STUDY OF WEAR CHARACTERISTICS OF AISI D3 STEEL AGAINST AISI 1020 STEEL

Rajeev Ranjan
Asst. Professor, Department of Mechanical Engineering, Sarla Birla University Jharkhand, India
Email: *raj.apx.mech@gmail.com

ABSTRACT

The wear is the progressive loss or removal of material from a surface. It has important technological and economical significance because it changes the shape of the tool and die interfaces and hence that of the work-piece. Thus it affects the process, size & quality of the parts produced. AISI 1020 STEEL has the highest strength and ductility with excellent machinability and good bearing and wear properties and the AISI D3 steel are used as the die material in many pressure die casting industries due to its properties to withstand higher wear. The main objective of present work is to investigate the wear behavior of the AISI D3 hot die steel against AISI 1020 STEEL. The sliding parameters considered are load, speed and test duration in dry environments. An attempt has also been made to develop wear prediction model in terms of sliding parameters using response surface methodology (RSM) based on centre composite rotatable design (CCRD). The result shows that the predicted results are in good agreement with the measured ones. These relationships are applicable within the ranges of tested parameters. Also, all the three independent parameters (load, speed, time) seem to be the influential sliding parameters.

Keywords: pin on disk, wear rate, signal vs noise ratio, sliding parameters, anova, SEM,Taguchi methodology, orthogonal array

INTRODUCTION

Sheet metal forming dies are important tools used in press working industry. During the forming operation, the sheet metal slides on the surface of the die under a normal load. The sliding parameters such as normal load, sliding speed, sliding distance etc, play a vital role in controlling the wear of the die material in many forming operations. These parameters have a major effect on the quantity of production, cost of production and production rate; hence their judicious selection assumes significance.

The wear is the progressive loss or removal of material from a surface. It has important technological and economical significance because it changes the shape of the tool and die interfaces and hence that of the work-piece. Thus it affects the process, size & quality of the parts produced. Examples of wear in manufacturing processes are dull drills that have to be reground, worn cutting tools that have to be indexed and forming tools and dies that have to be repaired or replaced. In this study, the wear behavior of AISI D3 steel sliding against low carbon steel has been investigated at different sliding speed, loads and sliding distances using a pin-on-disk tribometer. The focus of the work has been on two main objectives. The first is to evaluate the wear behavior of the AISI D3 steel sliding against low carbon steel. The second 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 L_9 orthogonal array has been employed in the present research.

EXPERIMENTAL WORK

In order to simulate the different sliding conditions during different forming processes, sliding wear experiments have been performed using a pin-on-disk tribometer. In this study, specimens (pins) of AISI D3 steel were made to slide against a rotating disk of low carbon steel (AISI 1020) under specified normal load. In this study three independent variables were selected, i.e. normal loads, sliding speed and sliding time. Before and after each experiment, pins were weighted. The difference in wear volume was calculated from weight loss. The wear results were presented as a function of load, speed and test duration.

Fig. 1 PIN ON DISK (TR-20LE-PHM-400) (SLIET, Longowal, Punjab**)**

Fig. 2 PIN ON DISK (TR-20LE-PHM-400) (SLIET, Longowal, Punjab)

Fig. 3 PIN ON DISK (TR-20LE-PHM-400) (SLIET, Longowal, Punjab)

Table 1 Technical specification of PIN ON DISK (TR-20LE-PHM-400)

Parameters	**Min**	**Max**
Pin Size (mm)	6	8
Disk Size (mm)	-	165
Wear track dia. (mm)	0	160
Disk speed (rpm)	100	1500
Normal load (N)	10	200

Manufacturing of Pins

In this study, based on L9 orthogonal array based Taguchi methodology; total 9 pins of AISI D3 steel have been selected for experimentation.

.

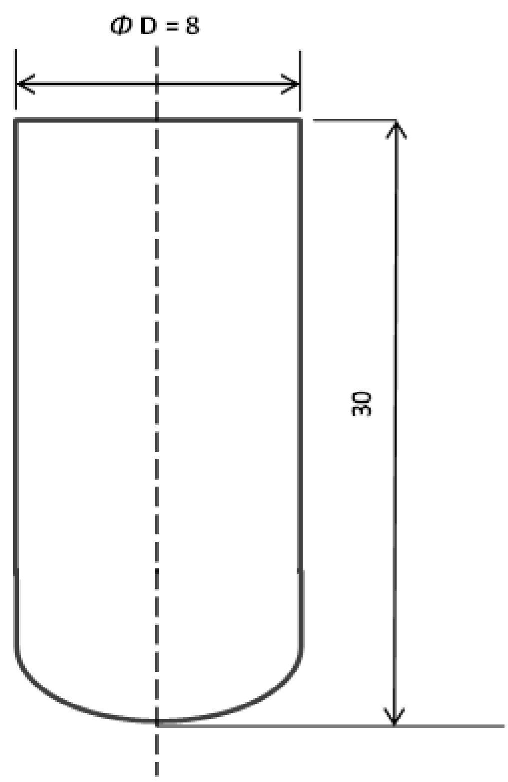


Fig. 4 Drawing, AISI D3 Steel pin (all dimensions are in mm)

Fig. 5 Pin specimen made of AISI D3 steel (before wear)

Fig. 6 Pin specimen made of AISI D3 steel (after wear)

The size of each pin was 8 mm × 30 mm. The drawing of pin is given in figure 4.5. The figure 4.6 and 4.7 shows the pictorial view of pins of AISI D3 steel before wear and after wear respectively.

The steps involved in manufacturing of PIN are as follows:

1. Facing and Turning on lathe machine.
2. Radius forming.
3. Radius finishing.
4. Total height maintaining.

Manufacturing of Disk

In this study total 2 numbers of disks of AISI 1020 steel were manufactured in order to perform all 9 experiments. Each disk was 165 mm in diameter and 6 mm in thickness.

