest coefficient of friction is registered by A2/D2 tribo-pair followed by EN31/D2 tribo-pair. The minimization of friction will be helpful for reduction in frictional heating. Further, considering the wear and frictional response, it can be commented that most suitable tribo-pair is A2/D2 steels.

3.7 *Worn Surface Analysis*

Figure 10 shows the SEM micrographs of worn pin and the corresponding counter flat. It can be observed that adhesive and abrasive wear modes were active on both pin and flat. Before heat treatment, pile-up, surface delamination, surface crack, and patches were observed on the surface, which is responsible for increase in wear. After heat treatment, micro-cutting, shallow scratches, clogging, surface crack, and surface burn marks were observed on the surface. The adhesive wear is more damaging and

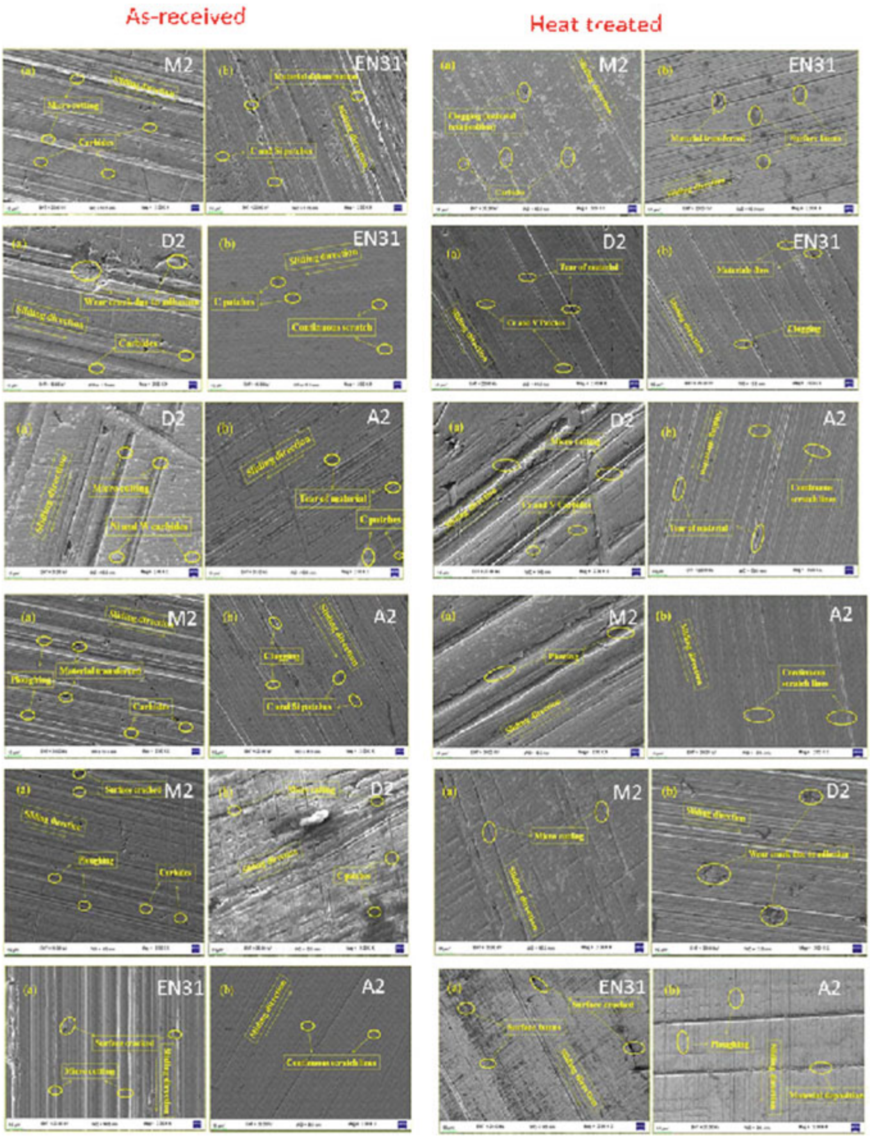

Fig. 10 SEM micrographs of as-received and heat treated worn surfaces

can be seen when steels are in as-received condition. Further, abrasive wear is less damaging and desired in present case.

The operation abrasive wear can be identified with the presence of surface cracks and micro ploughing/scratching marks. The switching of wear mode from adhesive to

Table 3 Wear mechanism of different steel tribo-pairs

Tribo-pair	Condition	Wear mechanism
EN 31/M2 steel	As-received	Abrasive
	Heat treated	Abrasive
EN 31/D2 steel	As-received	Adhesive
	Heat treated	Abrasive
A2/D2 steel	As-received	Abrasive
	Heat treated	Abrasive
A2/M2 steel	As-received	Abrasive
	Heat treated	Abrasive
D2/M2 steel	As-received	Abrasive
	Heat treated	Adhesive
A2/EN 31 steel	As-received	Abrasive
	Heat treated	Abrasive

abrasive may be responsible for reduction in wear and friction. The Wear Mechanism variation of different steels Tribo-pairs is shown in Table 3.

4 Conclusion

Suitable heat treatment can improve the mechanical property (H, E, H/E ratio) which in turn controls the friction and wear characteristics. Based on tribological observations, it is recommended that A2/D2 steel tribo-pair is suitable for minimally lubricated contact (as seen in sheep hair shearing device). The suitability of A2/D2 tribo-pair is suggested based on H/E ratio, MDP and brittleness index. Activation of abrasive wear mode over adhesive is desired for lower friction and wear. Further, in context of sheep hair shear device, it may be recommended that comb should be made of A2 steel and cutter with D2 steel.

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