Abstract—In this study, the wear behavior of AISI D3 steel sliding against low carbon steel has been investigated at different sliding speed, load and sliding distance. The analysis has been carried out in two stages. The first stage is to evaluate the wear behavior of the AISI D3 steel sliding against low carbon steel. The second stage is to construct wear maps of AISI D3 steel under dry sliding conditions. The sliding parameters considered are load, speed and test duration in dry environments. In order to reduce the experimental work load and maximize the result quality, Taguchi methodology based on L9 orthogonal array has been employed in the present research. The load, sliding speed and time seem to be the influential sliding parameters. The SEM observations clearly show that the effect of sliding speed seems to be the most significant factor followed by time and load.

Keywords: AISI D3, AISI 1020, Wear, SEM

I. INTRODUCTION

In sheet metal forming, the wear of deforming dies continues to be a great concern to the automotive industry as a result of increasing die maintenance cost and scrap rate. The demand to reduce the use of lubricants and increase tool life in sheet metal stamping has resulted in increased research on the sliding contact between the die and the sheet materials.

The AISI D3 tool steels are used as the stamping die material in many cold roll forming industries due to its properties to withstand higher forming forces and wear. However under the actual working conditions, wear of these tool steels is a common problem in the press working industry.

Many researchers studied and investigated the effect of sliding wear parameters for the optimization of the wear parameters for minimum wear. Published work of different researchers in this area is mentioned here.

Rigney [1] investigated the effect of material hardness during sliding behaviour of materials. It was observed that hardness of material is key factors that influence the sliding behaviour and the effects of hardness are much more complex.

So [2] studied the mechanism of oxidation, microscopic analysis on the wear surfaces. The pin specimens were made from cold forging die steel and disc specimens were made from AISI 4340 steel. The sliding speed and load were considered as wear parameters. The wear rate has been found directly depends upon the rate of spalling of the oxide film from the rubbed surfaces.

Mohanty et al. [3] studied the effect of sliding speed and load on wear after coating. The oxy fuel sprayed CrC2/NiCr (75% by weight of CrC2 & 25% by weight of NiCr) was used for coating. This study showed that pin-on-disk test is a well-controlled test and can be used to understand certain basic relationships between sliding frictions and wear behaviour of thermally sprayed coatings.

Wang [4] studied the wear behaviour of Cr12MoV, 65Nb and GCr15 steels. Sliding speed, applied load and sliding distance were considered as wear parameters. The sliding speed was found most significant parameter that affects the wear followed by load. As sliding speed and load increases, the wear rates of Cr12MoV, 65Nb and GCr15 steels also increased.

Iyer et al. [5] studied the effect of wear parameters on wear rate. AISI H11 steel was used as a disc material while SAE 52100 as a pin specimens. Normal load, sliding speed and sliding distance were taken as wear parameters. It was observed that all three wear parameters affect the wear rate.

Vera and Wolf [6] established the correlation between corrosion and mechanical properties of the TiN layers and TiO2/TiN multilayers on steel (Ck45, 0.45% C) produced by ion beam assisted deposition (IBAD). Friction and wear resistance of the layer was determined by pin-on-disk measurements. The results revealed that the hardness and wear resistance directly affected by the degree of crystallinity of the coatings.

Podgornik et al. [7] studied the AISI 4140 steel with respect to their micro hardness, residual stress, coating adhesion and dry sliding wear resistance. These specimens were treated at the surface by plasma nitriding and coated with a hydrogen-free hard carbon coating. The results show greatly improved sliding wear resistance of plasma nitried hard coated specimens compared with un-coated and pre hardened ones, observed for both unidirectional and reciprocating sliding conditions.

Staia et al. [8] investigated the effect of pulsed plasma nitriding process on the wear behaviour of AISI 4140 steel. The tests were carried out at room temperature in
air, without lubrication, by employing CVD TiN coated balls of 6 mm in diameter. Different wear mechanisms were detected such as abrasion, adhesion and oxidative wear for the pairs under study.