4 HOLES φ 8 EQUISPACED ON PCD $155^{\pm 0.2}$ AS SHOWN

HOLE M3 (THROUGH) AS SHOWN

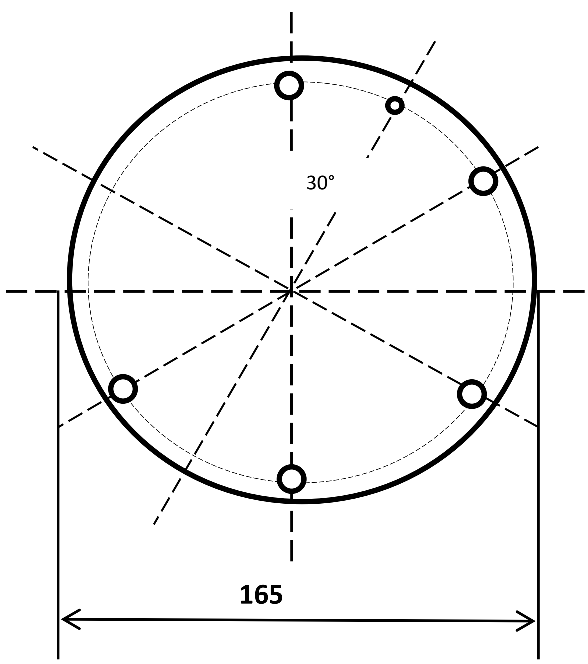


Fig. 7 drawing of AISI 1020 steel disk (all dimensions are in mm)

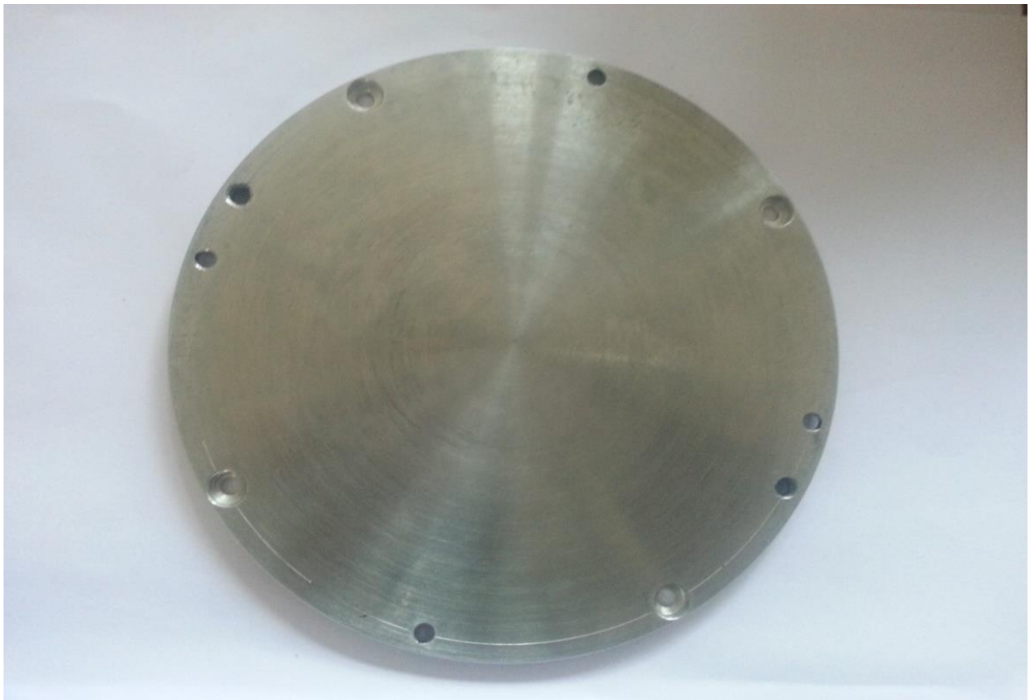
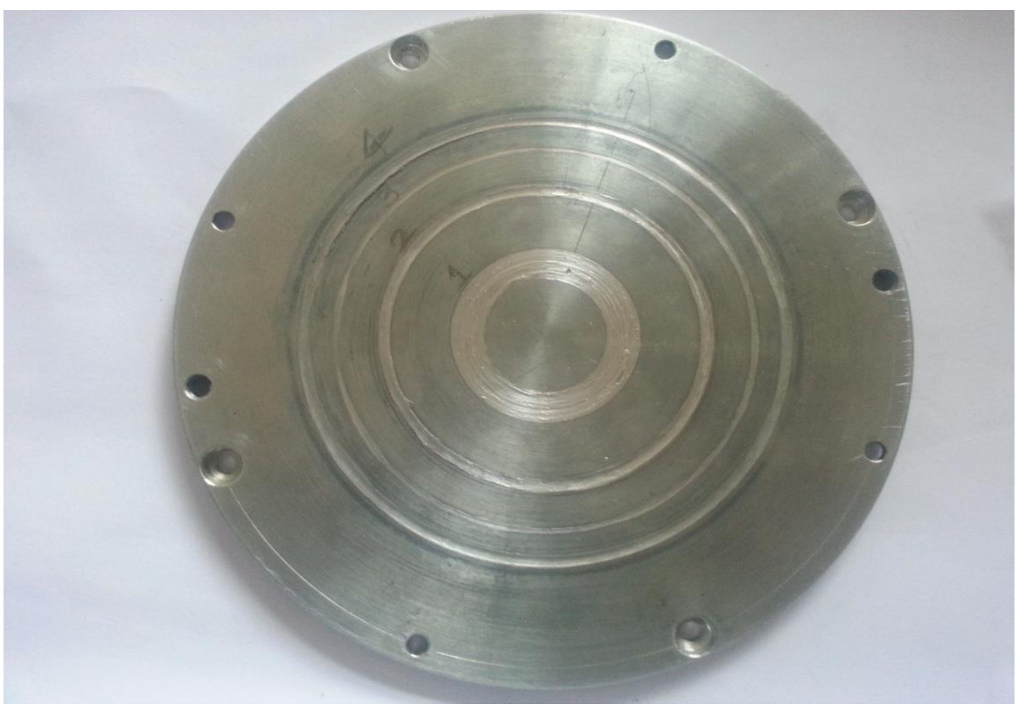


Fig. 8 AISI 1020 steel disk specimen (before wear)



1, 2, 3 & 4 are Run numbers

Fig. 9 AISI-1020 steel specimen (after wear)

The drawing of disk is shown in fig.7. The pictorial view of disk before wear and after wear is shown in fig.8 and 9 respectively.

The steps involved in the manufacturing of disk are as followed.

1. Slicing on power hack-saw cutting machine.
2. Turning and facing on lathe machine.
3. PCD circle hole on drilling machine.
4. Hand tapping.
5. Maintaining of parallelism by surface grinding.

TAGUCHI METHODOLOGY

Taguchi adopted an outstanding philosophy for quality control in the manufacturing industries. Indeed, his doctrine is generating an entirely changed breed of engineers who think breath and live quality. He has in fact given birth to a new quality culture in the country. His philosophy has far reaching consequences, yet it is found on three very simple and essential concepts. The entire of the technology and techniques arise entirely out of these three ideas. These concepts are:

- Quality should be designed into the product and not examined into it.
- Quality is best achieved by minimizing the deviations from the objective. The product or process should be so designed that it is protected to uncontrollable environmental variables.
- The cost of quality should be sedate as a function of deviation from the average and the losses should be sedate system-wide.

