CHAPTER 2
LITERATURE REVIEW

2.1 PROBLEM STATEMENT
The review study on wear showed the strengths and findings of various mathematical models. The investigation of the same should be utilized to allow new work to progress and therefore improve our knowledge. It is in the view of this author that a multi-orientational set-up is need of the hour, so that wear should be checked at different angular position, this will not only add the new dimension to study the wear but will also gives the better understanding of wear behavior of different metal at different orientation. This approach might be very different and new when compared to approaches discussed earlier in different models. A comprehensive literature review was done according to problem selected, due to the uniqueness of the same, it was decided that research paper concerning abrasive wear will be taken in to consideration.

2.2 LITERATURE REVIEW

- **Pramila Bai et. al. 1987** [83] reported “that Si additions (4-24% Si) improved wear resistance of aluminium, no relationship between wear rate as a function of Si content was found. Wear rate increased linearly with applied pressure but was independent of sliding velocity. The value of the friction coefficient was found to be insensitive to applied pressure, Si content and sliding velocity. The fact that no transition in wear mechanism was observed with increased pressure, as reported by other authors could be due to the narrow range explored (0.105-1.733 MPa).”
• **Liang Y. N. et. al. (1995)**[84] Reported that the MMCs containing SiC particles exhibit improved wear resistance. Particle size is one of the most important factors in determining wear of particulate-reinforced metal composites. However, it appears to be difficult to draw a fundamental conclusion from the reports about this problem. Some reports have suggested that wear resistance of the composites increased with increasing particle size, while others indicated that an increase in particle size had a negligible influence on the wear rate. A further problem is that nearly all the studies have been carried out with such methods as pin on disc or sand rubber wheel abrasion tests, in which the sliding speed was maintained in a narrow range and the applied load in a steady state. It is thus necessary to study the effect of particle size on wear properties of the composites under a variety of experimental conditions. In this work, the effect of particle size on wear behavior of SiC particulate-reinforced 2024 Al composites has been investigated using three tests: sliding wear, impact abrasion and erosion.

• **H.C. How and T.N. Baker (1997)**[85] In their investigation of wear behavior of Al6061-saffil fiber, concluded that “saffil are significant in improving wear resistance of the composite”. The steady-state wear of aluminium alloy AA6061 and AA6061-based Saffil fibre-reinforced composites, manufactured by a PM route, was investigated with a pin-on-disc configuration under dry sliding conditions. Using a constant sliding velocity, the wear rates of the monolithic alloy and the composites increased proportionally with the applied load. The benefit of Saffil reinforcement at volume fractions of 5, 10 and 20% was not substantial at
loads ranging from 4.9 to 48.3 N. As the applied load decreased to 1.1 N, the composite showed a promising improvement in wear resistance as the volume fraction of Saffil reinforcement increased. At loads of 19.2 N and above, the wear resistance of the AA6061 composite was slightly impaired when the volume fraction of the Saffil reinforcement was increased from 5 to 20%. Compared with over-aged samples, the improvement of the wear resistance due to peak-ageing was not significant, although the Vickers hardness of the peak-aged samples was double that of the over-aged samples. The surface morphology of both the monolithic alloy and the composites after testing under loads of 9.8 or 48.3 N revealed a compacted layer which comprised mainly aluminium and iron. The amount of iron transferred increased with the applied load and with the volume fraction of Saffil in the composite. Energy Dispersive X-ray (EDAX) analysis indicated that the wear debris was generated mainly from the compacted layer. On the basis of the experimental observations, delamination was considered to be the controlling wear mechanism for the monolithic specimens tested at all loads and the composite specimens tested at loads ranging from 4.9 to 48.3 N. At a load of 1.1 N, surface fatigue, which caused surface cracking, was evident for the composite specimens.

- **R. Dasgupta, R. Thakur, and B. Govindrajan (2002)** [86] concluded in their study that “the high stress wear behavior is dependent on the combination of a number of experimental factors. The behavior can be explained based on the material removal mechanism operating under a combination of experimental factors. A regression analysis of the experimental data shows that the dependence is nonlinear. The equation arrived at by regression analysis helps in predicting the wear rate. A
comparison between the experimental and predicted observed values indicates a variation of ±15%. Such an analysis should aid in predicting the high stress abrasive wear behavior of steels exposed to various combinations of load, particle size, and sliding distances”.

- **M.S. Zaamout (2004)**[87] the objective of this research is to investigate the abrasive wear behaviour of polymer base automotive paint, which is locally used for steel painting. Research has been conducted under dry, water lubricated, and water-soap lubricated conditions. The effects of applied load, sliding distance, abrader surface roughness, and paint drying time on the abrasive wear volume and abrasive wear rate were investigated under controlled environment of 23 C temperatures and 40% humidity. The examined paint was used directly on steel substrate with no primer. Preliminary results show that wear volume increases with increasing applied load, sliding distance and abrader roughness. However, results also show decreasing wear volume with increasing drying time up to 50 hr. Beyond this value, time seems to have little effects on abrasive wear behaviour. This argument is valid for all four conditions of tests. As for abrasive wear rate, results show decreasing abrasive wear rate with applied load, sliding distance, abrader surface roughness, and drying time. Results clearly indicate that the presence of water significantly increases the wear volume and wear rate. Furthermore, the addition of soap to water increases the wear volume and rate to even higher levels.