Bressan et al. [9] compared the wear behaviour of M2 high speed steel and WC hard metal coated with TiAlN and TiCN, using the pin on disk standard test with different loads. The removed volume and temperature at the pin end have been measured during the wear test. The performance of TiAlN is found superior to TiCN.

Lin and Wang [10] investigated the wear behaviour of a cladded layer on a medium-carbon steel surface of S50C. The gas tungsten arc welding (GTAW) method was used for cladding purpose. The experimental results revealed that the key influences on wear resistance performance are cladding powders composition, welding current and travelling speed.

Cueva et al. [11] compared the wear resistance of three different types of gray cast iron (gray iron grade 250, high-carbon gray iron and titanium alloyed gray iron), used in brake disc rotors with the results obtained with a compact graphite iron (CGI). The pins were manufactured from friction material usually used in light truck brake pads. The results showed that compact graphite iron reached higher maximum temperatures and friction forces as well as greater mass losses than the three gray irons at any pressure applied.

Karakan et al. [12] analysed the structural, mechanical and tribological properties of nitrocarburized steel which is formed from AISI 4140 steel, nitrocarburized at a gas mixture of 49%N2 + 49%H2 +2%CO2, for different process times, at a temperature of 570 °C. The results have shown that the compound layer was composed of the ε and γ iron carbonitrides. The wear rate improves after plasma nitrocarburizing, and decreases with increasing surface hardness.

Polok et al. [13] investigated the effect of different type of coatings (CrN, TiN, TiN/ N PVD) onto X37CrMoV5-1 type hot work steel in context of wear. Based on the results of metallographic examinations of microstructure it was observed that TiN, TiN(Ti,Al)N coatings have compacted, columnar structure, while CrN coating has compacted sub-microcrystalline structure.

Boher et al. [14] conducted an experimental study on a low-carbon steel sheet and X160CrMoV12 steel die radius. It revealed that the die radius surface was degraded by ploughing and transfer mechanisms.

Toro et al. [15] investigated the effect of sliding wear parameters on sliding wear. The AISI 1070 pearlitic and AISI 15B30 bainitic materials were used as pin materials and AISI 1085 pearlitic used as a disk material. The pearlitic steel showed higher sliding wear resistance than bainitic steel, due to the excellent strain hardening of pearlite compared to bainite.

Deshmukh et al. [16] performed an extended duration pin-on-disk experiments to determine the relative performance of a wide range of lubricant combinations in a commercial brake valve assembly. In the experiments, the lubricants were initially applied to the disk surface but were not replenished over a sliding distance of more than 6000 m. The experimental results revealed that the environmentally friendly lubricant boric acid was highly ineffective for reducing the wear in the surfaces tested. When combined with a commercial transmission fluid, however, the boric acid mixture proved to be highly effective in terms of both friction and wear performance.

Sahin [17] used Taguchi method to investigate the effect of abrasive grain size, applied load and sliding distance on wear behaviour of various steel. The wear resistance model for three types of steels was developed in terms of abrasive grain size, applied load and sliding distance. The results demonstrated that the type of materials was found most significant parameter that affects the weight loss of steels. For AISI 1340 steel, the abrasive grain size exerted the greatest effect on the wear, followed by sliding distance.

Eyre and Grimanelis [18] studied the tribological behaviour of low alloy sintered steel, with and without a plasma nitrocarburizing surface treatment. The effect of sliding speed and load on wear was investigated. The discs were of high carbon chromium steel (EN31), which had a hardness of 800 HV. A prealloyed and premixed powder grade was used for the pins. For the plasma surface treatment, the transition loads has been found slightly higher than the base sintered steel, not consistently though. The operating life of the plasma treated sintered steel was further prolonged in the presence of lubricant, impregnated in the sintered material.

