MACHINABILITY STUDIES ON CARBON AND ALLOY STEELS USING FACE TURNING

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by

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D E C L A R A T I O N

by the Ph.D. Research Scholar

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ABSTRACT

The present study is an experimental investigation on the machinability of carbon and alloy steels by face turning method. This study finds its usefulness in economic machining solution to fulfil the local objectives of knowing, in advance, the machinability of selected carbon and alloy steel material of grade**:** AISI-1050, AISI-51100, AISI-52100, AISI-4320 and AISI-9320. The face turning method makes use of cylindrical steel bar specimen as test pieces for testing the machinability of the steels. The technical effectivity of the face turning method is assessed by studying: the cutting time required for the tool to reach flank wear upto 0.3mm (tool life criterion); tool wear development and wear mechanisms involved in machining; tool life studies and machinability indices of the work-material; surface roughness and microhardness investigations (SEM) of the machined surfaces; and chip morphology and crater wear studies. These aspects are further tested and verified for its repeatability and reproducibility. The tests are being carried according to some of the guidelines laid in the international standards, ISO 3685:1993(E) and American Foundry Society (AFS) standard machinability tests. The results presented here demonstrate the ability of the face turning method to assess the tool wear development while machining different work-materials; to evaluate the tool life for each of the work-material under consideration; to differentiate very distinctly and rank these materials according to their machinability; to investigate surface finish due to tool wear and micro-hardness of the machined surface generated after the tool wear reached its tool life criterion; to analyse the chip morphologies with crater wear; and to overall characterize the machinability of steels under consideration. The face turning method used here is simple and effective for the given tool-work material pair.

Index terms: Carbon and alloy steels, Face turning, Machinability, Tool wear, Surface roughness, and Chip morphology.

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NOMENCLATURE

AA	Arithmetic Average
AFS	American Foundry Society
AI	Artificial Intelligence
AISI	American Iron and Steel Institute
ASTM	American Society for Testing Materials
BHN, HB	Brinell Hardness Number
CI	Coppini Index
CLA	Centre Line Average
C, n	Empirical constants for material and conditions used
H	Hardness of the tool
HRA	Rockwell Hardness Number, A scale
HRC	Rockwell Hardness Number, C scale
HSLA	High Strength Low Alloy steel
ISO	International Organization for Standards
K_w	Wear co-efficient
L_s	The Distance slid
MQL	Minimal Quantity Lubrication
MR	Machinability Rating
N	Normal force to the sliding interface
PM	Powder Metallurgy
Ra	Arithmetic mean deviation of profile, µm
Rq	Root mean square deviation of profile, µm
Rz	Ten point height of irregularities, µm
SAE	Society of Automobile Engineers

SEM	Scanned Electron Microscope
SPD	Surface Plastic Deformation
T	Cutting time to produce a standard amount of flank wear
TCMS	Tool Conditioning Monitoring System
V_b	Flank wear width used as tool wear criterion of 0.30 mm
V, V_c	Cutting speed
V_o	Volume of material worn away

CHAPTER 1

INTRODUCTION

Machinability is an attribute of a material characterising its ability to be machined by removing material to shape it into an engineering component. Steel machinability involves interaction of: machining process; steel chemistry and matrix structure; and inclusion chemistry and morphology. The machinability of steels is affected by many factors, such as: machining process, continuous or intermittent; cutting tool geometry; cutting fluid type and application; machining parameters like speed feed and depth of cut; and rigidity of holder and machine tool. This intricate combination makes machinability of steels an intrinsic technological property which is complex to understand and difficult to determine. Then the assessment of the machinability of steel becomes a matter of prime activity to make proper decision to improve productivity**.**

The engineering industries strive to achieve either a minimum cost of production or a maximum production rate in machining. The use of high speed machining has become more relevant in recent years. This means cutting velocities have increased many folds than normal speeds. Approximately 75% of the manufacturing activities in the industrialized countries deal with production of a small batch size with a large variety of products which are diverse in nature (Gaurav Bartarya and S.K.Choudhary 2012). Moreover every year numerous varieties of new products with new material specification enter the market. Many manufacturers encounter difficulties in selecting the most appropriate work material (Elso Kuljanic et al. 2010). Thus it is becoming increasingly necessary to relate the available engineering raw materials and semi-finished products to specify its machinability indices. Most of the manufacturers consider tool wear as the important criterion to evaluate the machinability. It is advantageous for the industries to know in advance the behaviour of wear and life of tool with respect of specific work-material grades which needs to be processed along with chemical composition and mechanical data, which by themselves is not enough to cover the machining characteristics of the material.

There are six reported types of tests to determine machinability of steels performed at specialized laboratories with complex set-ups, which are long term in nature (Hiroshi Yaguchi 2005). The main drawback in long term test is that the tools require a fairly long time before reaching the stipulated wear limit. Moreover the long term test is possible only in the industries with research and development centres where adequate recording of industrial experience is essential. Trent, E. M and Wright, P. K (2000) reported that such tests are apt to be expensive in material and manpower, not least because of the large scatter in individual test results. This work involves very careful measurement of the very small amounts of wear, the use of a microscope being essential. Judgement is required by the investigator on what is significant and what can safely be ignored. Such tests are beyond the reach of small and medium industries which are working with four and more grades/variety of commercially available steels. Thus the efforts to minimize consumption of the material and to save time on the long tests have led to the development of short time tests. Face turning operation is one of the short time and specialized test taken here as a method to test the machinability of the steels. This can be conveniently done with minimum amount of resources. Salak A., et al. (2006) has successfully demonstrated the face turning method for assessing machinability of five different grades of powder metallurgy steels where flank wear, V_b, of 0.3mm was taken as tool life criterion. Karin Bjorkeborn et al. (2008) recommended the Volvo Standard Machinability test (one of the short term) as a potential method for assessing machinability of materials. A common case hardening steel, 20MnCrS5 was chosen here for investigations. With suitable altered heat treatment four varieties of microstructures of the same steel were obtained. The Volvo test here made it possible to rank the work-material by tool wear with relatively small samples and low material volumes. The authors stated that approximately 800 mm length of bar and 50 mm in diameter is needed for testing a material and the other traditional test with respect to tool wear are more costly to perform, both in time and material consumption. Trent, E.M and Paul Wright, P.K (2010) reported tool testing standards set by Taylor, F.W (1908). These tests were all carried out by lathe turning of very large steel billets using single point tool. Such elaborate tests have been too expensive in time and manpower to repeat frequently, and it has become customary to use standardized conditions, with cutting speed and feed as the only variables. The results are presented using what is called Taylor's equation, which is Taylor's original relationship reduced to its simplest form

$$V\,T^{n} = C \tag{1}$$

Where V = cutting speed,

T = cutting time to produce a standard amount of flank wear and

C, n = empirical constants for the material or conditions used.

There is no published data regarding machinability studies of carbon and alloy steels using face turning. The aim of this research work is to present: tool wear development and wear mechanisms involved in machining; tool life studies; machinability ranking and indices of the work-material; surface roughness and micro hardness investigations (SEM) of the machined surfaces; and chip morphology and crater wear, using face turning method.

CHAPTER 2
LITERATURE REVIEW

Exhaustive literature is available on the machinability of steels. This chapter gives brief narration of significant research, specifically related to 'Machinability studies of carbon and alloy steels', till this date. The standard and specific literature survey includes the topic which characterises the machinability aspects in sequential order: machinability test methods, machinability index and its evaluation approaches; tool wear and tool life, surface roughness and surface integrity studies; micro hardness and SEM investigations; and chip morphology and crater wear studies. The literature survey also includes interaction of cutting parameters with respect to the work materials undertaken for the present work. The brief summary and conclusions of the literature survey are drawn to the objectives laid in the current research at the end of chapter.

2.1 Machinability test methods

Fredrickson, G.O et al. (1954) developed a 'Method and Apparatus for Machinability Testing'. The method of determining the machinability of a steel workpiece of known composition comprising the steps of feeding an alternating current at a controllable amperage and at a predeternined voltage between two predetermined positions on the workpiece, and measuring the reactance to said current flow between two predetermined intermediate positions on said work piece.

Valembois, P.V et al.(1982) developed Optical Inspection method for determining machinability. In a method for determining the machinability of a metal substrate for use in an electromechanical recording apparatus a surface of a foundation is coated with a layer of metal. The metal layer is machined such that the metalized surface of the foundation is substantially flat and smooth. After the machining step, the metal surface is inspected for depressions with a microscope using a differential interference contrast technique. The number of depressions observed is indicative of the machinability of the coated foundation.

Zeng, J. (2000) developed automatic machinability measuring and machining methods and apparatus. Here a method for measuring the machinability of a material which includes piercing a hole through a material to be tested while simultaneously measuring a pierce time duration and calculating a machinability number from the pierce time duration. The apparatus includes any of a pressure sensor, an acoustic sensor, an optical sensor, a load cell, a mechanical switch and combinations thereof to measure the pierce-time duration.

Hiroshi Yaguchi (2005) reported six methods of machinability testing of carbon and alloy steels that are carried out at the author’s company Inland Steel Company. The six methods are (1) Automatic screw machine test, (2) Plunge test, (3) Drill force test, (4) Single-point turning test for carbide tools, (5) Single-point turning test for high speed steel tools and (6) Drill eccentricity test. The first one is a long term test in which various machining operations such as drilling, forming and parting are performed in sequential fashion. The part growth and roughness’s are the responses that are used to characterise the machinability of these materials. Also this method requires a large amount of steel, close monitoring and manpower. The second test is a bit modification of the first one with less amount of steel required, whereas other aspects are similar to the first test. The third test is not used to characterize machinability but to present only relative rating of machinability. The fourth and fifth test uses modified form of ISO 3685-1977(E). Here, machinability is compared based on either wear rate at a common cutting speed among all the samples tested or the higher cutting speed used to reach a certain length of tool life, which is determined by the length of flank wear. The sixth test is another test requiring specialised skill to monitor the entire test process.

Venkatrao R. (2006) discusses machinability evaluation of work materials using a combined multiple attribute decision-making method and presented a logical procedure to evaluate the machinability of the work material for a given machining operation and also proposed global machinability index to evaluate and rank the work materials. The proposed method is used: to select the best work-tool combination for a given machining operation; and to find proper cutting conditions for machining the given work material.

Salak A. et al. (2006) presented a short time face turning as a new method for machinability testing of PM steels, using common ring shaped test specimens, performed at constant revolutions of the lathe. The method was tested on five different grades of Fe–C and Distaloy type materials. The critical number of cutting passes up to a tool flank wear of V_b= 0.3 mm, critical time, critical volume of removed material, surface finish and morphology of the chips were the criteria for checking the technical effectivity of the applied method. The results attained show that the face turning test method used here is simple and easy and can fulfil many requirements for assessing the machinability of PM steels in turning. The authors also confirmed here the sensitivity of the test method used to the workpiece material properties with regard to the evaluated criteria, as, e.g. critical number of passes up to flank wear of the tool V_b-0.3 mm, critical time to test an alloy, critical volume of removed material, surface finish and morphology of the chips.

Karin Bjorkeborn et al. (2008) recommended the Volvo Standard Machinability test (one of the short term) as a potential method for assessing machinability of materials. A common case hardening steel, 20MnCrS5 was chosen here for investigations. With suitable altered heat treatment four varieties of microstructures of the same steel were obtained. The Volvo test made it possible to rank material by tool wear with relatively small samples and low material volumes. The authors stated that approximately 800 mm length of bar and 50 mm in diameter is needed for testing a material and the other traditional test with respect to tool wear are more costly to perform, both in time and material consumption.

Coppini et al. (2009), discusses and proposes new approach for applications of machinability and machining strength under a new point and index called Coppini Index(CI). The reliability of the proposed test was based on experimental data from the literature. The best way to apply machinability index and machining strength index is put forward. Otherwise, at this moment, the authors are doing experimental laboratory research to evaluate the best way to organize appropriate samples to attend different kind products for respective materials makers.

Arriola et al.(2011) made an attempt to develop a practical tool for the scientific design of more machinable materials by short run test and to reduce the need for tedious, time consuming and expensive machinability tests, ISO-3685. The relationship between machinability index of the analyzed steels and in-process parameters (feed forces, temperature and plastic strain) measurements results was determined. Lower feed forces, lower friction values, lower temperatures and higher plastic strain values correlate with better machinability index.

2.2 Machinability Index Evaluation Approaches

Table 2.1: Machinability ratings in percentage of various common metals

AISI Steel	MR	Hardness Brinell
C1109	85	137-166
C1115	85	147-179
C1118	80	143-179
C1132	75	187-229
C1137	70	187-229
B1111	90	179-229
B1112	100	179-229
B1113	135	179-229
A4023	70	156-207

Elso Kuljanic et al. (2010) summarized various machinability evaluation approaches. The authors states that the first publications in machinability of steel rating were done by Sorenson.J and Gates. W in 1929. A graphical representation of the general relation of machinability ratings - relative cutting speeds to hardness for hot-rolled SAE steels was made. A 100% rating was given to SAE 1112 steel cold rolled. Later on in 1943 Boston et al. published a general machinability index-rating for more common metals and alloys as in Table 2.1 (Annealed prior to cold drawing or cold rolling in the production of the steel specially mentioned). The ratings are expressed in terms of relative values. These figures are often called “percent machinability”, and are representing the relative speed to be used with each given material in order to obtain a given tool life. For example, a material whose rating is 50 should be machined at approximately half the speed used for the material rating 100, if equal tool life is desired for either of them. The rating values in Table 2.1 are based on a

Table 2.2: Machinability ratings in grades of some common stainless steel (hot-rolled, annealed)

AISI Steel	Hardness Brinell	MR
410	135-165	C
416	145-185	A
430	145-185	C
446	140-185	C
302	135-185	D
303	130-150	B
316	135-185	D

A – Excellent, B – Good, C – Fair, D - Poor rating of 100 for steel AISI B1112, cold rolled or cold drawn when machined with a suitable cutting fluid at cutting speed, V_c = 56 m/min under normal cutting conditions using high-speed-steel tools. In Table 1 the ratings given for different classes of alloys, represent their relative machinability within a given class, but the ratings for any class is not comparable with those for any other class.