- **L.J. Yang (2005) [88]** in their study found that the Wear coefficient values obtained from different investigators can vary significantly up to a deviation of 1000% due to lack of a standard test method. Higher wear coefficient values can be obtained when the wear tests are carried out
within the transient wear regime, or with an excessive sliding distance in the steady-state wear regime.

- **Basavarajappa S. and Chandramohan G (2006) [89]** reported that “the sliding distance has the highest effect on the dry sliding wear behavior of MMCs than that of the load and sliding speed”.

- **Y. Reda et al (2008) [90]** studies on Al6061-SiC and Al7075 - Al2O3 Metal Matrix Composites and **R. Clark et al.[91]** in their studies on Al7075 reported that “pre-aging at various retrogression temperatures improves the hardness, tensile properties and electrical resistivity”.

- **Q Wang, Z H Chen, Z X Ding and Z L Liu 2008 [92]** “Conducted study on Performance of abrasive wear and erosive wear of WC-12Co coatings sprayed by HVOF. They used WC-Co cermets as wear resistant materials. Their work examines the performance of such conventional and nano-structured materials in the form of coatings deposited by high velocity oxy-fuel (HVOF) thermal spraying. The results indicated that: microstructures of nano-structured and multimodal WC-12Co coatings prepared by HVOF are dense with little porosity, and their microhardness values are obviously higher than conventional WC-12Co coatings, though Nano WC did during spraying. As well, it was found that nanostructured and multimodal WC-12Co coatings exhibited better abrasive and erosive wear resistance in comparison with conventional one”.

- **B. Sidda Reddy, G. Padmanabhan and K. Vijay Kumar Reddy(2008) [93]** in their study deals with the development of a surface roughness prediction model for machining aluminum alloys using multiple regression and artificial neural networks. The experiments have been conducted using full factorial design in the design of experiments (DOE) on CNC turning
machine with carbide cutting tool. A second order multiple regression model in terms of machining parameters has been developed for the prediction of surface roughness. The adequacy of the developed model is verified by using co-efficient of determination, analysis of variance (ANOVA), residual analysis and also the neural network model has been developed using multilayer perception back propagation algorithm using train data and tested , using test data. To judge the efficiency and ability of the model to predict surface roughness values percentage deviation and average percentage deviation has been used. The experimental results show, artificial neural network model predicts with high accuracy compared with multiple regression model. This study uses statistical multiple regression model for prediction of surface roughness in machining of aluminum alloys, which is used to determine the correlation between a criterion variable and a combination of predicted variables. It can be used to analyze data from any of the major quantitative research designs such as fundamental comparative, correctional and experimental. This method is also able to handle interval ordinal or categorical data and provides estimates both of the magnitude and statistical significance of the relationships between variables (Gall et al., 1996). Therefore, multiple regression analysis will be helpful to predict the criterion variable finish surface roughness via predictor variables, such as spindle speed, feed and depth of cut. The second order multiple regression model for the surface roughness($R_a, \mu m$) is developed as a function of cutting parameters such as cutting speed ($V$), federate ($f$) and depth of cut ($d$). This analysis is carried out at a significance level of 5% i.e., confidence level of 95%. The optimal neural network architecture was used in this study. It was designed using
NEURO SOLUTIONS 5.0. The network consists of one input, two hidden and one output layer. Hidden layers have eight neurons each, whereas the input and output layers have three and one neuron, respectively. Using full factorial design in the design of experiment, the machining parameters which are influencing the surface roughness on the machining of Al Alloys has been modeled using Multiple Regression and Artificial Neural Networks. It concluded that:

(a) The Multiple Regression Model is developed to predict the Surface Roughness for Turning of Al Alloys and the predicted model was tested with three sets which were never used in modeling and average percentage deviation calculated as 8.76%.

(b) The neural network model is developed to predict surface roughness and predicted model was tested using the same test data which were used in Multiple Regression Model and the Average Percentage Deviation was calculated as 0.9853%.

(c) After analyzing the Multiple Regression Model and Artificial Neural Network Model, the Artificial Neural Network Model has good prediction capability and has given minimum percentage deviation compared to the Multiple Regression Model.

- **S.S. Mahapatra and Vedansh Chaturvedi (2009)** [94] found “that the hardness of the composite monotonically decreases as the fibre length increases but tensile strength first increases and then decreases as length of the fibre is increased. In contrary to common belief that hardness and tensile strength improve wear resistance, it has been observed that parameters encountered in wear process strongly influence wear resistance. In future, the study can be extended to other natural fibres to
find out the optimum fibre length. The abrasive wear behaviour of chemically treated sugarcane fibre and aging effects of the fibre on abrasive behaviour of the composite can be studied”.