Taguchi believed that the better way to advance quality was to design and built it into the product. Quality improvement starts at the very beginning, i.e., during the design stages of a product or process and unceasing through the production phase. Taguchi proposed an "off-line" strategy for emerging quality improvement in place of an attempt to inspect quality into a product on the production line. Poor quality cannot be improved by the process of inspection, screening and salvaging. Therefore quality idea should be based upon and developed around the philosophy of prevention. The product design must be so robust that it is in immune to the impact of uncontrollable environmental factors on the manufacturing process. To achieve desirable product quality by design, Dr. Taguchi recommends a three stage process.

- System design
- Parameter design

- Tolerance design

The focus of the system design phase is on defining the suitable working level of design factors.

SIGNAL TO NOISE RATIO

The signal to noise ratio is a simultaneous statistic. A simultaneous statistic is able to look at two characteristics of a delivery and roll these characteristics into a single number or figure of merit. The signal to noise ratio combines both the parameters into a single metric.

A high value of signal to noise ratio implies that is much higher than the random effects of noise factors. Process operation consistent with higher signal to noise ratio always yields best quality with minimum variation.

A. Nominal the best

It is expressed by the equation,

$$({}^{S}/_{N})_{NB} = 10 \log (MSD_{NB}) = 10 \log \left[\frac{y^2}{s^2} - \left(\frac{1}{n}\right)\right] \quad (1)$$

Where y = signal factors

s = noise factors

It is used whenever there is a nominal or target value and a variation about the value, such as dimensions, voltage, weight and so forth. The target is limited but not zero. For robust design, the S/N ratio should be maximized. It is maximum when the average is large and the difference is small.

B. Smaller the better

The S/N ratio for smaller the better is used for situation where the target value is zero, such as computer response time, automotive emission, corrosion. The equation for smaller the better ratio is

$$({}^{S}/_{N})_{LB} = - 10 \log (MSD_{LB}) = - 10 \log \left[{}^{(\Sigma y^2)}/_{N}\right] \quad (2)$$

The negative sign is used to ensure that the target value gives the best value for the response variable and therefore robust design. Mean standard deviation is given to display the relationship to the loss function.

C. Larger the better

It is used where value is desired, such as weld strength; material removal rate etc. for the mathematical view point, the objective value is zero. It is the reciprocal of the smaller the better. The equation is

$$(S/N)_{HB} = -10 \log (MSD_{HB}) = -10 \log \left[\Sigma(1/y)^2/N\right] \quad (3)$$

Table 2 Parameters and their levels according to Taguchi methodology

Parameter	symbol	Type	Levels		
			1	2	3
Load (N)	A	Numeric	20	30	40
Time (min.)	B	Numeric	3	6	9
Speed (m/sec.)	C	Numeric	1	1.5	2

Table 3 Complete design layout and experimental results

Std. order	Load (N)	Time (min.)	Speed (m/sec)	Wear (gm)
1	20	3	1	0.102
2	20	6	1.5	0.0926
3	20	9	2	0.078
4	30	3	1.5	0.0286
5	30	6	2	0.0317
6	30	9	1	0.0972
7	40	3	2	0.0338
8	40	6	1	0.1078
9	40	9	1.5	0.0884

WEIGHT LOSS MEASUREMENT

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.

IDENTIFICATION OF MOST SIGNIFICANT WEAR PARAMETERS

The complete results along with respective treatments of the 9 experiments performed as per the L_9 orthogonal array based experimental plan were input into the MINITAB 15 software for further analysis. The ANOVA has been carried out for a significance level of $\alpha = 0.05$, i.e. for a confidence level of 95%. 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