The second approach in machinability rating is in terms of equivalent cutting speed. The cutting speed number is the cutting speed which causes a given flank wear land in 60 minutes. Such a cutting speed is called economical cutting speed. However, the tool life of 60 minutes is not always economical any more. At times the economical tool life for minimum machining cost is about 10 minutes or less in turning. Therefore, the corresponding cutting speed in such cases is much higher than the tool life of 60 minutes.

The third approach in machinability ratings represents relative cutting speed values where the ratings are given as letters, Table 2.2. “A” indicates a high permissible cutting speed and “D” a lower cutting speed.

The fourth approach is the correlation of tool life and the microstructure of the metal. Generally speaking hard constituents in the structure (oxides, carbides, inclusions) result in poor tool life, and vice versa. In addition, the tool life is usually better when the grain size of the metal is larger. Woldman (1947) studied the correlation of microstructure of steels and tool life. Average relations of tool life and surface finish to microstructure of steel were reported as “good”, “fair”, “fair to good” and “poor” as in Table 2.3.

Table 2.3: Relation of tool life and surface finish to microstructure of steels

Class of steel	**Structure**	**Tool Life**	**Surface Finish**
Low – carbon steels	Cold drawn, small grain size	Good	Good
	Normalised	Good	Fair
Mild medium carbon steel	Pearlitic, moderate grain size	Good	Good
	Pearlitic, small grain size	Fair	Good
	Pearlitic, large grain size	Good	Fair
	Spheroidized	Fair	Poor

Machinability index is an approximate value indicating the machinability of different engineering materials. Such information can be useful in the design of mechanical parts. For example, if there are different materials that can be used for a given part and have different machinability index, the material with greater machinability index should be chosen in order to increase the productivity and decrease the machining cost. It has to be pointed out that data published approximately 70 years ago reflect the workpiece materials and especially the tool material which were very different from those in use today.

2.3 Tool wear and tool life

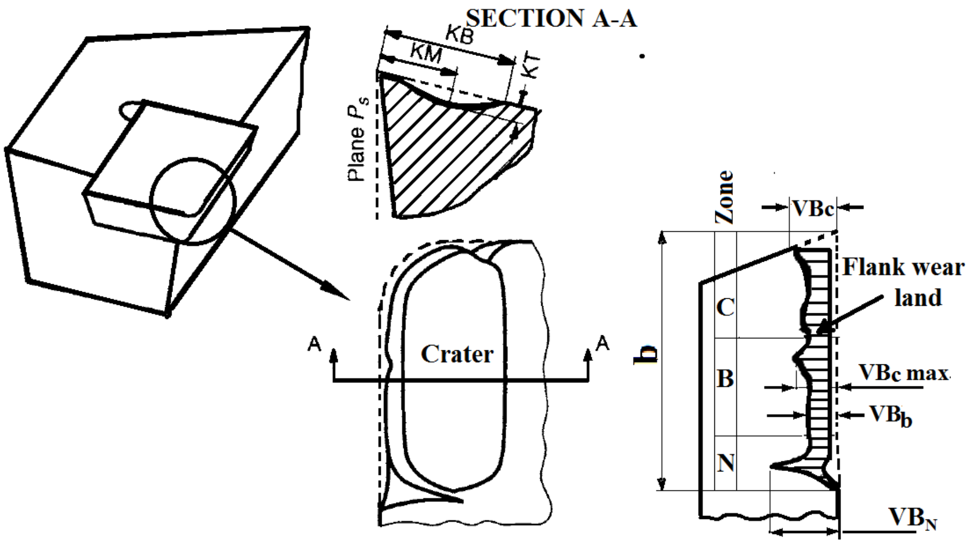


Figure 2.1: ISO Characterization of flank wear land and rake face wear crater

ISO 3685:1993(E) is an international standard for tool-life testing with single-point turning tools which contains recommendations applicable to both laboratories and manufacturing units. This standard can be used with suitable modifications for specific applications. It states that flank wear is the best known type of tool wear which has uniform width along the middle portion of the straight part of the cutting edge. The width of the flank wear is easy to measure. The growing width of the flank wear land leads to a reduction in the quality of the tool. The crater wear occurs on the rake face which can be measured as additional information but should not be used as tool-life criteria. Further surface roughness, cutting forces, and temperature may be measured as additional information only and is not covered in this standard. Chip formation is normally not recommended for determining tool life but, however it is useful as a ‘control instrument’.

Trent, E. M (1958) clearly stated that flank wear occurred under all cutting conditions and does not follow the same laws as cratering, build-up and deformation. There are often no critical changes in the rate or type of flank wear with varying cutting speed and feed, except those associated, for example, with deformation, which already delineated. The flank wear occuring in short time cutting tests has been studied. The results suggest that the rate of wear is greatly influenced by the pattern of temperature distribution and flow of the work material around the cutting edge .

Hong Tsu Young (1996) studied the cutting temperature responses to flank wear.Tool wear has been shown to be strongly temperature dependent and therefore an attempt can be made to measure and control the cutting temperature with a view to obtain optimum machining conditions.

Valery Marinov (1996) analyzed the influence of cuting conditions and parameters of the abrasive inclusions in the work material on the amount of abrasive wear of the carbide cutting loads. The results show that abrasive wear increases approximately linearly with the cutting temperature due to the change of the abrasive capability of some abrasive inclusions with work hardness comparable with that of the tool material. Another conclusion is that the amount of the worn metal increases to some extent with the size of the abrasive particles due to the larger size of the carbide conglomerates split off by the particles when they move along the tool surface.

Lim, .C.Y.H et al. (2001)studied the effects of work material on tool wear. Wear maps showing the wear behaviour of titanium carbide (TiC)-coated cemented carbide tools during dry turning of various types of steel have been presented in earlier studies. The maps have demonstrated that tool wear rates vary with cutting speeds and feed rates used. They have also shown that there is a range of cutting conditions, called the safety zone, within which tool wear rates are the lowest. Wear rate maps constructed for the machining of AISI 1045 and AISI 4340 steels show that flank wear rates are at least half an order of magnitude larger when machining the latter grade. It is believed that greater hardness, toughness and strength of the AISI 4340 grade result in higher cutting stresses and tool temperatures, leading to more severe flank wear. The wear maps also show that despite differences in actual wear rates, the contours of the two maps are similar at low to moderate cutting speeds and feed rates. However, the transition to severe flank wear occurs at lower cutting speeds and feed rates in AISI 4340 steels. This transition is not reflected accurately in the wear map for various grades of plain carbon and low-alloy steels presented in previous investigations. Nevertheless, the contour and location of the safety zone in all three wear maps are similar, suggesting that wear maps specific to the work material may not be necessary. The earlier map for general grades of steel remains a useful starting point in the selection of the machining conditions that will combine a maximum rate of metal removal with an acceptable level of tool wear.

Sumit Kanti Sikdar and Mingyuan Chen (2002) studied the relationship between flank wear area and cutting forces for turning operations of AISI 4340 steel with a single point carbide tool insert. The study indicates a good correlation between cutting forces and the three-dimensional flank wear surface area in turning operations. All cutting forces increase with the increase of the flank wear surface area. Increasing flank wear area results in an increasing area of contact between the tool tip and the workpiece. The greater the value of the flank wear area, the higher the friction of the tool on the workpiece and high heat generation will occur, this ultimately causes the higher value of cutting force. The rate of increase (the tangential force increases by 6%, the axial force increases by 13% and the radial force increases by 64%) of axial and radial cutting force is higher than the tangential cutting force, when tool insert begins to fail.

Tay, Francis et al. (2002) studied the topography of the flank wear surface and presented the relationship between the maximun flank wear and the topography parameters (roughness parameters) of the flank wear surface during the turning operation. The greater the roughness value of the flank wear surface, the higher the friction of the tool on the workpiece, so that greater heat generation will occur, which ultimately causes tool failure.

Flank wear of cutting tools is often selected as the tool life criterion because it determines the diametric accuracy of machining, its stability and reliability. Viktor P. Astakhov (2004) argues that the existing criteria of flank wear are insufficient for its proper characterization. Their existence is due to the lack of knowledge on the contact conditions at the tool flank-workpiece interface. The properties of the work and tool materials, tool geometry and the cutting regime determine the contact phenomena of the tool-workpiece interface. As such, the cutting speed has the strongest influence. The current paper compares different characteristics of the evaluation of flank wear. In the machining of difficult-to-machine materials and in high speed machining, plastic lowering of the cutting edge is the predominant cause of premature tool breakage. This lowering is a result of high-temperature creep of the tool material. The contact process at the mentioned interface is analysed through the experimental assessment of the contact stresses, and the full validity of Makarow's law is confirmed, i.e. 'minimum tool wear occurs at the optimum cutting speed'. A new concept of tool resources is proposed and discussed. This resource is defined as the limiting amount of energy that can be transmitted through the cutting wedge until it fails.

Boulger Francis (2005) discusses various aspects of machinability of steels. The machinability of carbon and alloy steels is affected by many factors: such as composition, microstructure, and strength level of steel; the feed, speeds, and depth of cut; and the choice of cutting fluid and cutting tool material. The measures of machinability are based on: tool life; cutting speed; power consumption; comparison with standard steel based on experience in machine shops; quality of surface finish; and feeds resulting from a constant thrust force.

Alden Kendall (2005) discusses in detail: the wear environment; wear mechanisms; machine, cutting test and tool wear interactions; tool replacement; tool life testing; and future trends. Cutting tool wear is localized on specific surfaces where stress, strain, velocity, and temperature are above critical levels. It is important to understand where these critical conditions exist and how they interact to cause tool wear. He describes the phenomenon of three wear mechanisms (initial, steady state, and tertiary) and it exists in all types of tool wear. A detailed in-house tool life testing program points have been discussed. Depending on off-line laboratory testing and model development will eventually become too costly and time consuming for the current and future automated machining systems. Local data bases that store performance information concerning to the production of each feature will be able to access the progressive wear of the tool more precisely.

Luo, X. et al. (2005) developed a flank wear rate model for accurate prediction of tool flank wear land width with minimum cost. The model is based on the cutting force, cutting temperature simulation and empirical model. The new tool wear rate model is also evaluated by the cutting tests. Results of the tool wear cutting test indicate that cutting speed has more dramatic effect on tool life than feed rate.

Bouzid Sai, W. (2005) investigated tool wear in high speed turning of AISI 4340 steel. A commercially available coated insert has been used to turn an AISI 4340 steel at speeds placed between 325 m/min and 1000 m/min. The flank wear was measured in connection to cutting time. This is to determine the tool life defined as the usable time that has elapsed before the flank wear has reached the criterion value. It is shown that an increase in cutting speed causes a higher decrease of the time of the second gradual stage of the wear process. This is due to the thin coat layer which is rapidly peeled off when high-speed turning. The investigation included the realization of a wear model in relation to time and cutting speed. An empirical model has also been developed for tool life determination in connection with cutting speed. On the basis of the results obtained it is possible to set optimal cutting speed to achieve the maximum tool life. A wear equation is proposed to describe the three stages of the wear process. For cutting speeds higher than 650 m/min, the tool life remains constant, so it is advantageous to use high values of cutting speed.

Factors such as cutting speed, feed rate, tool material, etc., are well known to have an effect on tool wear in metal turning. However, reliable methods of wear prediction over a broad spectrum of cutting circumstance remain elusive, suggesting that not all factors have been recognised as significant and thus considered. Boud (2007) studied the finding that bar diameter has an influence on tool temperature and, by implication, on tool wear. Thus, a factor not previously considered in wear theories in turning is shown to be significant. This finding is put forward to exemplify the need to identify all parameters influencing temperature and heat flow before theorising on tool wear. Such identification enables an objective benchmark to be set for assessing the validity of existing theories on wear.

Yahya Isik (2007) conducted a series of test in order to determine the machinability of tool steels. The tests have been done under various combinations of speed, feed and depth of cut. This study presents a different approach to investigate the correlation of tool wear, tool life and surface roughness. Cutting speed is the most influential parameter on tool life, feed rate is the second most one, and cutting depth is the least influential parameter. At the end of the tool life, considerable increase in cutting forces are observed, but the increase rate varies according to the cutting tool and the workpiece. The amount of flank wear and the cutting force are appropriate parameters to determine the tool life. Prediction of tool wear becomes possible on condition that the cutting speed range, recommended for the tools, is employed.
Beside the increase in the cutting forces, complications concerning the surface quality and dimensional tolerances, increases in vibration and heat are all indicators of that the wear amount has increased and the tool has come to the end of its tool life. In the experiments which were conducted by using coated tools, it was observed that the flank wear is a more influential parameter for the fracture than the crater wear. There is a direct relationship between cutting forces and flank wear. But it is always possible that the tool fracture occurs unexpectedly.