- **Sagbas, F. Kahraman, U. Esme (2009)**[95] studied the “modeling and predicting abrasive wear behaviour of poly oxy methylenes using response surface methodology and neural networks and found that the abrasive wear behaviour of poly oxy methylenes (POM) under various testing conditions was investigated. A central composite design (CCD) was used to describe response and to estimate the parameters in the model. Response surface methodology (RSM) was adopted to obtain an empirical model of wear loss as a function of applied load and sliding distance. Also, a neural network (NN) model was developed for the prediction and testing of the results. Finally, a comparison was made between the results obtained from RSM and NN”.

- **J. L. Xuan, I. T. Hong and E. C. Fitch (2009)**[96] Under fluid film lubrication, the particulate contaminants in the fluid cause three-body abrasive wear on critical surfaces. The wear not only depends on the hardness of the wearing surface (Hj), but also on the hardesses of its opposing surface (Hb) and the involved abrasives (Ha). In this paper, the hardness effect, particularly the relationships among these three hardesses, is studied, by exploring the interdependence between two hardness ratios: the ratio between two rubbing surfaces (Hb /Hj) and the ratio between the surface to be protected (usually the harder surface) and the abrasives (Hj /Ha). Three types of journal-bearing pairs (Hb /Hj = 0.75, 0.6, and 0.3) were tested, subjected to four abrasive particles (Hj /Ha ranges from 0.14 to 2.75). The wear linearly varies with the Hj /Ha value.
at each metal hardness ratio on log-log diagram. The empirical constants in the wear function are obtained. The critical hardness ratio and the wear coefficient are also analyzed.

- **Friedrich Franek, Ewald Badisch and Martin Kirchgaßne (2009)**[97] In many fields of industry, abrasion and erosion processes are dominant wear mechanisms that reduce lifetime of costly machine parts. Wear resistance against abrasion and/or impact or the ability to withstand other complex mechanical actions are often required. In order to quantify the specific properties of material that are applied in such fields, several test methods are in use. A certain discrepancy can be seen between the systems approach and the aim to get information about suitability of materials for practical applications simply from specific material tests. This paper gives an overview over a selection of relevant test equipment and procedures. In addition, some examples are given for advanced studies on materials behavior combining tribological test, material analyses respectively materialography, and mathematical methods in order to support – for selected cases – the acquired correlation of materials properties and wear resistance under severe conditions.

- **Chang Chongyi Wang Chenggu and Jin Ying 2010**[98] conducted their study on numerical method to predict wheel/rail profile evolution due to wear. “A wheel/rail profile wear prediction methodology was developed and applied to the wheel/rail disc test about the wear of flange and gauge. Three-dimensional nonlinear finite element dynamic analysis code ABAQUS was also used in the simulation of wheel/rail disc rolling contact process. The simulation results are compared with measurements
of laboratory wear test and the effectiveness of the wear prediction methodology was verified”.

- **Dharma R. Maddala, Arif Mubarok and Rainer J. Hebert 2010**
  [99] conducted study on Sliding wear behavior of Cu$_{50}$Hf$_{41.5}$Al$_{8.5}$ bulk metallic glass. Sliding wear behavior of a copper-based bulk metallic glass (Cu$_{50}$Hf$_{41.5}$Al$_{8.5}$) was investigated for both as-cast and annealed samples. “The wear resistance increased during isothermal annealing near the glass transition temperature. Nano-crystals developed during the annealing for annealing times up to 300 min. A linear relation between hardness and wear resistance was observed during the early stages of devitrification, but at longer annealing times the wear resistance increased less than the hardness”.

- **N R Prabhu Swamy, C S Ramesh and T Chandershekhar 2010**
  [100] “Studied the effect of heat treatment on strength and behavior of Al-SiC$_p$ composites and concluded that microhardness of composites increased significantly with increased content of SiC$_p$. Heat treatment has a significant effect on microhardness of Al6061 matrix alloy and its composites. Tensile strength of composites increased significantly with increased content of SiC$_p$. Abrasive wear loss of composites decreases, with the increase in content of SiC$_p$ in matrix alloy under identical test conditions”.

- **Veeresh Kumar G.B, C.S.P.Rao, Bhagyashekar M.S., Selvaraj N (2010)** [101] Reported that “artificial neural network (ANN) can be effectively applied to study the tribological behavior. The studies conducted regarding wear resistance properties of Al6061-SiC & found
that the ANN model can predict the Wear Factor and Wear Height Loss up to 95% accuracy”.

- **Dushyant Singh, K P Saha & D P Mondal (2011)** [102] conducted their study on development of mathematical model for prediction of abrasive wear behaviour in agricultural grade medium carbon steel and found that “the wear rate of ICA and QT specimens are much lower than that of AR and AN specimens due to formation of ferreto-martensitic, and tempered martensitic structure respectively during heat-treatment process. Wear rate follows a non-linear relationship with peening intensity as at first it is reduced up to a peening intensity of 0.17 A, then increases again with the increase in peening intensity due to increase in brittleness of the specimen with the peening intensity. Applied load, however the rate of growth may vary according to heat treatment applied to the material. The complex relationship between the influencing factors and wear rate can be illustrated by fitting a mathematical equation of quadratic form which shall help in prediction of wear rate accurately as the corresponding regression coefficients and the model are found to be highly significant”.