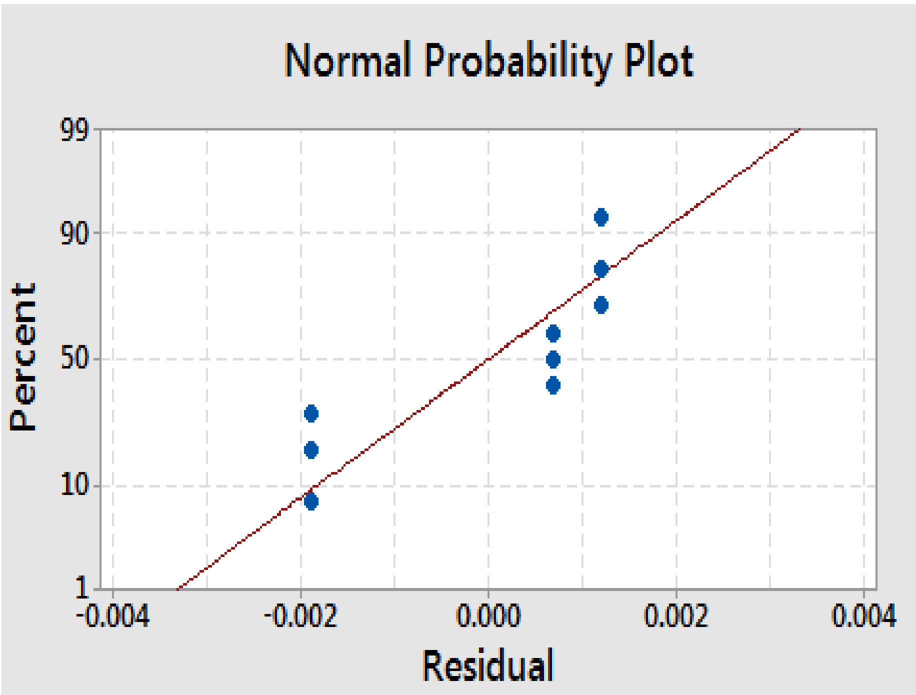


Figure 10 Normal probability plot of residuals for mean of wear

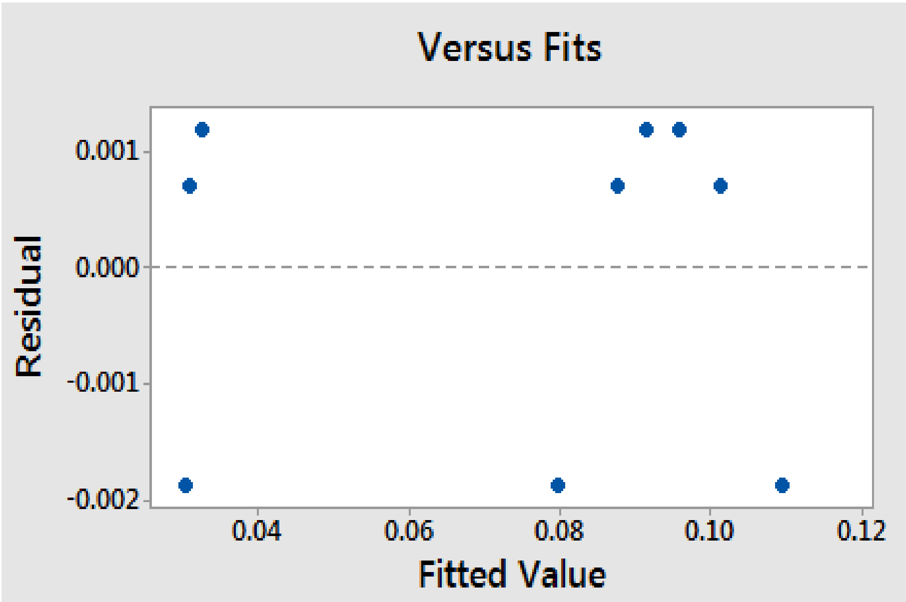


Fig. 11 Plot of residuals v/s predicted wear

ANOVA TABLE FOR MEAN FOR WEAR

As mention above, in this work the ANOVA was carried out for a significance level of α = 0.05, i.e. for a confidence level of 95%. The ANOVA for mean for wear is summarized in Table 4.

Table. 4 Resulting ANOVA table for wear

Source	Degree of freedom	Seq. sum of squares	mean square	F-Value	p-value Prob> F
Load	2	0.002258	0.001129	139	0.007
Time	2	0.001713	0.000857	105.46	0.009
Speed	2	0.00451	0.002255	277.66	0.004
residual	2	0.000016	0.000008		
Total	8	0.008497	0.001062		
R-square		99.8%	Adj. R-Square		99.2%

The table 4, 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^2value is equal to 0.998 or close to 1, which is desirable. The adjusted R^2value is equal to 0.992; it is particularly useful when comparing models with different number of terms. The result shows that the adjusted R^2value is very close to the ordinary R^2value.

MINIMIZATION OF WEAR

Table 5 presents 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.

Table 5: Response table for wear

Level					
Factors	1	2	3	Max.-Min.(Δ)	Rank
Load	0.09087	0.0525	0.07667	0.03837	2
Time	0.0548	0.07737	0.08787	0.03307	3
Speed	0.10233	0.06987	0.04783	0.0545	1

ANOVA FOR S/N RATIO FOR WEAR

The S/N ratio for smaller the better is used for situation where the target value is zero, such as computer response time, automotive emission, corrosion, surface roughness, tool wear, tool vibration etc. The equation for smaller the better ratio is

$$(S/N)_{SB} = -10 \log (MSD_{SB}) = -10 \log \left[(\Sigma y^2)/N\right] \quad (4)$$

In the present work, for wear, the smaller the better S/N ration has been applied to identify the main influencing factor that affects the wear. The ANOVA for S/N ratio for wear has been carried out for a significance level of α = 0.05, i.e. for a confidence level of 95%. To check the assumption of normal distribution, the normal probability plot of the residuals for S/N ratio for wear is shown in figure.12.The figure displays that the residuals generally fall on a straight line implying that the errors are distributed normally. The figure.13 represents residuals versus the predicted S/N ratio for wear plot. It tests the assumption of constant variance. 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.