Taylor, F. W (1906) has done extensive investigation on machinability testing to find an answer for the three significant questions: “What tool shall I use? What cutting speed shall I use? What feed shall I use?” After so many years and with availability of modern facilities, still there are difficulties to find the right answer to the above questions.

Michael Finn (2008) developed and proposed American Foundry Society (AFS) machinability test for evaluating the machinability of cast iron as the standardized test in his presentation. The International Standards Organisation specification for the machinability test in long turning steel bars was modified for face turning cast iron discs using an uncoated tungsten carbide insert to machine four grades of cast iron: two grades of ductile cast iron, ASTM A536 65-45-42 and 80-55-06; and two grades of gray cast iron, ASTM A159 G1800 and G3000. Except speed all the cutting parameters were common for all the work materials and flank tool wear was noted for each of the workmaterial. A Taylor curve was plotted for each of the work-material using the three different cutting speeds against flank tool wear. The machinability of the workmaterial was determined for 30 minutes of tool life, V_{30} . The validation of V_{30} for all the work material was done was done on another machine.

Attanasio, A et al. (2011) suggested that crater wear rate is influenced by both cutting speed and feed rate, while flank wear rate seemed to be mainly effected by cutting speed. This can be related to the wear mechanisms. When the crater wear is present, the wear mechanisms are the abrasion, deeply affected by cutting speed, and the diffusion, heavily influenced by cutting temperature. On the other hand, the flank wear mechanism is mainly due to abrasive phenomena which are strongly affected by cutting speed. Furthermore, it was found that the thickness of white and dark layers increase with increasing of tool flank wear. Moreover, higher cutting speed generates thicker white layers and thinner dark layers. In addition, smaller feed rates moderately influence the white layers thickness, while the latter rises with higher feed rate. In contrast, the dark layer thickness decreases with the increasing of the feed rate.

Ali Riza Morecu (2011) studied tool wear performances; wear mechanisms, surface roughness characteristics of AISI 52100 steel. The cutting speed had the greatest effect on the optimal testing conditions followed by the cutting tool’s hardness. The feed rate was also effective on the tool life of the cutting tool. It was shown that the cutting tool life was decreased with increasing cutting speeds in all cutting conditions. Finally he concluded that among all the cutting parameters, the cutting speed was found to be more effective for the tool life and a negligible effect for the surface roughness, but the feed rate was dominant for the surface roughness.

Michael Finn (2012) in his presentation discusses many aspects of Machinability Testing of steels. He enlisted some standard machinability tests: ISO 3685-E Spec

(Long Turning); ISO 8688-1-E Spec (Face Milling); ISO 8688-2-E Spec (End Milling); ASTM E618-81 Spec (Form Turning); Inland Steel Plunge Test (Plunge Turning); and AFS standard Machinability Test (Face Turning) and yet today he finds that 'machinability' still is an issue which needs to be addressed specifically. He proposed technical road map to handle the machinability related issues. He also promotes the idea of internal tool life standards.

Siddhapura, A and Paurobally, R (2013) reported that flank wear is the most commonly observed and unavoidable phenomenon in metal cutting. A wide variety of monitoring techniques have been developed for the online detection of flank wear. In order to provide a broad view of flank wear monitoring techniques and their implementation in tool condition monitoring system (TCMS), this paper reviews three key features of a TCMS; signal acquisition; signal processing and feature extraction; and artificial intelligence techniques for decision making. As many as 132 publications were discussed on tool condition monitoring or tool wear detection in turning only along with their benefits and limitations.

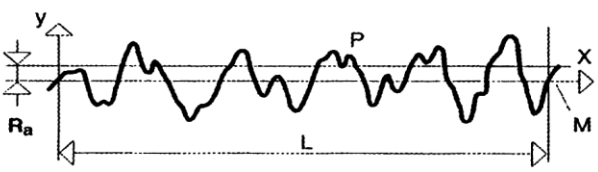


Figure 2.2: Ra of a surface profile P on a sampling length L

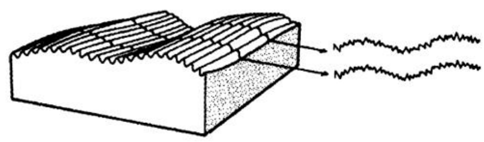


Figure 2.3: Parallel surface profiles on a turned surface

2.4 Surface roughness

Kopac, J and Bahor, M (2001) made analysis of surface roughness of fine turning process on workpieces with different work materials and technological past. The technological past of the workpiece material is very important input data in planning technological processes, but it is in practice sometimes unknown because of bad transparency or past technological operations. This is essential as the workpiece undergoes different destructive and non-destructive testing methods for assessing the required mechanical and chemical properties. These work-materials previously undergo hot-rolling, normalizing, annealing, cold-drawing, tempering or hardening.

Thus workpiece material properties and its machinability can differ from one steel to steel in spite of the same chemical structure.

Surface texture is an important quality characteristic of the machined surface. The authors concentrates on surface roughness as it is control variable. Roughness average (Ra) on the sampling length L is the arithmetic average value of the distance of the profile from the centre line throughout the sampling length (figure 2.2). Roughness average is in some literature denoted as CLA (center line average), although in America the term AA (arithmetic average) has been used. Mathematically, Ra can be calculated as:

$R_a = (y_1 + y_2 + \ldots\ldots.. + y_n) / n$ (2)

Characteristics of the roughness average (Ra) are as follows:

1. The Ra value over one sampling length represents the average roughness, therefore the effect of a single spurious, non-typical peak or valley will be averaged out and has only a small influence on the Ra value;

2. Usually in practice, assessments are made over several consecutive sampling lengths and then the average is accepted as the Ra value; this ensures that the Ra is typical for the examined surface;

3. The direction of measurement is very important for roughness assessment and depends on the kind of machining operation and on the shape of the workpiece;

4. The Ra gives no information about the shape of the irregularities or the profile;

5. The Ra value is in micrometer (mm) or micro inch (min) units

6. The Ra does not give full information about the surface roughness, because the same Ra value can be measured on different types of surfaces. Therefore to overcome that, the value R_{max} is very often added.

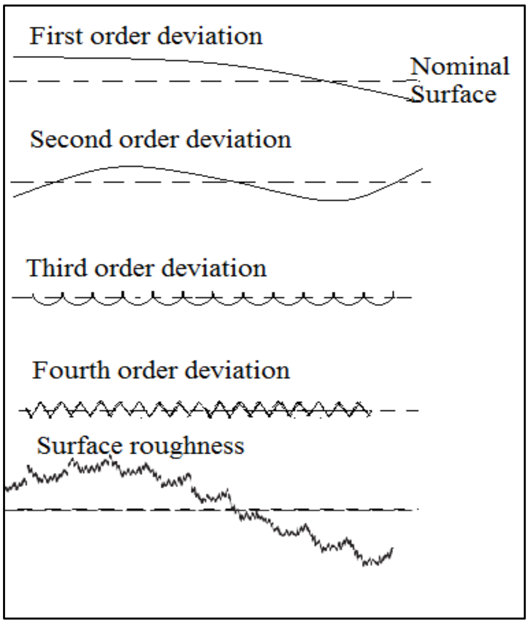


Figure 2.4: Surface form deviations

The usage of roughness average Ra is limited and is inappropriate for the characterization of very rough, very smooth and very short surfaces. The surface texture of the machined surface is fortunately the same within a proportionally large region. This means that if the surface roughness profile is assessed on two parallel locations of the examined surface, then only small differences can be noted `between, surface profiles. They differ one from another just in small details (figure 2.3). This fact enables us to control specified surface texture through the measurement of particular characteristics of the machined surface.

The effect of alloying elements and its corresponding mechanical properties of the samples were also assessed by the surface roughness. The roughness of the machined surface was taken both as mean value of the highest roughness peaks R_z and the mean arithmetic deviation of the roughness Ra.

The authors have analyzed the interaction between workpiece material and machining conditions for the two tempered steels which are frequently used in practice. Experimental results show what machining parameters have to be used at different combinations of cutting tool-workpiece material for the achievement of desired roughness of the machined surface.

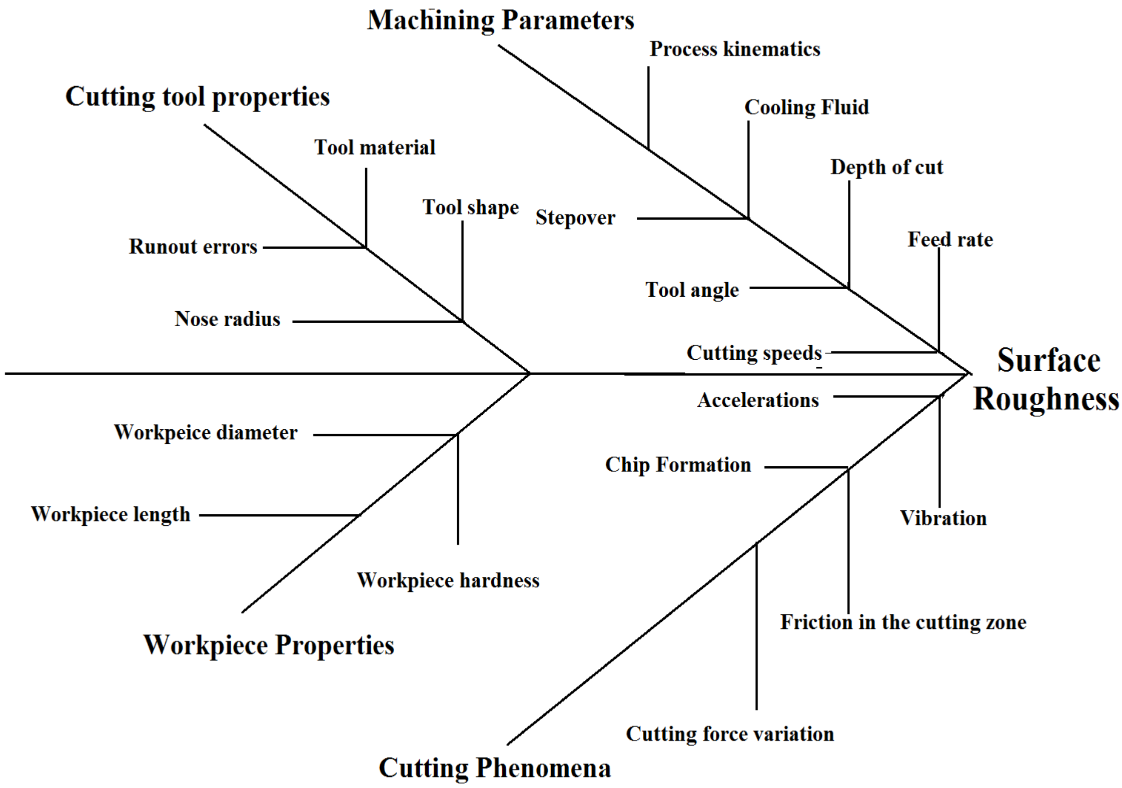


Figure 2.5: Fish bone diagram with the parameters that affect surface roughness

Benardos, P.G and Vosniakos,G.C (2003) discussed and presented various methodologies and strategies that are adopted by researchers in order to predict surface roughness. The author discusses various surface form deviations as shown in figure 2.4. Surface roughness refers to deviation from the nominal surface of the third up to sixth order. First-order and second-order deviations refer to form, i.e. flatness, circularity, etc. and to waviness, respectively, and are due to machine tool errors, deformation of the workpiece, erroneous setups and clamping, vibration and workpiece material inhomogenities.

Third-order and fourth-order deviations refer to periodic grooves, and to cracks and dilapidations, which are connected to the shape and condition of the cutting edges, chip formation and process kinematics. Fifth-order and sixth-order deviations refer to workpiece material structure, which is connected to physical–chemical mechanisms acting on a grain and lattice scale (slip, diffusion, oxidation, residual stress, etc.). Different order deviations are superimposed and form the surface roughness profile. All the methodologies that are presented in this paper have certain advantages and disadvantages when compared to one another, but AI is seen to be most promising approach of all. Finally, the author presents the set of parameters that are thought to influence surface roughness is diagrammatically displayed in figure 2.5.

Radu Pavel et al. (2005) presented the aspects related to surface quality for a case of interrupted and continuous hard turning. New findings concerning the evolution of common surface roughness parameters as well as the evolution of surface topography with the increase of tool wear are presented. A good correlation between flank wear aspect and machined surface were observed. The major wear mechanism was found to be the abrasion of the binder material by the hard particles of the workpiece. The analysis of surface topography confirmed that the negative of the flank wear profile is replicated on the machined surface. A `strong correlation between evolution of notch wear and that of surface finish was observed.

Cemal Cakir. M et al. (2009) presented a mathematical model of cutting parameters for predicting surface roughness. Among the cutting parameters, the feed rate has the greatest influence, followed by the cutting speed. Higher feed rates lead to higher roughness values, whereas cutting speed has a contrary effect and cutting depth has no significant effect.

Ebrahimi, A and Moshksar, M. M (2009) conducted an experimental investigation to determine the effects of cutting speed, feed rate, hardness, and workpiece material on the flank wear land and tool life of coated cemented carbide inserts in the hard turning process. The authors found that at low cutting speeds, in the range of 10-50 m/min, the flank wear of the tools were adhesive, abrasive and fracture of fatigue. For AISI 1045 and AISI 5140, because the existence of the hard particles of molybdenum and chromium in substrate of these materials, adhesive wear and micro chipping were the main factors of damage. At low cutting speed, each of material shows the high cutting forces, and then for high cutting speed these forces are reduced. The reason of the high cutting force at low speed was the low temperature and formation of BUE on the contact zone. In addition, because of high temperature at increased cutting speed, cutting forces decreased and plastic deformation occurred.