- **Jankauskas, V.; Skirkus, R.; Martinkus, N. (2011)** [103] Industrialized countries studies have shown that because of wear in the world suffered huge losses every year - up to 4% of the gross national product. It was found that investments in the tribological research annually can save from 1 to 1.4% of gross national product. In this paper, the abrasive wear research of arc welded Fe-C-Si-Cr-Ti-B surfaces into embedded abrasive. The microhardness of arc welded layers has a direct impact on abrasion - the harder layers, the higher resistance to abrasive wear. In SEM picture visible cutting traces of wear and only small fragments are chipped. This
phenomenon demonstrates the high abrasive and metal microhardness differences influence. The highest wear resistance shows sample with C - 1.6%, Cr - 4.4%, B - 0.56%, Mn - 0.9%, Si - 1.44%, Ti - 0.59% and Fe - 90.2%.

- **Punyapriya Mishra (2012)** [104] studied the “statistical analysis for the abrasive wear behavior of bagasse fiber reinforced polymer composite and found that the relationship of abrasive wear loss with fiber concentration, applied load and sliding velocity has been successfully obtained by using RSM at 95% confidence level. The response surface methodology analysis has been reviewed. RSM can be used for the approximation of both experimental and numerical responses. Two steps are necessary, the definition of an approximation function and the design of the plan of experiments. This model is valid within the ranges of selected experimental parameters of fiber concentration, applied load and sliding velocity. The accuracy of the RSM model was verified with three sets of experimental data which were never used in modeling and average percentage deviation calculated as 7.542%.

- **E. Y. H. Bobobee and F. Kumi (2013)** [105] developed and evaluated equipment for testing the abrasive wear off tillage tools in the laboratory. The abrasive wear experiment was arranged in a completely randomized design with the soils from the five sites as the treatment. Each treatment was replicated five times. The wear rate of soils from Akatsi and Ho showed increasing trend with increasing moisture content while that of Wenchi and Mampong showed a reverse trend up to 13% and 15% moisture content, respectively. The soil from Akatsi produced the highest wear of 4.11g. The wear in the soils from Ho, Mampong, Wenchi and
KNUST were 3.16g, 2.90g, 2.88g and 1.36g, respectively with the least wear from the KNUST soil. This confirms the long held belief that the wear rate of tillage tools is directly related to the sand content of the soil. The abrasive wear characteristics of the soils showed strong correlation between mass loss and dimensional loss of the ploughshare.

- M. Sudheer, N. Karthik Madhyastha, M. Kewin Amanna, B. Jonthan, and K. Mayur Jayaprakash (2013) [106] The present work reveals the effect of the addition of commercial MoS$_2$ (10wt%) particles on mechanical and two-body abrasive wear behavior of epoxy with/without glass fiber mat reinforcement. The abrasive wear testing was carried out using pin-on-disc wear tester for different loads and abrading distances at constant speed of 1m/s. A significant reduction in wear loss and specific wear rate was noticed after the incorporation of MoS$_2$ filler allowing less wear of matrix during abrasion which in turn facilitated lower fiber damage. The worn surface features were investigated through scanning electron microscopy (SEM) in order to investigate the wear mechanisms.

T.S. Barrett, G.W. Stachowiak, A.W. Batchelor (1992) [107] The study was done on friction and wear of ultra-high molecular weight polyethylene (UHMWPE) pins sliding against a stainless steel disc were measured for sliding speeds ranging from 1.25 to 10 m s$^{-1}$ and disc surface roughnesses $R_a$ from 0.07 to 0.53 $\mu$m ms$^{-1}$. Frictional heating was controlled by air jets and surface temperature measured with an IR pyrometer. It was found that the wear of UHMWPE is critically dependent on surface temperature and that, when the temperature exceeds a critical value, wear proceeds in a series of discrete steps caused by the sudden loss of a molten or softened layer of polymer. Wear was
also influenced by surface roughness. An optimum surface roughness, i.e. a minimum of wear was found at low and medium sliding speeds. At the highest speed tested, however, the influence of roughness on wear rate was much less distinct. Scanning electron photomicrographs of worn pins and disc surfaces revealed evidence of melting by UHMWPE at high sliding speeds and abrasion at high surface roughnesses. Transfer films on disc surfaces were limited to isolated deposits of polymer wear particles.

O. P. Modi, R. P. Yadav, D. P. Mondal, R. Dasgupta, S. Das, A. H. Yegneswaran (2001) [108] in their study of two body abrasive wear behaviour of a zinc-aluminium alloy - 10% Al2O3 composite at different loads (1–7 N) and abrasive sizes (20–275 µm) as a function of sliding distance and compared with the matrix alloy. The wear rate of the composite and the matrix alloy has been expressed in terms of the applied load, abrasive size and sliding distance using linear factorial design approach. The study suggests that the wear rate of the alloy and composite follow the following relations:

\[ Y_{\text{alloy}} = 0.1334 - 0.0336x_1 + 0.0907x_2 + 0.0219x_3 - 0.0296x_1x_2 + 0.0274x_2x_3 - 0.0106x_3x_1 - 0.0201x_1x_2x_3, \]

\[ Y_{\text{comp}} = 0.0726 - 0.028x_1 + 0.062x_2 + 0.03x_3 - 0.024x_1x_2 + 0.028x_2x_3 - 0.016x_3x_1 - 0.014x_1x_2x_3, \]