Rech et al. [19] developed a friction model able to describe the friction coefficient at the tool-chip-workpiece interface during the dry cutting of an AISI316L austenitic stainless steel with TiN coated carbide tools. The effect of cutting speeds and pressures were investigated. The result revealed that the friction coefficient is mainly dependant on the sliding velocity, whereas the pressure has a secondary importance.

Lee et al. [20] investigated the tribological performance of titanium alloy (Ti–6Al–4V) balls coated with a dual boride layer comprised of titanium diboride (TiB2) and titanium boride (TiB) whiskers mated against alumina ceramic disks using lubricated ball-on-disk wear testing. The wear rate of the boride-coated titanium alloy balls has been found 40 times less than that of 97% dense alumina balls.

Das et al. [21] examined the wear properties, hardness values and the microstructural characteristics of AISI D2 steel cryo- treated at 77 K for different soaking durations. An attempt was also made to optimized soaking time in cryogenic processing for maximization of its wear resistance. Examination of the structure–property relations of differently treated specimens indicates that the best wear resistance is obtained for specimens cryogenically processed for 36 h.

Dey et al. [22] experimentally investigated the effect of wear parameters on wear rate. The chemically etched Al–18.5% Si alloy material was used as pin material while AISI 52100 steel as a disk material. It was obtained that
damage occurred in different stages. Initially, silicon particles fractured, some of which became embedded in the matrix, as the contact stress increased. Abrasive wear on silicon particles was also observed.

Rajasekaran et al. [23] studied the wear resistance of thick cold work tool steel X190CrVMo20-4 against different types and sizes of abrasive papers. Different types of abrasive papers SiO\(_2\) (flint), Al\(_2\)O\(_3\) (corundum), SiC (silicon carbide) with different mesh sizes (80 Mesh and 220 Mesh) were fixed on the disc for the subsequent evaluations of wear resistance of coatings. The abrasive wear resistance of cold work tool steel coated pins was found to be superior against soft and fine abrasive papers than the standard high speed steel.

Slatter et al. [24] studied the effects of deep cryogenic treatment on the wear resistance of grey cast iron (SAE J431 G10) brake rotors. The results indicate an improved in the wear rate of grey cast iron of 9.1–81.4% due to deep cryogenic treatment where significant wear has occurred, although there was no significant change in the bulk hardness, matrix hardness or in the microstructure of the material under optical observation.

Sekharbabu et al. [25] studied the characterization of D2 tool steel friction surfaced coatings over low carbon steel. Wear performance of the coating is studied using pin-on-disk wear tests. Friction surfaced D2 steel coating showed fine-grained martensitic microstructure compared to the as-received consumable rod which showed predominantly ferrite microstructure. The combined effect of martensitic microstructure and refined carbides resulted in higher hardness and wear resistance of the coating.

The AISI D3 steel is widely used in the manufacturing industry for die components in the metal casting industry, and many other applications requiring high wear resistance in many other industries. The literature reveals that the earlier work reported on this material or other similar materials is very limited. In general, the authors performed experimental study only. Thus, the research work for optimization of wear parameters on AISI D3 needs to be strengthened. Hence conducting study of wear for AISI D3 steel sliding against AISI 1020 steel on pin-on-disk apparatus and optimization of sliding conditions to obtain minimum wear will be quite useful. In the present work the Taguchi methodology based on L9 orthogonal array has been selected for optimization of sliding parameters for minimum weight loss (wear volume) of AISI D3 steel.

II. EXPERIMENTAL AND MEASUREMENT DETAILS

In the present study, wear and friction monitor- TR 201 has been used for wear study of pins of AISI D3 steel against disk, made of AISI 1020 steel. All the pins used in experimentation were 8 mm in diameter and 30 mm in length. All the disks used in experimentation were 165 mm in diameter and 6 mm in thickness.

Wear is the progressive loss of material due to relative motion between a pin tested and disk. The pins tested were weighted before and after the test to within 10\(^{-4}\) g to calculate the weight loss.