2.5 Surface integrity and chip morphology studies

Meng Liu et al. (2004) studied the effect of the tool nose radius and the tool wear on the residual stress induced in hard turning process. With the increase of the tool wear, the residual compressive stress beneath the machined surface increases remarkably. The effect of the nose radius on the residual stress distribution decreases greatly with the increase of the tool wear.

Jawahir, I. S et al. (2011) proposed and summarized recent advances of surface integrity in material processes. The extensive Round Robin study conducted with 12 participants from 9 countries reveal the experimental process capability for producing surface integrity parameters such as surface roughness, hardness, depth of SPD layer and the associated residual stresses in a range of machining operations such as turning, milling, grinding, EDM, etc. Five different workmaterials: AISI 316L, AISI 1045, AISI 52100, IN 718 and Ti-6A-4V were studied for the analytical and numerical predictive capability for surface integrity parameters in terms of cutting forces, temperature and residual stresses.

Virginia G. N et al. (2012) studied the effect of cutting parameters in the surface residual stresses generated by turning in AISI 4340 steel. Surface integrity of the part deteriorates with increase in cutting feed. An increase in tool nose radius implies higher tool/workpiece contact areas, that results in higher temperature due to friction and less plastic deformation (the pressure per unit area diminishes), leading to more tensile surface residual stresses, although roughness improves. The use of coated tools results in better roughness values but the surface residual stresses tend to be more tensile, because the coating acts as a thermal barrier, introducing more heat into the workpiece and therefore favouring the thermal factor that leads to tensile stresses.

Kevin Chou (2002) proposed an approach to apply machining as an alternative to surface hardening of steel parts. The attempt is to utilize wear land rubbing, together with mechanical loading, to achieve hardening mechanism at machined surface. An AISI 4340 steel bar was machined with 1.2 mm flank wear land (V_b) showed 30 μm deep hardened layer (49 HRC versus 29 HRC). Furthermore the machined surface has about 7% austenite volume fraction, an evidence of phase transformation, these results suggest the possibility of utilizing the machining to surface harden the parts.

Surfaces that have undergone machining usually retain properties induced during processing. Some of these properties can be undesirable thus requiring that the component undergoes further treatment. Previous studies on cutting have shown that the cutting parameters can be regulated to produce machining outcomes beneficial for component service life. Hermann Autenrieth et al. (2009) studied surface workhardening and residual stresses induced by micro cutting processes for AISI 1045 steels. The influence of the ploughing effect on residual stresses, surface deformation and work hardening, and the tool quality were investigated. Tensile residual stresses, caused by the heat generated in the material during the cutting process, were observed in all investigated specimens. An increase of the ploughing effect resulted in higher residual tensile stresses at the surfaces of the specimens. The depth of plastic deformation created in the material by the micro-cutting process also increased with an increase of the ploughing effect. A gradient in the hardness of the material was observed after micro-cutting. A systematic study of the influence of the cutting tool edge radius revealed that additional processes inherent to the machining process, namely the build-up of new edges at the tool front, can significantly influence the results of the micro-cutting process.

Ben Salem. S (2012) investigated the effect of cutting parameters on chip formation in orthogonal cutting**.** The cutting parameters influence the morphology of chip. The type and the shape of chip depend directly on the physical and mechanical properties of machined material. As the cutting speed increases, the chips become relatively ductile. Thus, more the cutting speed increases more the chips are segmented microscopically The cutting force necessary to machining is decreased when machining is carried out with a higher cutting speed. This paper proposes some ideas for mathematical models for the cutting force and facilitates the choice of the cutting conditions in case of machining of the tool steel.

2.6 MOTIVATION AND OBJECTIVES OF PROPOSED RESEARCH

2.6.1 Summary of literature survey, research gaps and motivation

The highlights of research work on machinability studies made so far by the way of literature survey is summarised as ahead.

- The work-materials used for evaluating machinability as mentioned in the literature are past old and are meant for some special and specific purpose. Also it is doubtful that these machinability ratings could be duplicated.
- The tests of machinability for such work-materials are typically done by traditional longitudinal cylindrical turning method which is costly to perform, both in time and material consumption.
- The ability to reproduce such tests is possible at high end production/research centres and is impossible in ordinary shop floor conditions.
- Data available for machinability ratings are very disperse, old, do not have a common benchmark and not in line with the current grade of steel.
- Data for comparing and ranking machinability of variety of steels at common benchmark are not readily available either with retailer/end user or supplier. Also the available data is difficult to interpret on the local conditions.
- The study on machinability made so far are very material/process selective and does not take into account the complimentary studies of any other parameters like surface finish, work hardening and chip morphology.

Most researchers have made considerable study on machinability (using turning and milling operations) on specialised material like powder metal steels, tool steels, super alloys etc., for selecting optimum process parameters. There is a need for a simple, logical, easy and convenient procedure which affords industry with an efficient and effective means to evaluate the machinability of the work materials.

Considering the above research gaps as motivation, the work under the generalized title of "Machinability studies on carbon and alloy steels using face turning," has been undertaken for the purpose of research work, where five common grades of steels are taken for the study. This purpose shall provide useful economic machining solutions to fulfill the objectives of knowing in advance the machinability of steels.

Further the study shall demonstrate the technical effectivity of face turning method. The present research deals with the study of machinability of selected carbon and alloy steels (commonly used 5 grades) using face turning method. The face turning method of testing the machinability is cheaper, quicker, easier and reliable method of testing machinability ratings in comparison to the other available methods.

2.6.2 General objectives

Machinability is not a property of the material but an attribute. With this attribute, factors like tool life, cutting speed and surface finish has been taken as general objectives of the research under the title and problem statement of "Machinability studies on the carbon and alloy steel using face turning".

The machinability approach used herein is the machinability ratings in terms of equivalent cutting speeds which cause the stipulated flank wear, V_b-0.3mm, for 60 mins .of tool life (Elso Kuljanic et al. 2010).

The proposed study on the face turning method in the broader sense shall encompass:

- the machinability aspects of steels ranging from low carbon steel to high carbon steel which shall include alloy steels.
- the ability of the current method to detect the effect of slight change in chemical composition, microstructure and mechanical properties on the machinability.
- the effect of change in cutting speeds on : tool wear development and wear mechanisms involved in machining; tool life studies and machinability indices of the work-material; surface roughness of the machined surfaces; work hardening effects caused by face turning and chip morphology.
- the machinability ranking of group of steels varying closely in their chemical constituents namely carbon, chromium, nickel etc.
- the ability of the tested results to repeat and reproduce.

Thus the general objectives shall demonstrate and convince the ability of face turning method as a potential short time method for testing the machinability of carbon and alloy steels.

2.6.3 Specific objectives

The specific objectives for the said research as laid ahead are being undertaken according to some of the guidelines indicated in the International standard ISO-3685: 1993[E] and American Foundry Society (AFS) standard machinability tests.

1) To identify the work-material grade and geometry; tool-material grade and geometry; machining parameters and experimentation resources.

2) To determine the development of tool wear behavior and wear mechanism of the work-material for different cutting speeds by face turning.

3) To investigate the effect of slight change in chemical composition of the work-material by the face turning method

4) To investigate tool life for the work-material at different cutting speeds and establish a tool life curve [Taylor’s curve] and tool life equation model for the work-materials and validate the results.

5) To rank the work-materials according to their machinability tests by face turning operation.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Face turning method

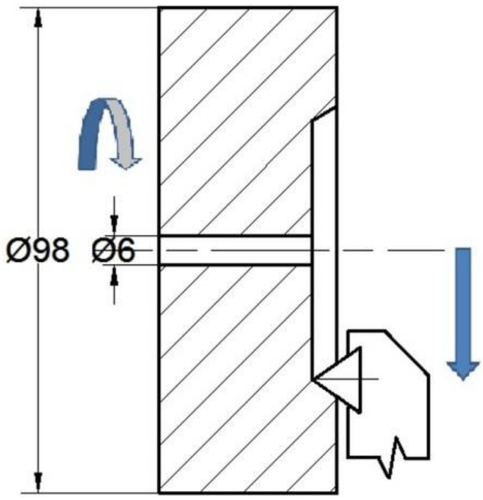


Figure 3.1: Principle of face turning method

The principle of this method is shown in figure 3.1. In this test, face turning of cylindrical standard steel bars is done from the surface of the center of the hole, ø6mm, to the circumference of the cylindrical products at constant workpiece revolutions, feed and depth of cut. After finishing the first pass, a second face turning from the center of the hole follows. The consecutive passes are repeated up to the critical flank wear (V_b) is reached to 0.3mm. This face turning test enables determining Taylor's relationship as, $V T^n = C$, where V = cutting speed, T = cutting time to produce a standard amount of flank wear and C and n are empirical constants for the material or conditions used.

This test method can represent more accurately modern production which often involves short series including mixed cutting cycles and operation. At such stage, a conventional longitudinal operation involving a large number of short (compared to total tool life) cutting and non-cutting cycles was defined by the terminology 'interrupted machining mode, (IMM) (Chandrashekaran. H 1994).This is in reality the case of this face turning method using work pieces where cut is interrupted after arriving at the outer diameter with repeated tool entry. For very short cycles below the critical time, as can be the case in this method, the tool wear can exceed the corresponding wear in continuous machining. This method can occasionally give a positive result, as interruption appears to facilitate the cooling of the tool and lowers the average temperature of tool giving realistic value of tool life.

3.2 Machining parameters

The advantage of this test is that it can be performed with comparatively small amount of material volume. In the present study it is maximum 766.5 cm^3 for the highest machinable grade of the work-material. The process parameters are chosen so as to promote rapid tool wear at minimum material removal. Different sets of three cutting speeds are selected for each of the five work materials under consideration. The range of cutting speed for this experimentation varies from 123 m/min to 391 m/min. The chosen cutting speed for each work-material grade are due to its industrial relevance and are bit higher than the optimum value according to Makarovs' law, 'minimum tool wear occurs at the optimum cutting speed' (Viktor.P.Astakhov 2004). In general the cutting speed is so selected that the tool life at the highest speed is not less than five minutes (ISO-3685 1993). The depth of cut of 0.4mm chosen is enough to get a measurable flank wear land with minimum consumption of work material. The feed rate chosen was 0.145mm/rev. Research works have shown that the temperature of the tool is highly affected by the cutting speed than the depth of cut and the feed rate (Bartarya G and Choudhary S.K 2012). Further the work-material bar diameter of 100mm chosen was also on higher side to aggravate the tool wear. Boud, F (2007) investigated that the bar diameter has an influence on the tool temperature and, by implication, on tool wear. The tests are being carried according to some of the guidelines laid by the international standard ISO 3685 (1993) and AFS Standard Machinability Tests.

The ISO-3685:1993(E) is an International standard which specifies and contains set of guidelines for tool life testing with single point turning tool. The test can be suitably used for steel and cast iron workpieces. With suitable modification these tests can be developed for specific application.

The AFS standard machinability test is a modified ISO-3685 specifically designed only for bar turning to face turning of a cast disc. The AFS test is used to: compare material of the same grade from different grade lots made in the same foundry; and qualify material of the same grade to a benchmark material. This test thus will help to optimise time and money spent on chemical and mechanical rechecks of the work materials. The test can initially be used for comparative references and later compile databases.

3.3 Workpiece Material

Table 3.1: Chemical Composition of workmaterial in % weight

Work-material	C	Si	Mn	P	S	Cr	Mo	Ni
AISI 1050	0.52	0.31	0.73	0.03	0.03	-	-	-
AISI 51100	1.12	0.26	0.48	0.06	0.05	1.1	-	-
AISI 52100	1.19	0.34	0.53	0.05	0.05	1.49	-	-
AISI 4340	0.48	0.23	0.58	0.04	0.04	1.32	0.22	1.11
AISI 9320	0.18	0.28	0.46	0.02	0.02	0.93	0.13	3.09

Carbon and alloy steels to be used for investigations are as shown in table 3.1 with their chemical composition. Before the commencement of test, the work-material of ø100 mm was reduced to ø98 mm to remove skin, scales and uneven effect on the peripheral surface of the as received work material. Prior to machining tests, turning and facing on the workpiece was done by a different tool at a lower speed (as a part of specimen preparation). Then a drill of ø6 mm was made at the center along the axis of the work material to facilitate the easy entry of the tool at the beginning of every pass. The test specimen of each work-material was finally prepared to the size as shown in figure 3.1.

The table 3.1 shows the chemical composition of various grades or work-materials in percentage of weight which shall be dealt at large for the entire research work. Chemical composition of each work material was determined over the cross-section at three places and average values were obtained. Before conducting the experiments the hardness of all the workpieces over the complete cross-section was determined. The hardness' were within the prescribed limits of ± 5% over complete cross-section of the work piece. Since the work-material is the test variable the above procedure needs to be complied.

3.4 Tool Material

A hard metal P-30, uncoated, carbide insert is used for cutting all of the above workpiece material with a general purpose ISO tool holder CTLPR2020L16. The hardness of tool and the workpiece as measured is given in the table 3.2 in HRA. The work piece hardness were determined in BHN and then converted to HRA, only for the sake of comparison with tool insert hardness to determine tool to work-material hardness ratio.