where, \(x_1, x_2\) and \(x_3\) are the coded values of sliding distance, applied load and abrasive size respectively. It has been demonstrated through the above equations that the wear rate increases with applied load and abrasive size but decreases with sliding distance. The interaction effect of the variables exhibited a mixed behavior towards the wear of the material. It was also noted that the effect of load is less prominent for the composite than the matrix alloy while the trend reversed as far as the influence of the abrasive size is concerned.
D. Kakas, B. Skorić, S. Mitrović, M. Babić, P. Terek, A. Miletić, M. Vilotić (2009) [109] The influence of applied load and sliding speed on the tribological performance, i.e. friction and wear of TiN IBAD coating in sliding with corundum ball has been evaluated using reciprocating sliding wear test. Post characterization of wear zones was conducted using AFM, SEM and EDX. The results show that coefficient of friction decrease with decreasing applied load and with increasing the sliding speeds.

Hua-Nan Liu, Keisaku Ogi (1999) [110] In this study the tribological properties of Al2O3 continuous fibre reinforced Al-4.43 wt %Cu alloy composites with a fibres’ volume fraction of about 0.55 were measured for five types of fibre orientations under a dry sliding contact with a bearing steel. Fibres were in a plain perpendicular to wear surface and parallel to sliding direction, and had the angles 0°, 45°, 90°, or 135° with respect to the direction of motion of the counterface; or were anti-parallel the sliding direction. The results show obvious dependence of wear characteristics on fibres orientation: for the 45°, 90°, and 135° orientations, the larger the fibres’ angle, the lower the volume loss; while the 0° orientation resulted in a higher steady-state wear rate than those of the 45°, 90°, and 135° orientations, except that the anti-parallel orientation caused the highest volume loss at all sliding distances. The wear mechanism was inferred as a oxidation-microgrooving process through the analyses of worn surface and subsurface with the aid of optical microscope and scanning electron microscope. Also it was found that the fibres’ broken and subsurface deformation had played an important role in causing wear anisotropy.

matrix composites containing hard (brittle) reinforcement particles. The model is based on the assumption that any portion of the reinforcement that is removed as wear debris cannot contribute to the wear resistance of the matrix material. The size of this non-contributing portion (NCP) of reinforcement is estimated by modeling three primary wear mechanisms, specifically, plowing, cracking at the matrix/reinforcement interface or in the reinforcement, and particle removal. Critical variables describing the role of the reinforcement, such as relative size, fracture toughness and the nature of the matrix/reinforcement interface, are characterized by a single contribution coefficient, C. Predictions are compared with the results of experimental two-body (pin-on-drum) abrasive wear tests performed on a model aluminum particulate-reinforced epoxy-matrix composite material.

D. Tao, G. L. Chen, and B. K. Parekh (2004) [112] A statistical Box-Behnken design (BBD) of experiments was performed to evaluate effects of individual operating variables and their interactions on the wear rate of grinding ball mills used in the phosphate industry. The wear tests were conducted using a specially designed grinding mill. The variables examined in this study included grinding time, solution pH, rotation speed, mill crop load, and solids percentage. The most significant variables and optimum conditions were identified from a statistical analysis of the experimental results using response surface methodology. Experimental results show that solution pH has the most significant effect on the wear rate for both Type 1018 (UNS G10180) carbon steel (CS) and a high-chromium alloy. The optimum process parameters for minimum wear rate were solution pH at 7.36, rotation speed at 70.31 rpm, a solid percentage at 75.50, and a crop load at 71.94% for Type 1018 CS; for the high-
chromium alloys, they include a solution pH at 8.69, rotation speed at 61.13 rpm, a solid percentage at 64.86, and a crop load at 57.63%.

**A.A. Torrance (2005) [113]** In his study the abrasive wear rates of materials may be very simply related to their mechanical properties, provided wear takes place under very simple conditions. However, wear rates in many practical situations can be controlled by effects which either relate to mechanical properties in more subtle ways, or which are controlled by quite different parameters. Mechanics models of the abrasive process provide a means of linking these different effects together to understand better the effects, which may determine wear under particular conditions. They can also help to design tests to measure the properties of a material under conditions similar to those pertaining in abrasion. Some progress has been made in producing integrated models of real abrasive processes, but much more could be done to improve existing models and develop new ones.

**S. Kumar , V. Balasubramanian (2008) [114]** This paper reports the dry sliding wear behaviour of AA7075 aluminium/SiCp composites fabricated by powder metallurgy technique. Five factors, five levels, central composite, rotatable design matrix is used to optimize the required number of experiments. The wear test has been conducted in a pin-on-roller wear testing machine, under constant sliding distance of 1 km. An attempt has been made to develop a mathematical model by response surface method (RSM). Analysis of variance (ANOVA) technique is applied to check the validity of the developed model. Student's t-test is utilised to find out the significance of factors. The effects of volume percentage of reinforcement, particle size of reinforcement, applied load, sliding
speed and hardness of counter part materials on dry sliding wear behaviour of AA7075 aluminium/SiC<sub>p</sub> have been analysed in detail.