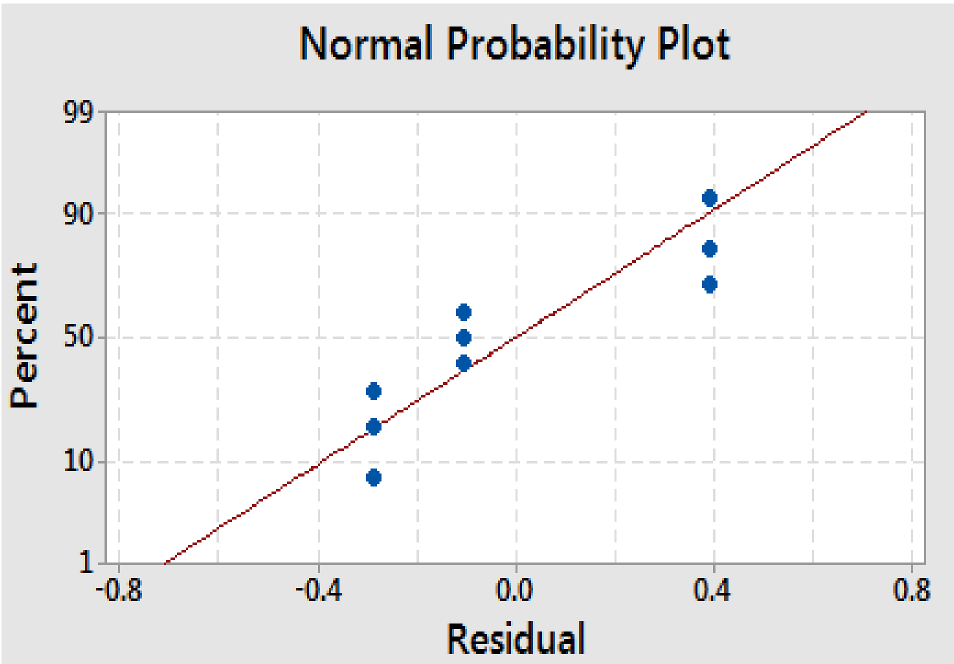


Figure.12 Normal probability plot of residuals for S/N ratio for wear

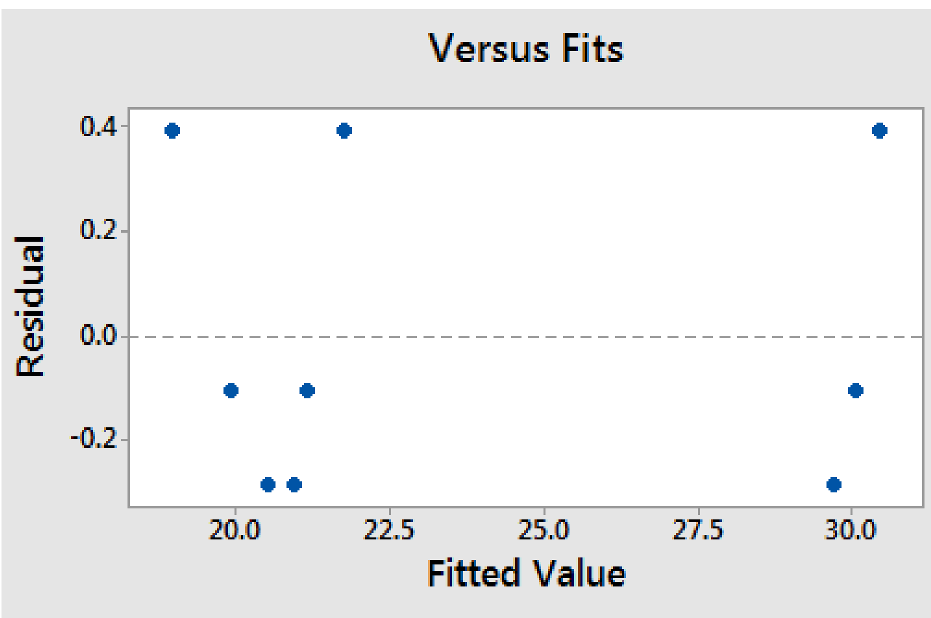


Fig. 13 Plot of residuals v/s predicted S/N ratio for wear

ANOVA TABLE FOR S/N RATIO FOR WEAR

As mention above, in this work, the ANOVA for S/N ratio for wear has been carried out for a significance level of α = 0.05, i.e. for a confidence level of 95%. . The ANOVA for S/N ratio for wear is summarized in Table 6.

Table 6: ANOVA table for S/N ratio of wear

Source	Degree of freedom	Seq. sum of squares	mean square	F-Value	p-value Prob> F
Load	2	57.62	28.81	77.21	0.013
Time	2	46.909	23.4545	62.86	0.016
Speed	2	82.669	41.3345	110.78	0.009
residual	2	0.746	0.373		
Total	8	187.944			
R-square		99.6%	Adj. R-Square		98.4%

The table 6, shows that the value of "Prob. > *F*" for S/N ratio of load is less than 0.0001 which is less than 0.05, that indicates the S/N ratio of load is significant. In the same manner, the value of "Prob. > *F*" for S/N ratio of time and speed, are less than 0.05 so these terms are significant model terms. The R^2value is equal to 0.996 and adjusted R^2value is equal to 0.984. The result shows that the adjusted R^2value is very close to the ordinary R^2value.

MINIMIZATION OF WEAR USING S/N RATIO

Table 7 presents the difference between the maximum and the minimum value of the S/N ratio for wear parameters for sliding wear values.

Table 7: Response table for S/N ratio (minimum is best) for wear

Level					
Factors	1	2	3	Max.-Min.(Δ)	Rank
Load	20.88	27.03	23.28	6.15	2
Time	26.71	23.33	21.16	5.55	3
Speed	19.81	24.2	27.19	7.38	1

The most effective controllable factor corresponds to the maximum of these values. Thus the speed has been found most significant parameter with that affects the wear followed by load and time. Same result has been obtained as obtained through means for wear. To investigate the influence of each parameter on wear, different graphs between the wear parameters and wear has been plotted. Different types of wear processes also revealed out with the help of SEM observations.

EFFECT OF NORMAL LOAD 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.14.

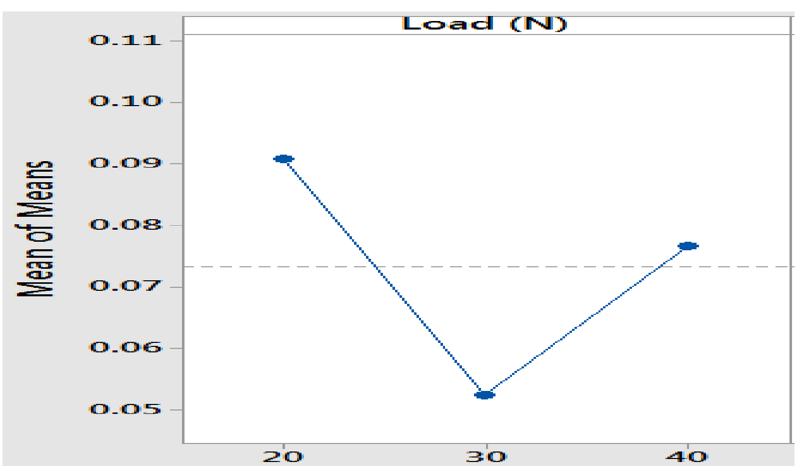


Figure 14 Effect of load on wear

The result shows that the effect of normal load on weight loss of AISI D3 steel is scattered within the range of testing parameters. The weight loss decreases as the normal load increases from 20 N to 30 N. The weight loss reaches at a minimum level when the load is 30N. However when the load increases from that minimum level of weight loss, the weight loss also increases until it reaches to 40 N.

EFFECT OF SLIDING SPEED ON WEIGHT LOSS

The effect of sliding speed on weight loss at constant load of 30 N and time 6 min is shown in fig. 15.

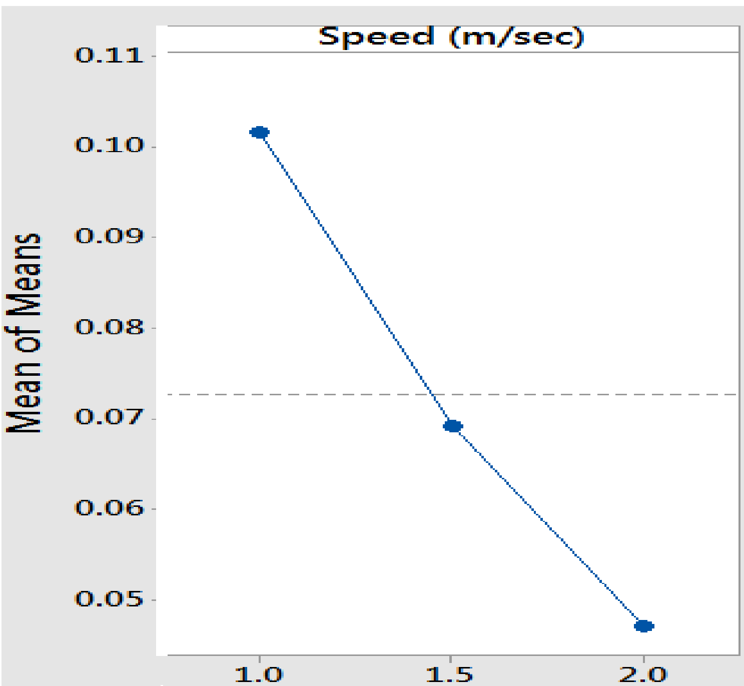


Figure 15 Effect of sliding speed on wear

The effect of sliding speed on weight loss is usually depends upon 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 1m/s to 2 m/s, the weight loss decreases.