Table 3.2: Tool and workmaterial hardness with hardness ratio

Material	**Hardness**		**Hardness Ratio**
	BHN	**HRA#**	
Tool Insert	-	88	1
AISI 1050	208	55	1.6
AISI 51100	198	52	1.69
AISI 52100	218	58	1.52
AISI 4340	294	66	1.33
AISI 9320	243	61	1.44

(# Work material hardness converted to HRA from standard conversion table)

For the purpose of machinability testing, the cutting tool material must be at least 35% to 50% harder than the work material. The condition of hardness ratio of the tool to workpiece has been proposed by T.N.Loladze (1968), taking care of the elevated temperature and high strain rate of the work material while machining. The hardness ratio (Tool hardness / Work material hardness) is shown in table: 3.2. The ratio far below 1.35 does not give reliable and consistent results. While the hardness ratio far above 1.5 will result in longer tool life making the tool wear test longer and tedious. Keeping this in view the ratio, the combination of tool insert and workpiece steel grades were chosen for the purpose of study.

3.5 Equipment details

- Center lathe, model HMT L-20G, having spindle power up to 5.5 KW .[Machine Shop-I]
- Toolmaker's Optical microscope of 30x magnification with a 0.01 mm least count. [Metrology Laboratory]
- A Mitutoyo Surface Roughness Tester, SJ-301, with resolution of 0.01μm, [Metrology Laboratory]
- Hardness measuring instrument: Rockwell A for Insert and Rockwell C and Brinell hardness tester for work material hardness measurement.[Materials &

Metallurgy Department]

- Zeiss stereotype microscope to record images of tool wear [Materials & Metallurgy Department]
- Optical microscope(x100) and other equipments necessary for specimen preparation for SEM analysis. [Materials & Metallurgy Department]
- Scanning Electron Microscope, Back [Materials & Metallurgy Department]
- An all geared precision lathe of 1.5 KW, Panther make [Machine Shop-I]
- Micro-hardness Tester (Clemex Digital with diamond indenter, computer attached, with dwell time 10 sec.).[Physics Department]
- Spectrometer chemical composition analyzer (in % weight) of each element in the work-material.[Gwasf Quality Castings(P) Ltd., Baikampady Industrial estate, Mangalore / Servel Engineers, Yeyyadi industrial estate, Mangalore.]

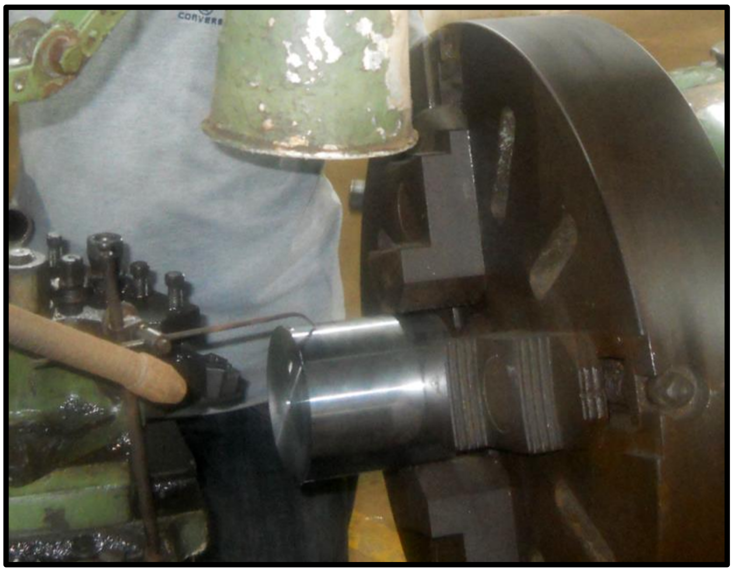


Figure 3.2: Work piece preparation and set up prior to machining on a four jaw chuck of a HMT-Lathe.

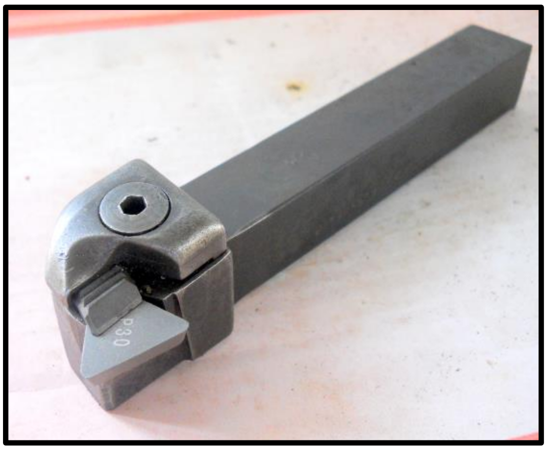
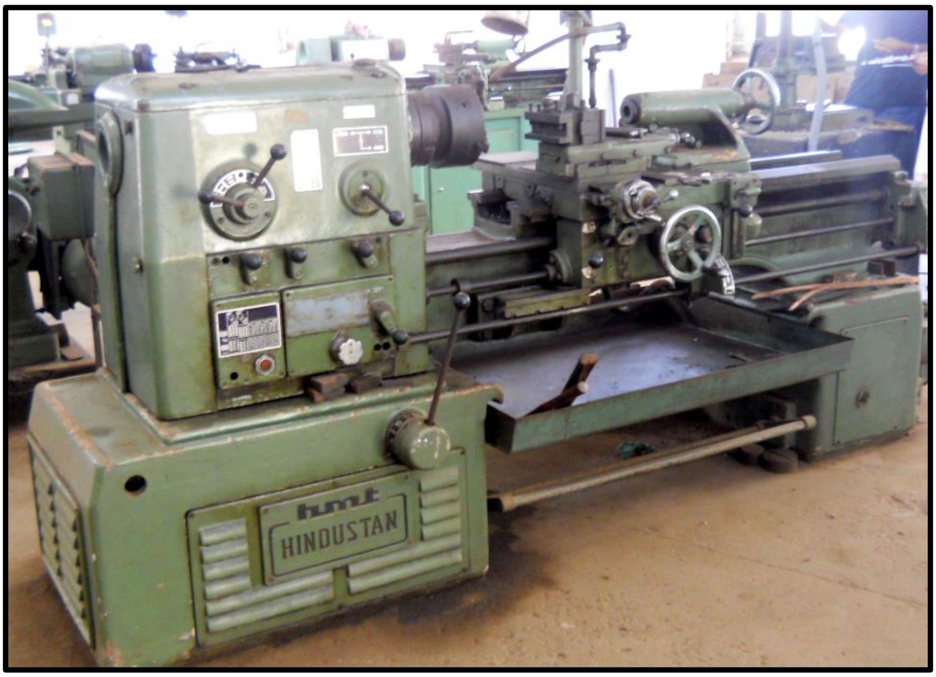
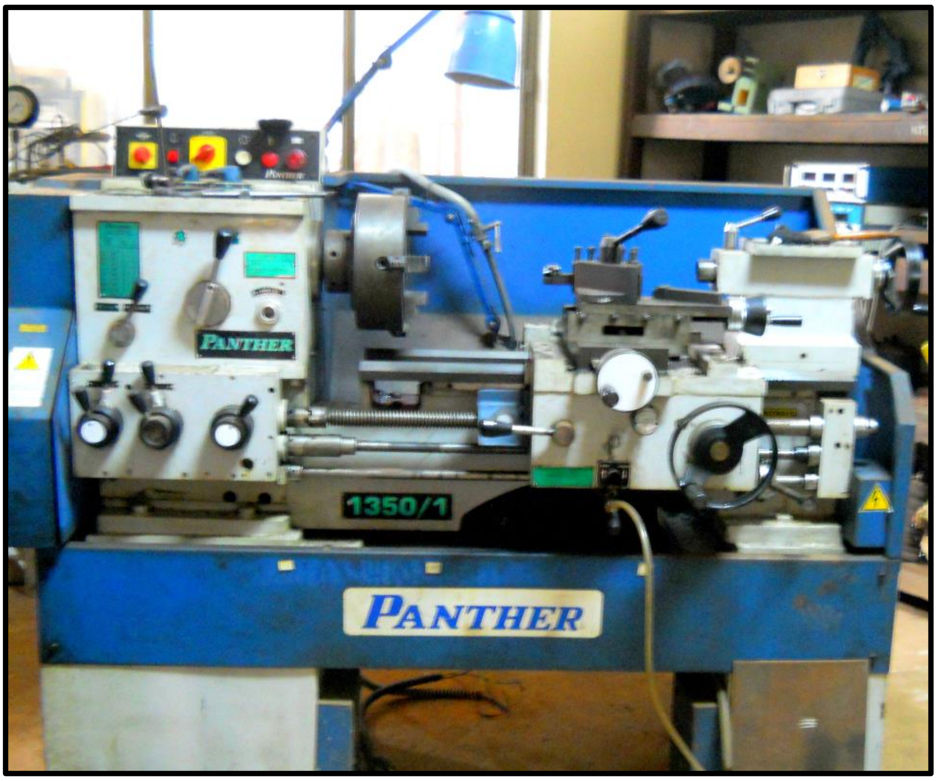


Figure 3.3: Carbide insert with a general purpose ISO tool holder CTLPR2020L16

Figure 3.4: Work piece showing the spectrometric analysis location.



(a)



(b)

Figure 3.5: Machine Tools on which face turning was performed (a) HMT Lathe (b) Panther Lathe.

(a)

(b)

(c)

Figure 3.6: Equipment for measuring and recording the tool wear and surface roughness (a) Tool-makers microscope to measure the flank tool wear (b) Zeiss stereotype microscope to record the images of flank wear, crater wear (c) Surface roughness tester.

Figure 3.7: Spectrometer

Figure 3.8: Scanning Electron Microscope equipment.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Tool wear development

Flank and crater wear are the most important forms of tool wear. However flank wear is the most widely measured form of tool wear for the purpose of tool monitoring. Even a wide variety of monitoring techniques have been developed for the online detection of the flank wear (Siddhapura, A. and Paurobally, R 2013). Flank wear is used here for tool wear monitoring since it occurs virtually in all single point tool machining. Standard tool life tests use flank wear criteria to define the end of the tool life. The tool life criteria used here is the flank wear V_b=0.3 mm for a carbide tool, which is as per the guide lines indicated in ISO 3685:1993(E).

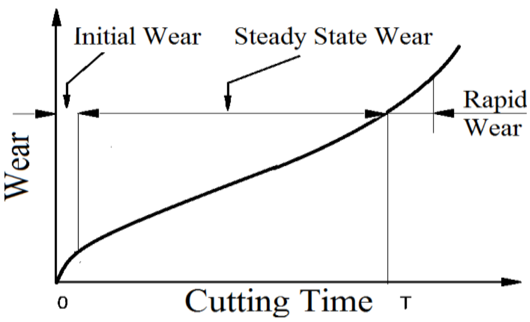


Figure 4.1: Development of wear for single point carbide tool

The tool wear development in traditional turning at single speed with time for a carbide tool is shown in figure 4.1.The growth of wear on the flank face of tool consists of three distinct stages (wear mechanisms); a short initial region of rapid wear (Initial wear or Primary wear), an approximately constant wear-rate region (Steady state wear or Secondary wear or Gradual wear) and finally a very rapid wear-rate region (Accelerated wear or Tertiary wear) which indicates tool failure (Yoram Koren et al. 1991).

The experimental investigations suggest that for machining hard material; crater wear rate is influenced by both, cutting speed and feed rate while flank wear rate is influenced mainly by cutting speed (Attanasio, A et al. 2012). Also research works have shown that temperature of the tool is highly affected by the cutting speed than the depth of cut and feed rate (Gaurav Bartarya and S.K.Choudhary 2012).

The face turning operation is performed on the work-materials as mentioned in table 3.1 to investigate the tool wear development and machinability aspects in comparison with its traditional expensive longitudinal turning operation. Also the other traditional tests with respect to tool wear are more costly to perform both in time and material consumption (Karin Bjorkeboren et al. 2008). The discussion regarding the three wear mechanisms in traditional turning made by most researchers is very much applicable to these samples. This difference in their wear development due to slight change in chemical composition, mainly carbon and chromium (thereby their hardness) is evident in the discussion made in the sections ahead. Accordingly each of the work-material under consideration was tested for three different speeds namely : AISI-1050 at 197m/min (640 rpm), 246 m/min (800 rpm) and 308 m/min (1000 rpm); AISI-51100 at 197m/min (640 rpm), 246 m/min (800 rpm) and 308 m/min (1000 rpm); AISI-52100 at 123 m/min(400 rpm) 197m/min (640 rpm) and 246 m/min (800 rpm); AISI-4340 at 123 m/min(400 rpm) 197m/min (640 rpm) and 246 m/min (800 rpm); and AISI-9320 at 246 m/min (800 rpm), 308 m/min (1000 rpm) and 391 m/min (1270 rpm).

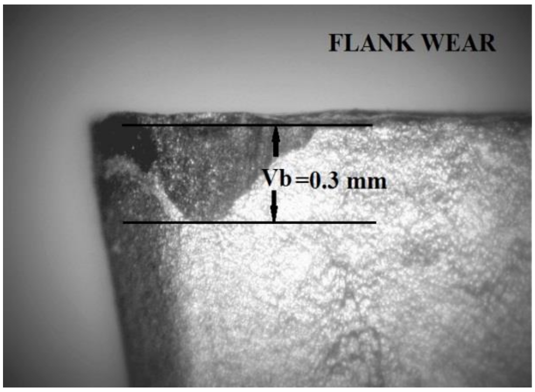


Figure 4.2: Flank wear image of single point tool after reaching wear criterion of 0.3mm

The flank wear on the tool was recorded periodically after every stipulated number of passes for these samples at all testing speeds. The test is continued until the flank wear of the tool reaches the critical wear limit of 0.3mm. Flank wear measurement was made periodically in Toolmaker's optical microscope. The recording was terminated when the flank wear reached its tool life criterion of 0.3mm (V_b) as shown in Figure. 4.2.