Kleber S. Cruz, Elisangela S. Meza, Frederico A.P. Fernandes, Jose´ M.V. Quaresma, Luiz C. Casteletti, And Amauri Garcia(2010)[115]
The aim of the present study was to contribute to a better understanding about the relationship between the scale of the dendritic network and the corresponding mechanical properties and wear behavior. The Al-Sn (15 and 20 wtpctSn) and Al-Si (3 and 5 wtpct Si) alloys were directionally solidified under unsteady-state heat flow conditions in water-cooled moulds in order to permit samples with a wide range of dendritic spacings to be obtained. These samples were subjected to tensile and wear tests, and experimental quantitative expressions correlating the ultimate tensile strength (UTS), yield tensile strength, elongation, and wear volume to the primary dendritic arm spacing (DAS) have been determined. The wear resistance was shown to be significantly affected by the scale of primary dendrite arm spacing. For Al-Si alloys, the refinement of the dendritic array improved the wear resistance, while for the Al-Sn alloys, an opposite effect was observed, i.e., the increase in primary dendrite arm spacing improved the wear resistance. The effect of inverse segregation, which is observed for Al-Sn alloys, on the wear resistance is also discussed.

J.J. Coronado (2011) [116]In this study, white cast iron with 7.39% Cr was casted into an exothermic mold on a copper chill plate to solidify unidirectionally. The microstructure is composed of oriented M<sub>3</sub>C carbides and ledeburitic matrix. The specimens were cut both parallel and transversally to the billet axe and pin-abrasion tests were carried out using fixed alumina abrasive grains at loads between 2 and 15 N. The microhardness, elastic modulus and
fracture toughness were determined using an indentation technique on transversal and longitudinal directions. The abrasion resistance was correlated with the carbides microhardness and fracture toughness. The $M_3C$ carbides showed similar values of fracture toughness in both directions. The carbides in transversal direction showed higher hardness and elastic modulus than longitudinal carbides. The results reveal that for lower loads the mass loss is similar in both directions. However, for loads higher than 10 N the $M_3C$ carbides in the transversal direction show higher abrasion resistance than longitudinal carbides. The wear surface was examined by scanning electron microscopy for identifying the wear micromechanisms. Bending and slip planes on longitudinal cementite were observed at 15 N.

Raviraj Shetty, Raghuvir Pai, Srikanth S. Rao and Vasanth Kamath (2011) [117] This paper discusses the use of Taguchi’s design of experiments and response surface methodology (RSM) for minimising the surface roughness in turning of discontinuously reinforced aluminium composites (DRACs) having aluminum alloy 6061 as the matrix and containing 15 vol. % of silicon carbide particles with a mean diameter of 25μm under dry cutting condition. The measured results are then collected and analysed with the help of a commercial software package MINITAB15. The experiments are conducted using Taguchi’s experimental design technique. The matrices of test conditions include cutting speed, feed rates and depth of cut. The effect of cutting parameters on surface roughness is evaluated and the optimum cutting condition for minimising the surface roughness is determined. A second-order model is established between the cutting parameters and the surface roughness using RSM. The experimental results reveal that the most significant machining parameter for surface roughness is feed, followed by cutting speed. The predicted values and measured
values are fairly close, which indicates that the developed model can be effectively used to predict the surface roughness in the machining of DRACs.

**Satpal Sharma (2012) [118]** In the present investigation, Ni-WC composite powder was modified with the addition of CeO$_2$ in order to form a new composition of Ni-WC-CeO$_2$. The Ni-WC and Ni-WC-CeO$_2$ compositions were used for coating deposition by high-velocity oxy-fuel (HVOF) spraying process so as to study the effect of CeO$_2$ addition on microstructure, distribution of various elements, hardness, formation of new phases, and abrasive wear behavior. Further, the effect of load, abrasive size, sliding distance, and temperature on abrasive wear behavior of these HVOF-sprayed coatings was investigated by response surface methodology. To investigate the abrasive wear behavior of HVOF-sprayed coatings four factors such as load, abrasive size (size in micrometers), sliding distance (meters), and temperature (°C) with three levels of each factor were investigated. Analysis of variance was carried out to determine the significant factors and interactions. Investigation showed that the load, abrasive size, and sliding distance were the main significant factors while load and abrasive size, load and sliding distance, abrasive size and sliding distance were the main significant interactions. Thus an abrasive wear model was developed in terms of main factors and their significant interactions. The validity of the model was evaluated by conducting experiments under different wear conditions. A comparison of modeled and experimental results showed 4–9% error. The abrasive wear resistance of coatings increases with the addition of CeO$_2$. This is due to increase in hardness with the addition of CeO$_2$ in Ni-WC coatings.
The effect of heat treatment on the abrasive wear behavior of high chromium cast iron (NF253AHT) under dry sliding condition has been investigated. Rectangular cross-sectioned samples of the alloy were produced by sand casting. After casting, the samples were machined to equal dimensions of 50 mm x 15 mm x 10 mm and heat treated by annealing, hardening and tempering. Abrasive wear tests were carried out on the samples using the pin-on-disc wear test. The tests were carried out under restricted values of speed, load and time. Within this limit, the hardened sample displayed a superior wear resistance, while the annealed sample displayed the weakest wear resistance. A graphical model (wear map) displaying all the wear regimes of the alloy, which may serve as a wear predictive tool was subsequently developed from the results of the wear tests. With the exception of the as-cast and annealed specimen, all other specimens (hardened and tempered) have functioned adequately in wear prone environment, but with different degree of effectiveness. Hence, the hardened and tempered samples can be used in shot blast equipments and in the grinding of minerals.