III. DESIGN OF EXPERIMENT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Type</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (N)</td>
<td>A</td>
<td>Numeric</td>
<td>20, 30, 40</td>
</tr>
<tr>
<td>Time (min.)</td>
<td>B</td>
<td>Numeric</td>
<td>3, 6, 9</td>
</tr>
<tr>
<td>Speed (m/sec.)</td>
<td>C</td>
<td>Numeric</td>
<td>1, 1.5, 2</td>
</tr>
</tbody>
</table>

In the present research L\(_9\) orthogonal array based Taguchi methodology has been employed for the experimentation and analysis. The parameters and their levels are shown in Table 1. Complete design layout for experiments and experimental results are summarized in Table 2. This demonstrates a total of 9 runs required for complete experimentation.

IV. ANOVA ANALYSIS

The first step of ANOVA is to check the assumptions of ANOVA. The analysis of variance (ANOVA) is based on two assumptions. (1) The variables are normally distributed (2) Homogeneity of variance.

![Normal Probability Plot of Residuals for Wear](image-url)

Fig. 1: Normal Probability Plot of Residuals for Wear

To check the assumption of normal distribution, the normal probability plot of the residuals for surface roughness is shown in Fig. 1. The normal probability plot indicates whether the residuals follow a normal distribution.
or not, if the residuals follow a normal distribution majority of points will follow a straight line except some moderate scatter even with normal data. The figure displays that the residuals generally fall on a straight line implying that the errors are distributed normally.

The Fig. 2 represents residuals versus the predicted wear plot. It tests the assumption of constant variance. The plot should be a random scatter. The figure shows that there is no obvious pattern and it shows unusual structure. This implies that there is no reason to suspect any violation of the independence or constant variance assumption.

The ANOVA has been carried out for a significance level of \( \alpha = 0.05 \), i.e. for a confidence level of 95%. The ANOVA for mean for wear is summarized in Table III.

<table>
<thead>
<tr>
<th>Source</th>
<th>Degree of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>p-value Prob &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>2</td>
<td>0.002258</td>
<td>0.001129</td>
<td>139</td>
<td>0.007</td>
</tr>
<tr>
<td>Time</td>
<td>2</td>
<td>0.001713</td>
<td>0.000857</td>
<td>105.46</td>
<td>0.009</td>
</tr>
<tr>
<td>Speed</td>
<td>2</td>
<td>0.00451</td>
<td>0.002255</td>
<td>277.66</td>
<td>0.004</td>
</tr>
<tr>
<td>Residual</td>
<td>2</td>
<td>0.000016</td>
<td>0.000008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>0.008497</td>
<td>0.001062</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-square</td>
<td>99.8%</td>
<td>Adj. R-Square</td>
<td>99.2%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Table 3, shows that the value of “Prob. > F” for load is less than 0.0001 which is less than 0.05, that indicates the load is significant. In the same manner, the value of “Prob. > F” for time and speed, are less than 0.05 so these terms are significant model terms. The \( R^2 \) value is equal to 0.998 or close to 1, which is desirable. The adjusted \( R^2 \) value is equal to 0.992; it is particularly useful when comparing models with different number of terms. The result shows that the adjusted \( R^2 \) value is very close to the ordinary \( R^2 \) value.

V. MINIMIZATION OF WEAR

Table 4 represents the difference between the maximum and the minimum value of the wear parameters for sliding wear values.

The most effective factor affecting performance characteristics is obtained by comparing these values. This comparison gives the level of importance of controllable factors. The most effective controllable factor corresponds to the maximum of these values. Thus the speed has been found most significant parameter that affects the wear followed by load and time.

VI. EFFECT OF WEAR PARAMETERS ON WEIGHT LOSS

Influence of normal load on weight loss at constant speed of 1.5 m/s and time 6 min is shown in Fig. 3.
the current normal load as well as the materials of rubbing pairs.