According to the ISO-3685 standard, five to ten flank wear (for one cutting speed trial) measurements should be made before the critical wear limit is reached. Since it is not possible to stop exactly at the critical wear limit, linear interpolation is used to determine when the wear limit is reached (Karin Bjorkeboren et al. 2008). Figure 4.3 shows the recording of progressive flank wear for all work-material samples in the current research at different cutting speeds. The wear mechanisms while machining these samples at different stages are discussed in the following sections.

4.1.1 Initial wear mechanism

The initial wear in this investigation is mainly due to nose wear and contributes to nearly 10% to 15% of the tool life. The initial wear causes some roughness on the flank wear. The greater the roughness value of the flank wear surface, the higher the friction on the tool and on the work piece, so that the greater heat generation will occur, which ultimately causes the tool failure (Alden Kendall 2005). In the initial wear mechanism, the tool and the work material in contact have surface roughness irregularities in the form of protrusions or asperities. At the tool-work interface, asperities create small contact areas. In the cutting process, the stresses and heat are intensified in asperities resulting in fracture of melting.

In the current investigation at higher range of speeds (246 m/min and above) the initial wear mechanisms is higher as the nose of the tool having thin cutting edge is rubbed off when it comes in contact of the work-material running at an increasingly higher speeds. The active wear mechanisms change to plasticity and/or mild oxidation/diffusion dominated wear. At lower range of speeds (197 m/min and below) abrasion dominates the wear mechanisms. There is no clear distinction in the end of initial wear mechanism and the beginning of steady state wear mechanism for the entire samples understudy. It is evident that at even lower range of experimental speeds the initial wear mechanisms fairly exists for high carbon grade of work-material.

4.1.2 Steady state wear mechanism

Normal stress and temperature carry over the wear surfaces. The plasticity mechanism that dominates in one wear zone may not dominate in another. Also the maximum tool temperature occurs on the rake surface, at a small distance, about 0.5 to 0.8 mm, from the cutting edge. At this point the crater starts to build and the diffusion wear comes into play. The diffusion wear is dominant in machining ductile material. However in bearing steel material, the diffusion wear (i.e. formation of crater wear) has little presence and does not contribute actively in tool failure. This may be due to the presence of carbides in high carbon steels. Also the chips formed are small, intermittent and arched (about 5mm in length) in turning bearing steel work-material (AISI 51100 and AISI 52100). These chips are unlikely to form BUE condition on tool due to the presence of hard carbide particles. The crater wear which is more of diffusion wear dominance showed its little presence here. The hard particles from work material abrade the flank face. The abrasion is the most common wear process in machining these samples and hence measurements of flank wear as tool failure criterion. Wear can also occur as chipping along the cutting edge. Chipping occurs when the cutting edge, intermittently removes chip. In face turning, this results in cyclic impact and thermal loading of the cutting edge. The wear phenomenon discussed above is referred to as steady state wear period, which lasts for a considerable period of time in comparison to the other two types of wear. In this region the variation in surface roughness is very less. The steady state wear occurs at lower range of speeds for each of the samples.

4.1.3 Rapid /Accelerated wear mechanism.

This wear mechanism is also known as tertiary tool wear mechanism. Over a period of time, steady state mechanism enlarges the wear surfaces to a critical size that triggers the rapid wear. The pressures and speed on this enlarged surfaces gives rise to high temperature resulting in rapid oxidation/diffusion and local seizure causing rapid destruction of the tool. Thus a tool change is to be made before this point is reached. Figure 4.1 shows the three wear zones (as discussed) in terms of amount of wear over time (Alden Kendall 2005). As the rapid wear progresses, the surface finish on the work material also deteriorates.

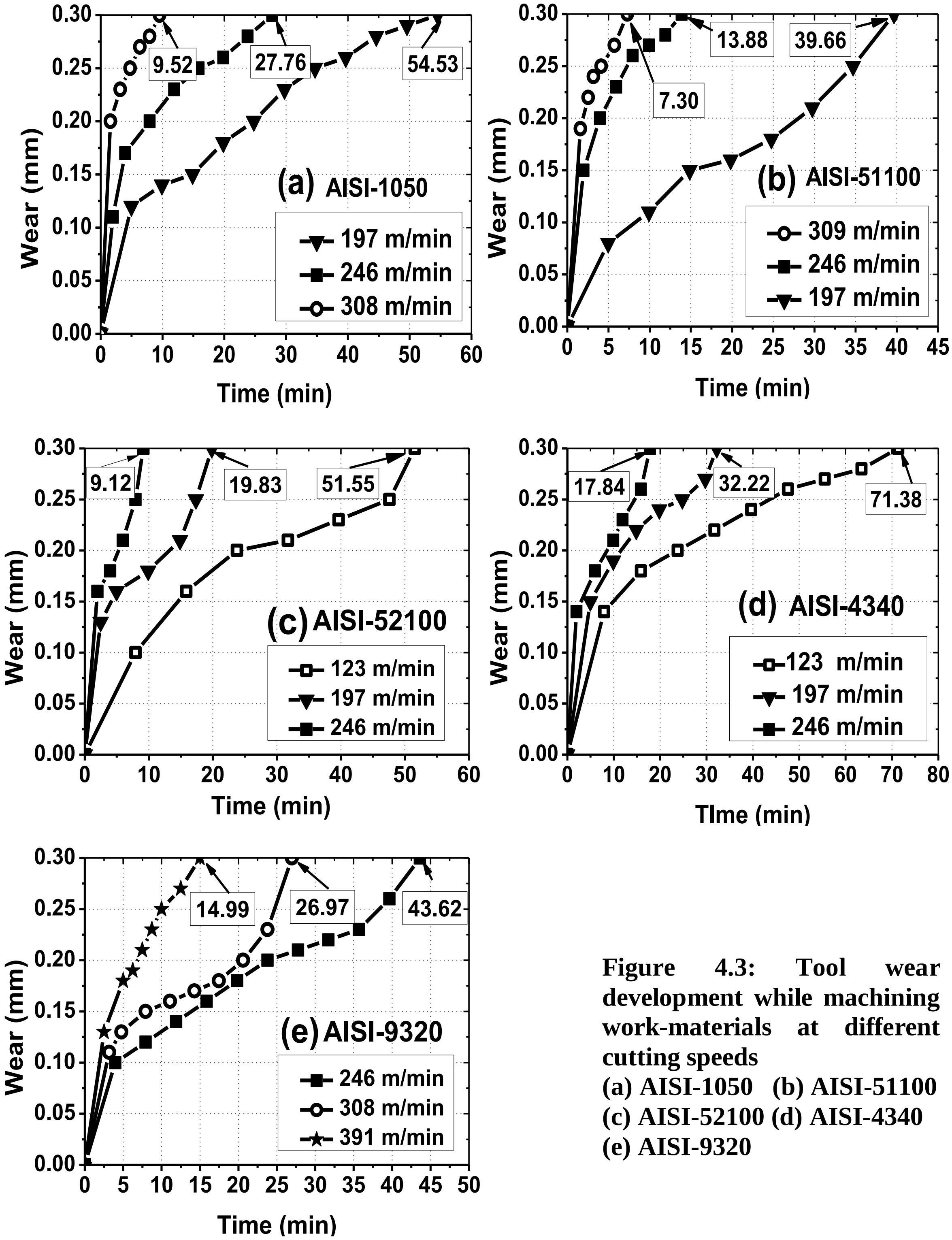


Figure 4.3: Tool wear development while machining work-materials at different cutting speeds
(a) AISI-1050 (b) AISI-51100
(c) AISI-52100 (d) AISI-4340
(e) AISI-9320

4.1.4 General observations and discussions

The phenomenon of wear mechanisms with three zones is evident at lower range of speeds for the current experimentation for each of the work-material The scenario of tool wear development changes as the testing speed for both the samples is increased at the next higher level. The steady state wear zone relatively is reduced to a very short time because diffusion wear mechanism dominates the abrasion wear as the speed increases. At still higher level range of speeds, there is no evidence of steady state wear zone. At such higher speeds the wear environment alters dramatically. More thermal energy is removed by the chip due to decrease in contact time between the tool and chip. The higher velocities increase the absolute temperature on the tool wears surfaces. Abrasive wear here becomes less important. The diffusion and oxidation processes dominate in creating and enlarging the wear surfaces (Alden Kendall 2005).

4.1.4.1 Tool wear observations for AISI- 1050, AISI-9320 and AISI-51100

The regular flank wear rate changes with time as shown in figure 4.3.The initial wear in this investigation is mainly due to nose wear and contributes to nearly 10% and 15% of the tool life criterion at lower speeds for all low to medium carbon steels grades and high carbon steels respectively. The initial wear causes some roughness on the flank wear. The greater the roughness value of the flank wear surface, the higher the friction of the tool on the workpiece, so that greater heat generation will occur, which ultimately causes tool failure (Francis. E. H et al. 2002). This phenomenon is observed on all the tool and work-material combination. The initial wear is due to adhesive or attrition wear when small particles of the tool adhere or weld to the chip due to friction and are removed from the tool surface. This phenomenon is accompanied by BUE continuous chip formation. Usually BUE is formed due to high pressure generated during cutting and chemical affinity of the tool to the work-material (Kadirgama et al. 2011).Continuous increase in speed over the length of cut in face turning does not allow the formation of BUE particularly at higher speeds over 240 m/min. However at speeds near 110 m/min the BUE formation at the early passes were observed in toolmakers microscope. Abrasive wear is the primary cause of flank wear in initial stages.

Both the adhesive and abrasive wear (David. A. Stephenson and John. S .Agapiou 2006) has been described quantitatively by an equation

$$V_o = Kw\ N\ Ls\ /H \tag{3}$$

where V_o=Volume of material worn away, K_w =Wear Co-efficient, N=Normal force to the sliding interface, L_s =the distance slid, H=hardness of the tool.

This equation shows that an effective method of controlling wear is to increase the hardness, H, of the tool.

However, wear can be accelerated keeping tool hardness low constant and using work material hard enough to comply hardness ratio in between 1.33 to 1.5.

During turning at low speeds, adhesion and micro chipping are the basic wear mechanisms and at higher speeds, diffusion and thermal fatigue cracking became severe for AISI- 1050, AISI-9320 and AISI-51100 work material. Similar observations were recorded by Ebrahim, A and Moshkar, M. M (2009) while evaluating tool wear of AISI 1045 and micro-alloyed steel (30MnVS6).

The flank wear rate change with time is as shown in figure 4.3. After an initial wear period, flank wear increases slowly at a steady rate is reached until a critical land width, after which wear accelerates and becomes severe.

4.1.4.2 Tool wear observations for AISI-4340 and AISI- 52100

The experimental investigations suggest that for hard material crater wear rate is influenced by both cutting speed and feed rate, while flank wear rate seemed to be mainly effected by cutting speed. When the crater wear is present the wear mechanisms are abrasion, deeply affected by cutting speed and the diffusion is heavily influenced by the cutting temperature. On the other hand the flank wear mechanism is mainly due to abrasive phenomena strongly affected by cutting speed (Attanasio, A et al. 2011). Research works have shown that temperature of the tool is highly affected by the cutting speed than the depth of cut and the feed rate (Gaurav Bartarya and S.K.Choudhary 2012).

The contributing factor to the differences in flank wear rates of all the material could be the hardness of the work-material. In general harder work material will result in higher cutting stresses and tool temperature, leading to greater tool wear. However, the hardness of the steel may not be the only variable affecting the flank wear. The composition and microstructure of the steels are likely to be important (Lim, C.Y.H et al. 2001).This is quite evident from the investigations made in this research.

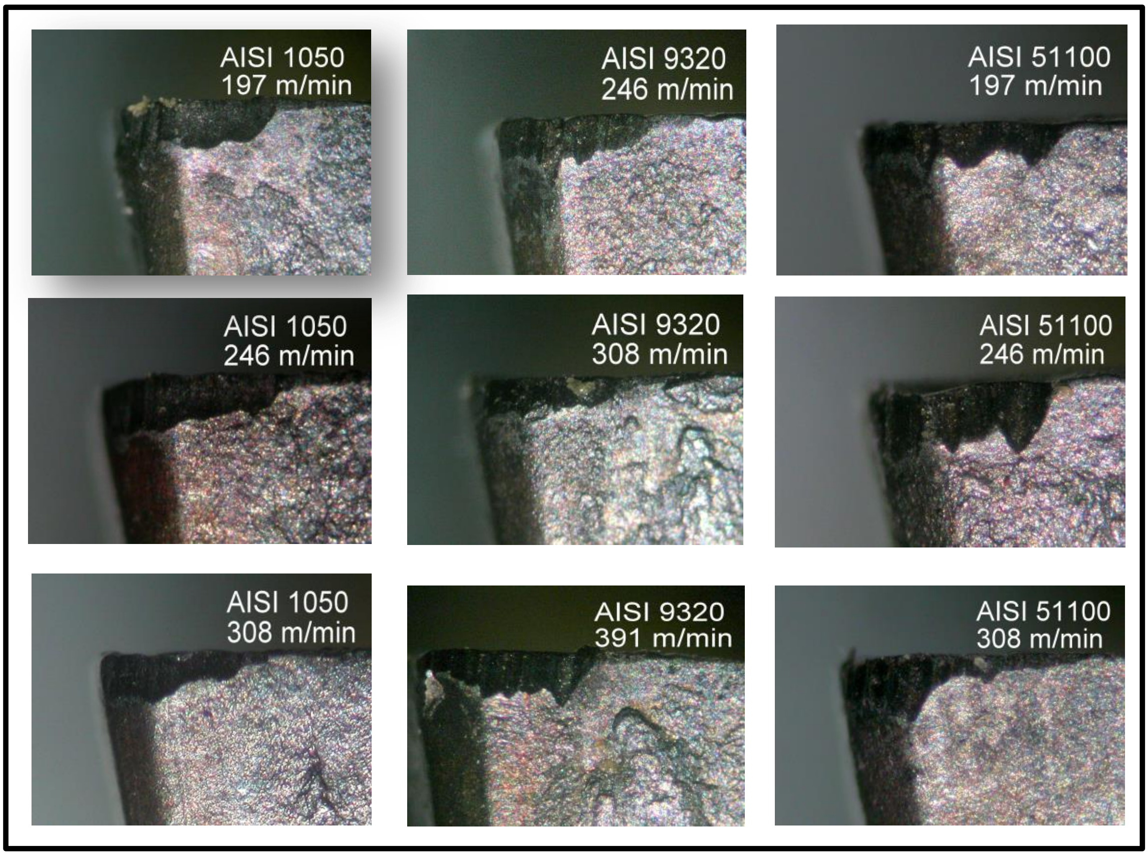


Figure 4.4: Flank wear images of the tool taken after the tool has reached stipulated tool life criterion, V_b, of 0.3 mm for the work materials AISI-1050, AISI-9320 and AISI-51100 materials at three different speeds.