In this work dry sliding wear behaviour of titanium (Grade 5) alloy has been investigated in order to highlight the mechanisms responsible for the poor wear resistance under different applied normal load, sliding speed, and sliding distance conditions. Design of experimental technique, that is, response surface methodology (RSM), has been used to accomplish the objective of the experimental study. The experimental plan for three factors at three levels using face-centre central composite design (CCD) has been employed. The results indicated that the specific wear rate increases with an increase in the applied normal load and sliding speed. However, it decreases with an increase in the sliding distance and a decrease in
the sliding speed. The worn surfaces of the titanium alloy specimens were analyzed with the help of scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), and X-ray diffraction (XRD) techniques. The predicted result also shows the close agreement with the experimental results and hence the developed models could be used for prediction of wear behaviour satisfactorily.

**C Greet, D Obeng, J Kinal and P de Bosscher (2013) [121]** The dual approach of examining the grinding media wear through a series of marked ball tests and investigating the impact of grinding chemistry on lead and zinc metallurgy using the Magotteaux Mill® at MMG’s Century mine (Century) has resulted in the conversion of the plant to high chrome grinding media. The consequences of this change have been positive in terms of wear, with a reduction in media consumption, and no adverse effect on either the lead or zinc metallurgy.

**Tevfik Küçükömeroğlu, Levent Kara (2014) [122]** In this study, the sliding friction and wear behaviour of copper alloy CuZn39Pb3 were investigated under both atmospheric and vacuum conditions, with the use of an environmentally controlled pin-on-disk apparatus. Experiments were conducted under pressures of 5 x 10^-3 mbar, 8 x 10^-6 mbar and normal atmospheric conditions (1013 mbar) with contact pressures of 0.3, 1.0 and 2.0 MPa and a 1 m/s constant sliding speed. Scanning electron microscopy was used to characterise the features of the wear surfaces, subsurface regions and debris particles. The wear mechanism of the CuZn39Pb3 alloy was mainly adhesive under both under atmospheric and vacuum conditions; however, some indications of abrasion were observed under atmospheric conditions. The wear rate of the CuZn39Pb3 was lower under vacuum conditions. Furthermore, increasing the applied pressure noticeably
increased the wear of the alloy under atmospheric conditions but only slightly increased it under an $8 \times 10^{-6}$ mbar. Extensive subsurface deformation was observed for the alloy tested in air.

**O.A. Zambrano, Yesid Aguilar, Jairo Valdés, S.A. Rodríguez, J.J. Coronado (2015) [123]** In this study a pin-abrasion test with 220 grit garnet paper as the counterbody, three austenitic steels of different SFEs were compared. The steels were: (i) FeMnAlC, (ii) Hadfield steel, and (iii) AISI 316 L steel. Following a pre-conditioning procedure, the normal loads on the 3 mm diameter test pins were 5 N, 10 N and 15 N, and the sliding speed along a spiral track of total length 430 m was 0.158 m/s. Data showed that the FeMnAlC steel had a higher wear resistance than AISI 316 L steel but lower wear resistance than the Hadfield steel. However, at the highest test load, all three steels had similar wear resistance. The steel with the lowest SFE had the highest abrasive wear resistance and the steel with the highest SFE had the lowest abrasive wear resistance. The main wear mechanisms were microcutting and microploughing. There was a transition from microploughing to microcutting as the normal load was increased.

**Yusuke Morioka, Yuki Tsuchiya, Masatoshi Shioya (2015) [124]** In this work, the abrasive wear, fatigue, and tensile properties of polyamide 6 (PA6) dispersed with titanium carbide particles, aluminum borate whiskers, and vapor-grown carbon fibers were determined. Moreover, the correlation between them was investigated using the equation $W_s = \frac{gf}{kH}$, where $W_s$ is the wear rate, $g$ is the shape factor of the abrasive particles, $f$ is the fracture probability, $k$ is a constant, and $H$ is the microhardness. The value of $1/f$ represents the number of deformation cycles imposed by the abrasive particles until a local fracture occurs.
at the material surface. At a low sliding velocity, a correlation was observed between $1/f$ and the low stress fatigue life. At a high sliding velocity, $f$ approached unity and a correlation was found between the wear rate and the tensile fracture work, which is in agreement with the Ratner–Lancaster plot.