EFFECT OF SLIDING TIME ON WEIGHT LOSS

Influence of sliding time on weight loss at constant load of 30 N and speed of 1.5 m/s is shown in fig. 16.

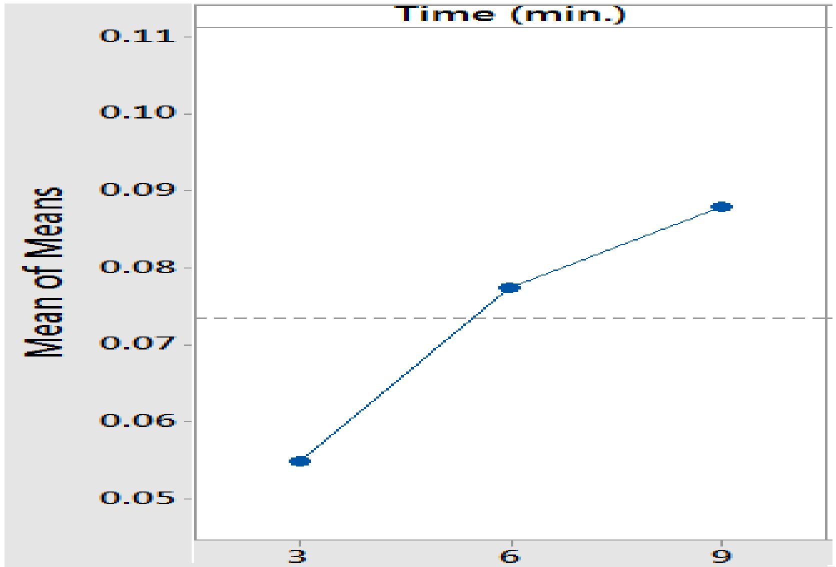


Figure 16 Effect of time on wear

It is clear from the plot that as the sliding time increases from 3 min to 9 min, the value of weight loss increases.

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 **17.** 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 18. 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 19. 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 (Yu & Chuang, 2002).

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. 17, 18 & fig. 19 respectively. These micrographs can be easily correlated with the weight loss measurements. As the increase in sliding speed cause the rate of generation of frictional heats 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 (So, 1995). SEM micrographs of the worn out pin surface at two different times of 9 min, 3 min and 6 min are shown in fig. 17, 18 & fig. 19 respectively. These micrographs can be easily correlated with the weight loss measurements (So, 1996).

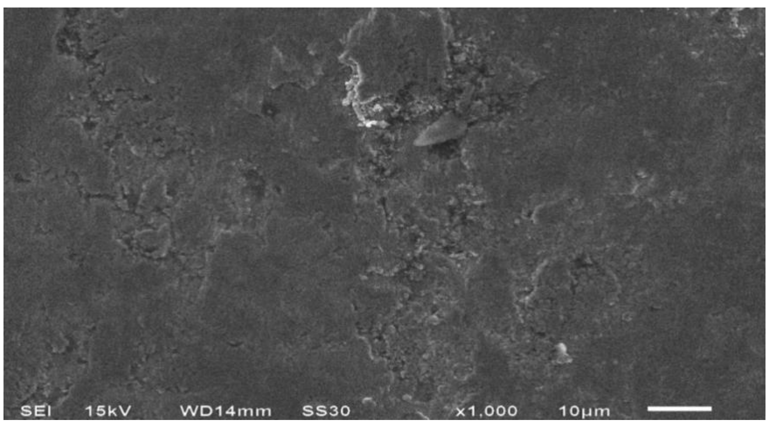


Fig. 17, SEM micrograph of worn surface of AISI D2 steel pin at load 20, speed 1 m/s, time 9 min

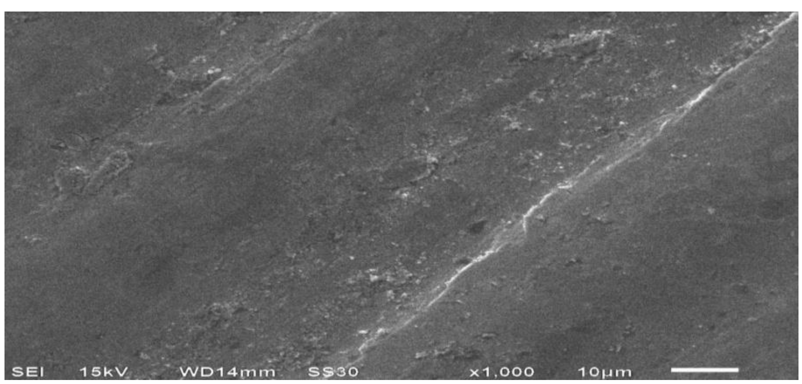


Fig. 18, SEM micrograph of worn surface of AISI D2 steel pin at load30N, speed 2 m/s, time 3 min

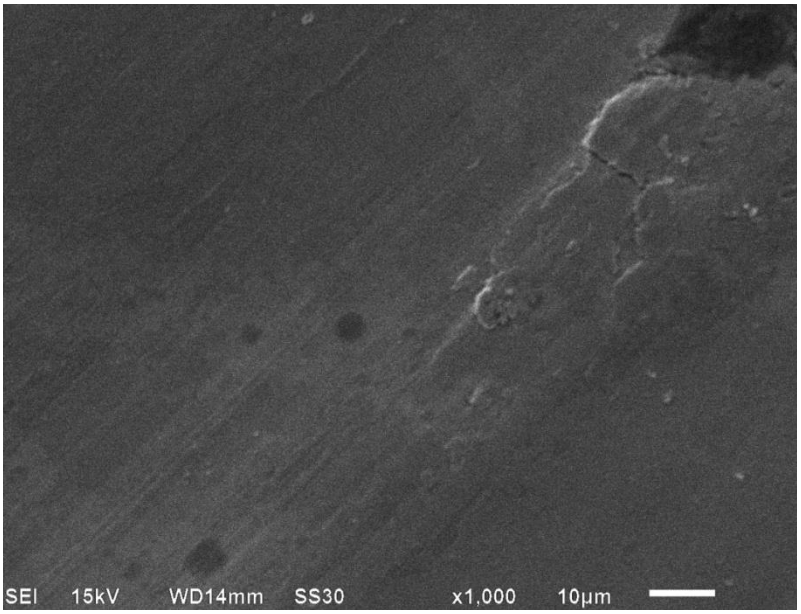


Fig. 19, SEM micrograph of worn surface of AISI D3 steel pin at load 40 N, speed 1.5 m/s, time 6 min