In high carbon steel, AISI-51100 and AISI- 52100, abrasive wear is dominant. The hard particles abrade and remove material from the tool. The flank images (figure 4.4) of tool are shown for speed 197 m/min, 246 m/min. 308 m/min and 391 m/min. It can be observed that the wear in flank and crater at the beginning stages is mainly due to abrasion and then diffusion wear occurs which is influenced by cutting temperature at higher speeds. Thermal cracks are observed on the tool at higher speeds. (for the cutting speeds 308 m/min and above as shown in figure 4.4). This is the result from cyclic loading of the tool in interrupted cutting or when machining materials which generate high tool-chip temperature.

AISI-4340 steel is further alloyed with nickel, chromium and molybdenum. Nickel dissolves in the ferritic matrix, imparting toughness and strength, as well as increasing the tendency to strain harden. Chromium and molybdenum combine with carbon to form numerous hard, stable carbides that improve the hardness of the steel, especially at elevated temperature. The tandem increases in hardness, toughness and strength in greater cutting higher wear rates when machining AISI-4340 steels. Thus the chips formed are hard, stable and uniform during machining, which is evident from the crater wear images at all speeds. The effect of chip hammering was also observed as the chip curled back and stroked the tool face away from the cutting edge. However the flank wear behavior is similar to AISI-51100 and AISI- 52100. The images clearly show the evidence of growing thermal cracks with increase in speed. In an another experiment with higher speed, 246 m/min (800 rpm), the tool chipped off as it was at the flank wear of 0.3mm as a result of thermal crack. Thus the tool life criterion chosen as 0.3mm of flank wear for the purpose of investigation proved to be appropriate with this event. Further the tool wear progress phenomenon for each of the work material is in line with the tests as obtained by cylindrical turning as according to standard machining handbooks (Alden Kendall 2005).

4.2 Machinability Ranking Tests

4.2.1 Repeatable test

Here the machinability of the all samples is repeated with the same cutting parameters on the same machine but at a speed of 246 m/min. The purpose of this test is to assess the ability to repeat the machinability of all the samples under same cutting conditions. On the same machine and at one speed if a particular sample shows better performance than another, it should repeat this at another speed, to ensure the consistency of the results. The results show the sensitivity of the applied

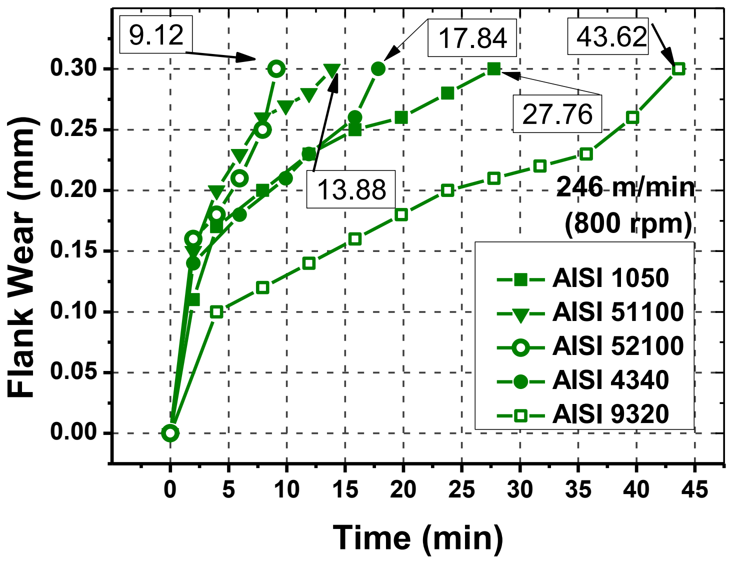


Figure 4.5: Relationship between the cutting time and flank wear for repeatable test at 246 m/min.

face turning test method even to the slight variation in the chemical composition of the two steels, namely AISI-51100 and AISI-52100. The effect of the differences in carbon, manganese and chromium is revealed in the tool wear development figures. The tool life at 246 m/min for the work-materials: AISI-1050 is 27.76 mins; AISI-51100 is 13.88 mins; AISI-52100 is 9.12 mins; AISI-4340 is 17.84 mins and; AISI-9320 is 43.62 mins. The tool wear progress at 246 m/min speed for all the work-materials is shown in figure 4.5.

4.2.2 Reproducible test

All the samples are tested on another machine with the same cutting condition and tool but at a different single speed (245 m/min). If the results of this test are

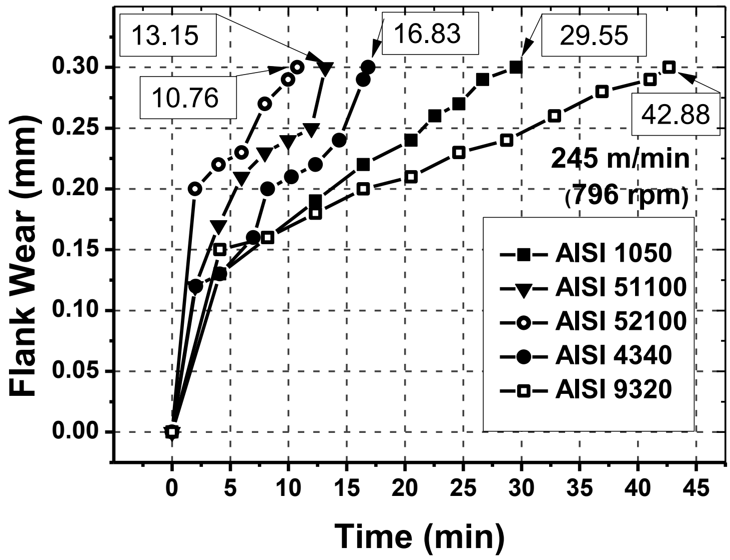


Figure 4.6: Relationship between the cutting time and flank wear for reproducible test (on another machine) at 245 m/min.

consistent with the previous one, it can said to have achieved the reproducibility. The tool life at 245 m/min for the work-materials: AISI-1050 is 29.55 mins; AISI-51100 is 13.15 min; AISI-52100 is 10.76 mins; AISI-4340 is 16.83 mins and; AISI-9320 is 42.68 mins.

The tool wear development of this test is shown in figure 4.6.

The repeatability and reproducibility test has proved consistent machinability ranking as I, II, III, IV, and V for the work-material, AISI-9320, AISI-1050, AISI-4340, AISI-51100 and AISI-52100 respectively**.** The summaries of machinability ranking results are shown in table.4.1. In a nut shell the wear mechanisms, tool wear development and machinability tests here in face turning operation confirms with the traditional longitudinal turning.

Table 4.1: Machinability ranking results done at 246 m/min on one machine and 245 m/min done on another machine

	Experimental results of tool life in minutes at speed 246 m/min[800 rpm]on one machine (HMT)	Experimental results of tool life in minutes at speed 245m/min [796 rpm]on another machine(Panther)	Machinability ranking
AISI-1050	27.76	29.55	**II**
AISI-51100	13.8	13.15	**IV**
AISI-52100	9.12	10.76	**V**
AISI-4340	17.84	16.83	**III**
AISI-9320	43.62	42.68	**I**

4.3 Tool life studies

4.3.1 Tool life equation and machinability index

The development of quantitative methods for predicting tool life has long been goal of metal cutting research as the tool life has a strong impact in production operations. The tool life model study includes flank wear of the carbide tool in mm and cutting speed in m/min as the parameters under consideration. Flank wear is a major form of tool wear in metal cutting (Luo.X et al. 2005).This wear is found to have detrimental effects on surface finish, residual stresses and microstructural changes in the form of rehardened surface layer (Attanasio. A at al. 2012)

Cutting speed is chosen as major machining parameter in tool studies because it is inferred that the cutting speed has major influence on the tool life/wear. Feed rate and depth of cut has little influence on the tool life (B.Giriraj et al. 2006). Thus three wear tests at three different cutting speeds were plotted for all the work-materials. The time required for tool failure, V_b 0.3 mm and the corresponding speeds used for all the workmaterials are shown in the figure. 4.3(a to e).

A line of best fit was drawn between the ends of the test wear points for all the work-materials as shown in figure. 4.7.

The proposed model equation of Tool life line plot for **AISI-1050** is

y = Intercept + B1*x^1 + B2*x^2

where, Intercept =272.23 ; B1= -1.55 and B2=0.00227

Goodness of fit:

SSE =5.00 e-014, R_{square} =1, Adjusted R_{square} = NaN, RMSE= NaN

The proposed model equation of Tool life line plot for **AISI-51100** is

y = Intercept + B1*x^1 + B2*x^2

where, Intercept =329.4 ; B1= -2.225 and B2 = 0.0038

Goodness of fit:

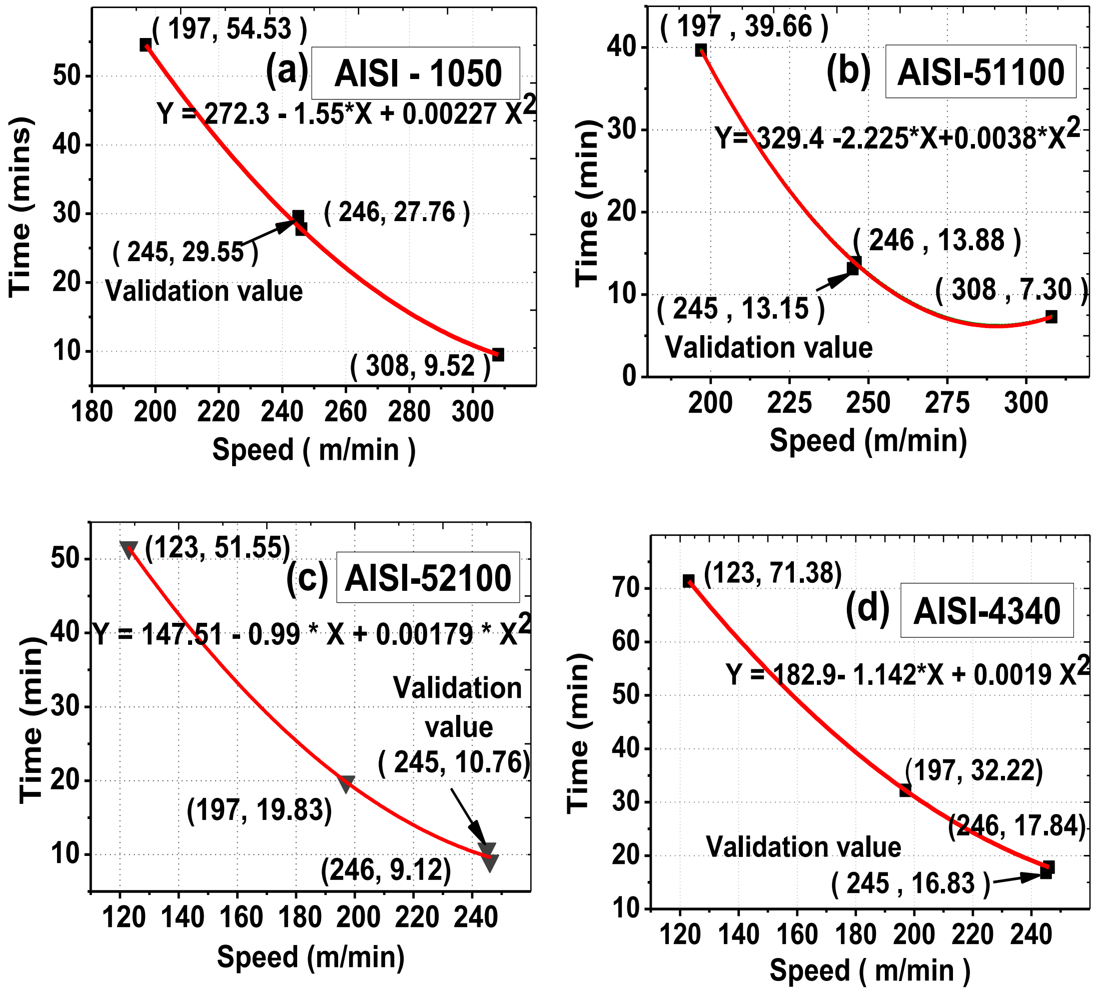
SSE =1.42 e-014, R_{square} =1, Adjusted R_{square} = 0.998, RMSE= 0.03285