It is explicable from the plot that the weight loss of pin is at higher level when the sliding speed is low and as the sliding speed increases, the weight loss starts decreasing. Hence the weight loss is more at 1 m/s and as the speed increase from 1 m/s to 2 m/s, the weight loss decreases.

Influence of sliding time on weight loss at constant load of 30 N and speed of 1.5 m/s is shown in Fig. 5. It is clear from the plot that as the sliding time increases from 3 min to 9 min, the value of weight loss increases

![Fig. 5: Effect of Time on Wear](image)

VII. SEM OBSERVATIONS

According to the SEM observations, when load was 20N, speed was 1 m/s and time was 9 min, the worn surface of AISID3 steel pin appears relatively rough as shown in Fig 6. The micrograph qualitatively correlates well with the weight loss measurements. This micrograph clearly demonstrates the signs of abrasion wear along with some patches of ploughing but abrasion wear is the dominating wear at given conditions. When load was 30N, the wear scar surface no longer appears clean as shown in Fig. 7. This micrograph clearly depicts that as the load was increased from the previous level, the surface visually appears rougher. There are the signs of abrasion wear along with the indications of adhesion wear. In adhesive wear of dissimilar metal couples it is commonly observed that material is transferred from the softer to the harder surface. The copious material transfer can be expected to effectively protect the D3 pins from wear. Since the transfer occurred at higher load, this observation can explain the lower weight loss measured for the D3 steel pins when the load was at a certain level. When load was 40 N and speed was 1.5 m/s and time was 6 min, the worn out surface is shown in Fig. 8. Hence this micrograph clearly depicts the effect of load. When load was increased from a certain level, like in this case load was above 30 N, the transition of wear mechanism took place and spalling and ploughing of D3 steel surface became the dominating wear mechanism as the signs of abrasion were disappear and surface becomes more and more rough [26]. SEM micrographs of the worn out pin surface at three different speeds of 1 m/s, 2 m/s and 1.5 m/s are shown in Fig. 6, 7 and Fig. 8 respectively. These micrographs can be easily correlated with the weight loss measurements. As the increase in sliding speed causes the rate of generation of frictional heat to increase, and so raises the surface temperature. The rise of surface temperature softens the substrate of the rubbing materials; these enhance the rate of delamination [2].

SEM micrographs of the worn out pin surface at two different times of 9 min, 3 min and 6 min are shown in Fig. 6, 7 and Fig. 8 respectively. These micrographs can be easily correlated with the weight loss measurements [27].

![Fig. 6: SEM Micrograph of Worn Surface of AISI D2 Steel Pin at Load 20, Speed 1 m/s, Time 9 min](image)

![Fig. 7: SEM Micrograph of Worn Surface of AISI D2 Steel Pin at Load 30 N, Speed 2 m/s, Time 3 min](image)

![Fig. 8: SEM Micrograph of Worn Surface of AISI D3 Steel Pin at Load 40 N, Speed 1.5 m/s, Time 6 min](image)
The objective of the present work is to obtain the effects of the sliding parameters (load, speed and time) on weight loss of AISI D3 steel using pin-on-disk apparatus. Design of experiment based on Taguchi methodology with three numeric factors and three level orthogonal array have been used for analysis of weight loss of AISI D3 steel pins. The important conclusions drawn from the present work are summarized as follows:

1. All the three independent parameters (load, speed, time) seem to be the influential sliding parameters.
2. The SEM observations clearly show that the effect of speed seems to be the most significant factor followed by time and load.
3. The weight loss (wear volume) increases with increasing sliding time but decreases with increasing sliding speed.
4. Different wear mechanisms were observed depending upon the current values of load and speed. Abrasion, adhesion and surface ploughing are the dominating wear processes, observed in the study through SEM observations.
5. The minimum weight loss has been observed at middle level of load, high level of sliding speed and low level of time.

REFERENCES