RESULT AND DISCUSSION:

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

1. A. Alsaran, A. Celik, M. Karakan (2005). Structural, mechanical and tribological properties of duplex-treated AISI 5140 steel, *Materials Characterization*, Vol. 54, pp. 85-92.
2. A. Alsaran, A. Celik, C. Celik, I. Efeoglu (2004). Optimization of coating parameters for duplex treated AISI 5140 steel, *Material Science and Engineering*, Vol. 371, pp. 141-148.
3. A.S. Galakhar, J.D. Gates, W.J. Daniel, P.A. Meehan (2011). Adhesive tool wear in the cold roll forming process, *Wear*, Vol. 271, pp. 2728-2745.
4. A. Toro, C. Viafara, M. Castro, J. Velez (2005). Unlubricated sliding wear of pearlitic and bainitic steels, *Wear,* Vol. 259, pp. 405-411.
5. B. Podgornik, J. Vizintin, H. Ronkainen, K. Holmberg (2000). Friction and wear properties of DLC-coated plasma nitrided steel in unidirectional and reciprocating sliding, *Thin Solid Films,* Vol. 377-378, pp. 254-260.
6. B. Rajasekaran, G. Mauer, R. Vaben, A. Rottger, S. Weber, W. Theisen (2010). Thick tool steel coatings using HVOF spraying for wear resistance applications, *Surface & Coatings Technology*, Vol. 205, pp. 2449-2454.
7. B.S. Yilbas, S.M. Nizam (2000). Wear behavior of TiN coated AISI H11 AISI M7 twist drills prior to plasma nitriding, *Journal of Materials Processing Technology,* Vol. 105, pp. 352-358.
8. C. Boher, S. Roux, L. Penazzi, C. Dessain (2012). Experimental investigation of the tribologicalbehavior and wear mechanisms of tool steel grades in hot stamping of a high-strength boron steel, *Wear*, Vol. 294-295, pp. 286-295.
9. C. Spero, D.J. Hargreaves, R.K. Kirkcaldie, H.J. Flitt (1991). Review of test methods for abrasive wear in ore grinding, *Wear,* Vol. 146, pp. 389-408.
10. C. Lee, A. Sanders, N. Tikekar, K.S. Ravi (2008). Tribology of titanium boride-coated titanium balls against alumina ceramic: wear, friction and micromechanisms, *Wear,* Vol. 265, pp. 375-376.
11. D.A. Rigney (1994). The roles of hardness in the sliding behavior of materials, *Wear*, Vol. 175, pp. 63-69.
12. D. Camino, A.H.S. Jones, D. Mercs, D.G. Teer (1999). High performance sputtered carbon coatings for wear resistant applications, *Vacuum,* Vol. 52, pp. 125-131.

13. D. Das, A.K. Dutta, K.K. Ray (2009). Optimization of the duration of cryogenic processing to maximize wear resistance of AISI D2 steel, *Cryogenics*, Vol. 49, pp. 176-184.
14. D. Das, A.K. Dutta, K.K. Ray (2010). Sub-zero treatments of AISI D2 steel: part II. Wear behavior, *Material Science and Engineering*, Vol. 527, pp. 2194-2206.
15. E. Schedin (1994). Galling mechanisms in sheet metal forming operations, *Wear*, Vol. 179, pp. 123-128.
16. E. Vera, G.K. Wolf (1999). Optimization of TiN-IBAD coatings for wear reduction and corrosion protection, *Nuclear Instruments and Methods in Physics Research*, Vol. 148, pp. 917-924.
17. F. Klocke, T. Mabmann, K. Gerschwiler (2005). Combination of PVD tool coatings and biodegradable lubricants in metal forming and machining, *Wear*, Vol. 259, pp. 1197-1206.
18. G.B. Wang (1997). Wear mechanisms in vanadium carbide coated steel, *Wear*, Vol. 212, pp. 25-32.
19. G. Cueva, A. Sinatora, W.L. Guesser, A.P. Tschiptschin (2003). Wear resistance of cast irons used in brake disc rotors, *Wear*, Vol. 255, pp. 1256-1260.
20. H. So (1995). The mechanism of oxidational wear, *Wear*, Vol. 184, pp. 161-167.
21. H. So (1996). Characteristics of wear results tested by pin-on-disc at moderate to high speeds, *Tribology International*, Vol. 29, pp. 415-423.
22. H. So, D.S. Yu, C.Y. Chuang (2002). Formation and wear mechanism of tribo – oxides and the regime of oxidational wear of steel, *Wear*, Vol. 253, pp. 1004-1015.
23. H. Sui, H. Pohl, U. Schomburg, G. Upper, S. Heine (1999). Wear and friction of PTFE seals, *Wear*, Vol. 224, pp. 175-182.
24. I.V. Kragelsky, A.I. Zolotar, A.O. Sheiwekhman (1985). Theory of material wear by solid particle impact – a review, *Tribology International*, Vol. 18, pp. 3-11.
25. J.D. Bressan, R. Hesse, E.M. Silva Jr. (2001). Abrasive wear behavior of high speed steel and hard metal coated with TiAlN and TiCN, *Wear*, Vol. 250, pp. 551-568.
26. J.K. Lancaster (1990). A review of the influence of environmental humidity and water on friction, lubrication and wear, *Tribology International*, Vol. 23, pp. 371-389.
27. J. Rech, C. Bonnet, F. Valiorgue, C. Claudin, H. Hamdi, J.M. Bergheau, P. Gilles (2008). Identification of a friction model, application to the context of dry cutting of AISI 316L

austenitic stainless steel with a TiN coated carbide tool, *International Journal of Machine Tools and Manufacture*, Vol. 48, pp. 1211-1223.