Richard Waudby, Gwidon Stachowiak, Marcin Wolski, Pawel Podsiadlo, Mark Gee, John Nunn, Carsten Gachot, Lawrence L (2015) [125] In this work the effect of surface roughness and topographical orientation on friction and wear has been investigated for diamond like carbon (DLC) coated and uncoated steel surfaces with three levels of surface roughness in the range of $0.004–0.11 \mu m$ $R_a$ value and with topographical orientations at $0^\circ$, $45^\circ$ and $90^\circ$ angles from grinding marks. In this first part we report the experimental observations that form the basis for future computational modelling of the tribological effects and mechanisms. The surfaces were characterised by the scanning electron microscopy (SEM) and focused ion beam (FIB) method and mechanical properties were measured. In the topographical characterisation measurements included the fractal signatures, the texture aspect ratio signatures and the texture direction signatures were measured and calculated by the variance orientation transform (VOT) method. The friction and wear were measured and observed in scratch testing, micro tribological testing and linear reciprocating testing in three directions of topographical orientation, as well as in rotational pin-on-disc testing. The topographical orientation had considerable effect on both friction and wear in DLC vs DLC contacts while the effect was minor and sometimes not even observable in steel vs steel contacts. A surface strengthening effect which is higher for smooth DLC surfaces and micro-cracking and micro-delamination on asperity tips at low loads for rougher surfaces is reported. The $45^\circ$ orientation resulted in higher friction and
considerably higher ball wear in linear reciprocating pin-on-plate testing of DLC surfaces compared with the 0° and 90° orientations.

E. Falconnet, J. Chambert, H. Makich, G. Monteil (2015) [126] This work presents a combination of finite element simulations of copper alloy thin sheet blanking and a wear algorithm based on Archard formulation for abrasive wear of the punch. Firstly, a tribometer has been specifically designed to measure wear coefficient, and punch worn profiles have been extracted by means of a double-print method. Secondly, the blanking process has been simulated through the finite element method by using an elasto-plastic constitutive model and the shear failure model. Thirdly, a wear algorithm has been programmed using experimental wear data and mechanical fields computed from blanking simulation. Then, a damage criterion, namely the shear failure model, has been calibrated by an original method based on stress triaxiality analysis and shear height value measured from blanked edge profile. Finally, punch wear predictions have been discussed and compared to experimental results.

F.L. Miguel, R. Müller, A. Rosenkranz, S. Mathur, F. Mücklich (2015) [127] The work here described aimed to assess the tribological behaviour of a Ni-matrix-nanocomposite film and to gain understanding of the role that the reinforcing phases play in it. The composite consisted of an array of Ag-coated SnO₂ nanowires grown onto a substrate, around which the Ni matrix was galvanostatically deposited. Friction and wear were evaluated under dry sliding conditions using a linearly reciprocating ball-on-flat setup, with a diamond ball of 5.8 µm radius as counterbody, subjected to loads ranging from 5 to 30 mN. The surface and cross section of the wear tracks were characterised by scanning electron microscopy, energy-dispersive X-ray spectroscopy and white light
interferometry. Ploughing-type abrasive wear was observed, with load-dependent dynamic friction coefficients, being this attributed to scale effect. Numerical models were developed for the analysis of wear volume and wear rate, as function of film hardness, applied load and wear track length. Due to their higher hardness, the composite films exhibited superior wear resistance with respect to Ni films produced using the exact same bath and deposition parameters as the composite's matrix. This was evidenced by reductions of up to 74 and 65% in wear volume and rate, respectively.

S. Hernandez, J. Hardell, H. Winkelmann, M. Rodriguez Ripoll, B. Prakash (2015) [128] In many industrial applications the occurrence of abrasive wear results in failure and replacement of components. Examples of these applications are found in mining, mineral handling, agriculture, forestry, process and metalworking industry. Some of these applications also involve operation of relatively moving surfaces at elevated temperatures which increases the severity of wear. A typical example of high temperature wear phenomena is that of tool steels during interaction with boron steel in hot forming. Some studies have been carried out regarding the high temperature tribological behaviour of these materials but results pertaining to their high temperature three body abrasive behaviour have not been published in the open literature. In this work, the high-temperature three body abrasive wear behaviour of boron steel and two different prehardened tool steels (Toolox$^{33}$ and Toolox$^{44}$) was investigated using a high temperature continuous abrasion machine (HT-CAT) at different temperatures ranging from 20 °C to 800 °C using a load of 45 N and a sliding speed of 1 ms$^{-1}$. The wear results were correlated to the hot hardness of the different materials measured by means of a hot hardness tester (HHT) at a load of 10 kgf. Scanning electron microscopy and energy dispersive spectroscopy (SEM/EDS) techniques
were used to characterise the worn surfaces. The hot hardness measurements of the three different materials showed a slight but continuous decrease of hardness from room temperature to 600 °C. At temperatures above 600 °C the hardness showed a sharp decrease. The wear rate of Toolox$^{44}$ was constant from 20 °C to 400 °C. On the other hand, Toolox$^{33}$ and boron steel, showed a reduced wear rate from 20 °C to 400 °C attributed to an increased toughness and the formation of wear-protective tribolayers respectively. At higher temperatures (from 400 °C to 800 °C), the wear rate for these materials increased mainly due to a decrease in hardness and the occurrence of recrystallization processes.
REFERENCES-CHAPTER 2


Mechanical And Physical Properties Of 7075-T6al Alloy” Engineering Failure Analysis, Volume 12, Issue 4, Pages 520-526.