28. K. Kubota, T. Ohba, S. Morito (2011). Frictional properties of new developed cold work tool steel for high tensile strength steel forming die, *Wear*, Vol. 271, pp. 2884-2889.
29. K.J.L. Iyer, N. Krishnaraj, P. Srinivasan, S. Sundaresan (1998). Optimization of compound layer thickness for wear resistance of nitrocarburized H11 steel, *Wear*, Vol. 215, pp. 123-130.
30. M.A. Moore (1974). A review of two body abrasive wear, *Wear*, Vol. 27, pp. 1-17.
31. M. Mohanty, R.W. Smith, M.D. Bonte, J.P. Celis, E. Lugscheider (1996). Sliding wear behavior of thermally sprayed 75/25 Cr_3C_2/NiCr wear resistant coatings, *Wear*, Vol. 198, pp. 251-266.
32. M. Yan, R. Liu (2010). Influence of process time on microstructure and properties of 17-4PH steel plasma nitrocarburized with rare earth addition at low temperature, *Applied Surface Science*, Vol. 256, pp. 6065-6071.
33. M.H. Staia, A. Fragiel, S.P. Bruhl, J.N. Feugeas, B.J. Gomez (2000). Behavior of the pulsed ion nitride AISI 4140 steel/ CVD TiN coatings as tribological pairs, *Thin Solid Films*, Vol. 377-378, pp. 650-656.
34. M. Polok, M. Adamiak, L.A. Dobrzanski (2005). Structure and properties of wear resistance PVD coatings deposited onto X37CrMoV5-1 type hot work steel, *Journal of Material Processing Technology*, Vol. 164-165, pp. 843-849.
35. M. Karakan, A. Alsaran, A. Celik (2004). Effect of process time on structural and tribological properties of ferritic plasma nitrocarburized AISI 4140 steel, *Materials and Designs*, Vol. 25, pp. 349-353.
36. M.P. Pereira, P.C. Okonkwo, G. Kelly, B. Rolfe (2012). The effect of temperature on sliding wear of steel – tool steel pairs, *Wear*, Vol. 282-283, pp. 22-30.
37. M.P. Pereira, P.C. Okonkwo, G. Kelly, B. Rolfe (2008). Effects of temperature in relation to sheet metal stamping, *Recent Advances in Manufacturing Engineering.*
38. N.P. Suh (1977). An overview of the delamination theory of wear, *Wear*, Vol. 44, pp. 1-16.
39. O. Banakh, C. Csefalvay, P. Steinmann, M. Fenker, H. Kappl (2006). Evaluation of adhesion and tribologicalbehavior of tantalum oxynitried thin films deposited by reactive magnetron sputtering on to steel substrate, *surface & coating technology*, Vol. 200, pp. 6500-6504.

40. O.N. Cora, K. Namiki, M. Koc (2009). Wear performance assessment of alternative stamping die material utilizing a novel test system, *Wear*, Vol. 267, pp. 1123-1129.
41. P.L. Hurricks (1973). Some metallurgical factors controlling the adhesive and abrasive wear resistance of steels. A review, *Wear,* Vol. 26, pp. 285-304.
42. P.L. Menezes, Kishore, S.V. Kailas (2009). Influence of surface texture and roughness parameters on friction and transfer layer formation during sliding of aluminium pin on steel plate, *Wear,* Vol. 267, pp. 1534-1549.
43. P.W. Shum, Z.F. Zhou, K.Y. Li (2004). Tribological performance of amorphous carbon films prepared on steel substrates with carbon implantation pre-treatment, *Wear*, Vol. 256, pp. 362-373.
44. P. Deshmukh, M. Lovell, W.G. Sawyer (2006). On the friction and wear performance of boric acid lubricant combinations in extended duration operations, *Wear,* Vol. 260, pp. 1295-1304.
45. S. Krol, W. Grzesik, Z. Zalisz, P. Nieslony (2006). Investigations on friction and wear mechanisms on PVD-TiAlN coated carbide in dry sliding against steels and cast iron, *Wear*, Vol. 261, pp. 1191-1200.
46. S.F. Scieszka (1987). A technique to study abrasive wear in contacts with particulate materials, *Wear*, Vol. 119, pp. 237-249.
47. S.K. Dey, T.A. Perry, A.T. Alpas (2009). Micromechanisms of low load wear in an Al-18.5% Si alloy, *Wear*, Vol. 267, pp. 515-524.
48. T.F.J. Quinn (1971). Oxidational wear, *Wear*, Vol. 18, pp. 413-419.
49. T.F.J. Quinn (1983). Review of oxidational wear. Part I: The origins of oxidational wear, *Tribology International*, Vol. 16, pp. 257-271.
50. T.F.J. Quinn (1983). Review of oxidational wear. Part II: Recent developments and future trends in oxidational wear research, *Tribology International*, Vol. 16, pp. 305-315.
51. T. Slatter, R. Thornton, A.H. Jones, R. Lewis (2011). The effect of cryogenic processing on the wear resistance of grey cast iron brake discs, *Wear,* Vol. 254, pp. 492-500.
52. T.S. Eyre, D. Grimanelis (2006). Sliding wear mapping of an ion nitrocarburized low alloy sintered steel, *Surface & Coatings Technology,* Vol. 201, pp. 3260-3268.
53. V. Fervel, S. Mischler, D. Landolt (2003). Lubricating properties of cotton transfer films studied with a pin-on-disk apparatus, *Wear,* Vol. 254, pp. 492-500.

54. W.O. Winer, T.F.J. Quinn (1985). The thermal aspects of oxidational wear, *Wear*, Vol. 102, pp. 67-80.
55. W. Minxian, W. Shuqi, W. Lan, C. Kangmin (2011). Effect of microstructures on elevated temperature wear resistance of hot working die steel, *Journal of Iron and Steel Research*, Vol. 18, pp. 47-53.
56. X. Han, L. Hua (2011). Prediction of contact pressure and slip distance in cold rotary forging using finite element methods, *Tribology International*, Vol. 44, pp. 1742-1753.
57. Y. Sahin (2006). Optimal testing parameters on the wear behavior of various steels, *Materials and Design*, Vol. 27, pp. 455-460.
58. Y.C. Lin, S.W. Wang (2003). Wear behavior of ceramic powder cladding on an S50C steel surface, *Tribology International*, Vol. 36, pp. 1-9.
59. Z. Liu, J. Cabrero, S. Niang, Z.Y. Al-Taha (2007). Improving corrosion and wear performance HVOF-sprayed inconel 625 coatings by high power diode laser treatments, *Surface and Coatings Technology*, Vol. 201, pp. 7149-7158.
60. A.D. Sarkar, Friction and Wear, *Academic Press*, 1980.
61. B. Bhushan, Introduction to Tribology, *John Wiley & Sons*, 2002.
62. K.C. Ludema, Friction, Wear, Lubrication: A Textbook in Tribology, *CRC Press*, Boca Raton, 1996.
63. N.P. Suh, Tribophysics, *Prentice – Hall*, 1986.
64. P. Blau. Wear of materials, *Elsevier*, 2003.