The proposed model equation of Tool life line plot for **AISI-52100** is

y = Intercept + B1*x^1 + B2*x^2

where, Intercept =147.5 ; B1= -0.99 and B2 = 0.00178

Goodness of fit:



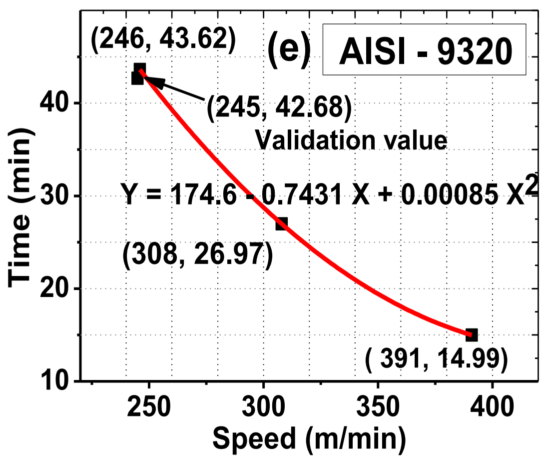


Figure 4.7: Tool life curve with an equation for a line of best fit and a validation value for each work-material.
(a) AISI-1050
(b) AISI-51100
(c) AISI-52100
(d) AISI-4340
(e) AISI-9320

SSE =7.10 e-015, R_{square} =1, Adjusted R_{square} = 0.998, RMSE= NaN

The proposed model equation of Tool life line plot for **AISI-4340** is

y = Intercept + B1*x^1 + B2*x^2

where, Intercept =182.9 ; B1= -1.142 and B2 = 0.0019

Goodness of fit:

SSE =1.42 e-014, R_{square} =1, Adjusted R_{square} = NaN, RMSE= NaN

And

The proposed model equation of Tool life line plot for **AISI-9320** is

y = Intercept + B1*x^1 + B2*x^2

where, Intercept =174.6 ; B1= -0.7431 and B2 = 0.00085

Goodness of fit:

SSE =7.638-014, R_{square} =1, Adjusted R_{square} = 0.97, RMSE= NaN

The sum of squares due to error, SSE has a value closer to 0, indicating that the model has a smaller random error component and that the fill will be more useful for prediction.

R_{square} measures how successful the fit is in explaining the variation of the data. It is the square of the correlation between the response values and the predicted response values. R_{square} value closer to 1 indicates that a greater proportion of variance is accounted by the model. The adjusted R_{square} statistic can take on any value closer to 1 indicating a better fit.

Root Mean Squared Error, RMSE, is also known as the fit standard error and the standard error of the regression. RMSE value closer to 0 indicates a fit that is more useful for prediction.

Table 4.2: Details of tool life for each of the work materials at various speeds and speed for 60 m/min.

Work-materials	Tool Life in mins	Speed in m/min	Speed for 60 mins tool life
(a) AISI 1050	9.52	308	189.43 m/min
	27.76	246	
	54.53	197	
(b) AISI 51100	7.30	308	171 m/min
	13.88	246	
	39.66	197	
(c) AISI 52100	9.12	246	108.82 m/min
	19.83	197	
	51.55	123	
(d) AISI 4340	17.84	246	140.43 m/min
	32.22	197	
	71.38	123	
(e) AISI 9320	14.99	391	203.5 m/min
	26.97	308	
	43.62	246	

4.3.2 Tool life validation test

Experimental tests were performed to verify the proposed model of all work-material mentioned earlier. The same were tested on an another lathe machine keeping the feed, 0.145 mm/rev and depth of cut as 0.40mm, similar to previous test. However the cutting speed was kept as 245 m/min (796 rpm). With almost similar cutting conditions, tool material and work-material (except the machine) the face turning test was carried. Performing such a test on another machine is known as Validation test. This test verifies the reproducibility and repeatability of the ongoing tool wear development and machinability test. These samples were face turned until the flank wear on the cutting tool insert reached the tool life criterion of 0.30 mm. The results of the validation test are presented in table 4.3 and indicated in the figure 4.7.

The time for the end of life for both the samples was fairly close to the Taylor line and within the error band. The error bars for each observed point is in 95 percent confidence range. The validation test of the face turning operation for both the samples ensured the reproducibility and repeatability of the proposed tool life model and machinability studies. The tool wear line for best fit plotted for all the work-materials are presented in the figures 4.7.

Thus the face turning method of investigating tool wear development and machinability studies tests confirms the reproducibility and repeatability.

Table 4.3: Experimental results of tool life cross checked with tool life model equation for validation

Work-material	Experimental results of tool life in minutes at speed 245 m/min[796rpm]	Theoretical results of tool life in minutes according to the model	Error	
			In mins	%
AISI-1050	29.55	28.59	0.96	3.36
AISI-51100	13.15	12.37	0.78	6.3
AISI-52100	10.76	10.20	0.56	4.5
AISI-4340	16.83	17.16	0.33	1.92
AISI-9320	42.68	43.56	0.88	2.02

4.4 Surface roughness

The roughness of the machined surface is a result of an interaction of the workpiece properties and the tool material and geometry under the cutting conditions used. The important parameters which affect the roughness of the machined surfaces are the tool nose radius, feed, cutting speed and depth of cut. In the present investigation the tool nose radius, feed and depth of cut are kept constant throughout the whole experimentation. Therefore the effect of cutting speed and tool wear on surface roughness is considered for discussion.

The surface roughness test was recorded periodically and simultaneously along with the flank tool wear measurement. Surface roughness tester, SJ-301, with resolution of 0.01μm least count was used for this purpose. After every stipulated number of passes performed by the face turning operation, the machined surface was evaluated for the surface roughness. The parameters Ra, Rz and Rq were recorded by the Surface roughness tester at three different places on the machined surface. The averages of these three values have been taken for the purpose of reporting. The results recorded this way at three different places are presented in the figure 4.8 to 4.12.

Table 4.4: Ratio of root mean square roughness (Rq) to arithmetic average roughness (Ra) for all work-materials at different speeds

AISI-1050			**AISI-51100**			**AISI-52100**			**AISI-4340**			**AISI-9320**		
Speeds in m/min														
197	**246**	**308**	**197**	**246**	**308**	**123**	**197**	**246**	**123**	**197**	**246**	**246**	**308**	**391**
The ratio Rq / Ra														
1.12	1.17	1.20	1.18	1.34	1.36	1.25	1.18	1.21	1.10	1.25	1.13	1.31	1.15	1.22
1.16	1.17	1.21	1.21	1.30	1.16	1.16	1.23	1.21	1.20	1.25	1.13	1.23	1.16	1.21
1.20	1.18	1.22	1.09	1.21	1.19	1.22	1.20	1.16	1.18	1.24	1.20	1.27	1.24	1.22
1.20	1.24	1.21	1.05	1.19	1.34	1.16	1.18	1.15	1.19	1.21	1.15	1.22	1.24	1.24
1.21	1.28	1.20	1.07	1.19	1.28	1.16	1.14	1.15	1.17	1.16	1.17	1.24	1.20	1.12
1.04	1.18	1.21	1.04	1.18	1.25	1.12	1.16	-	1.16	1.18	1.18	1.24	1.21	1.29
1.21	1.27	-	1.10	1.17	-	1.11	-	-	1.14	1.10	-	1.20	1.18	1.22
0.93	1.30	-	1.14	-	-				1.19	-	-	1.22	1.26	1.28
1.19	-	-							1.10	-	-	1.21	1.27	-
1.18	-											1.22	-	-
1.19	-											1.30	-	-

The surface roughness's of turning in the current investigation is the effect of cutting speed having kept parameters like feed, tool radius and end and side cutting edge angles. The surface roughness obtained from these calculations represents the best finish commonly produced by that particular turning tool and thus provide an indication of the minimum surface roughness possible with a designated tool shape. The actual surface roughness may be poorer due to BUE or any other unknown reason. Further the ratio of root mean square roughness to arithmetic average roughness for turning operation is 1.17 to 1.26 (Michael Field et al. 2008) .

From the table 4.4 the ratio of the root mean square (Rq) roughness to arithmetic average (Ra) roughness for face turning lies in between 0.93 to 1.36. This ratio is in good agreement with theoretical ratio (Michael Field et al. 2008) indicating that the exercised face turning method for the current studies here is valid

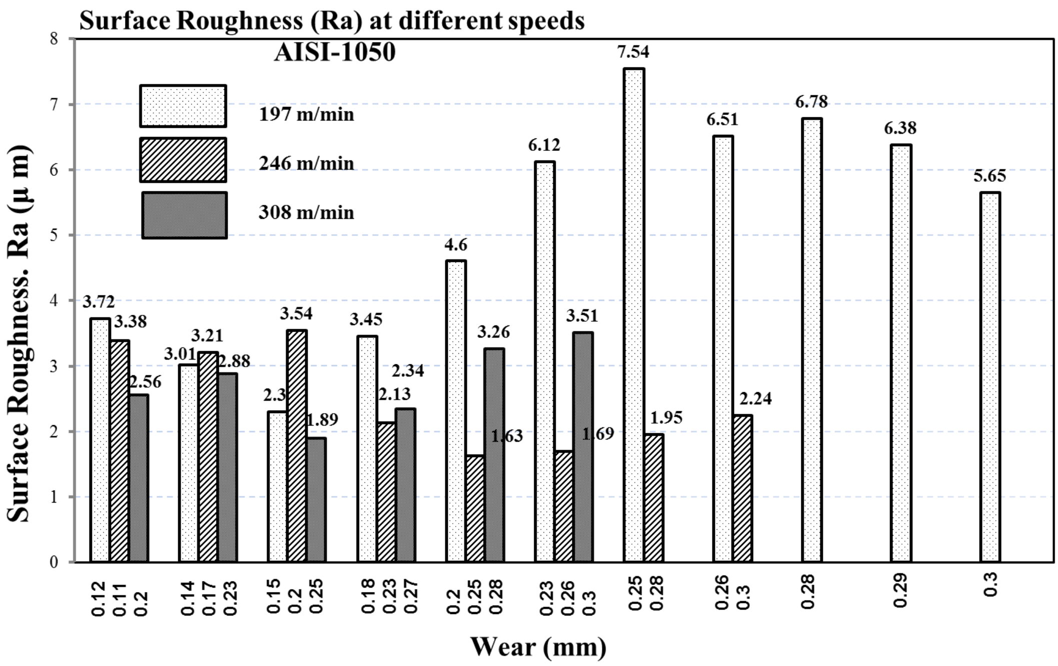


Figure 4.8: Surface Roughness in µm obtained at regular intervals at different speeds for AISI-1050 work-material.

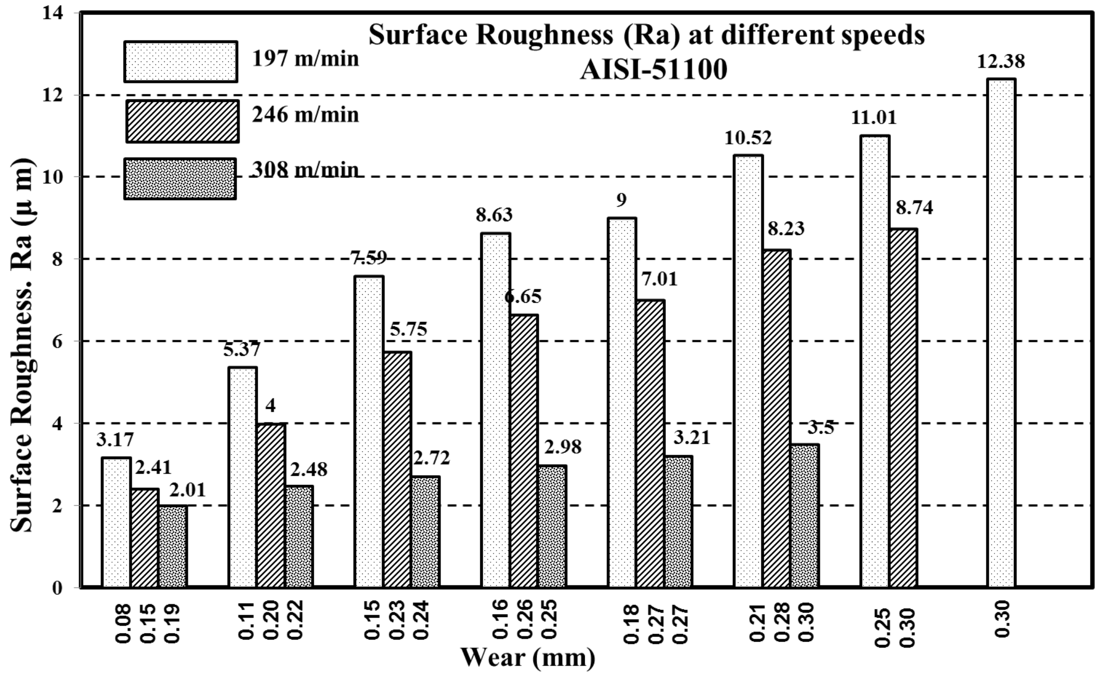


Figure 4.9: Surface Roughness in µm obtained at regular intervals at different speeds for AISI-51100 work-material.

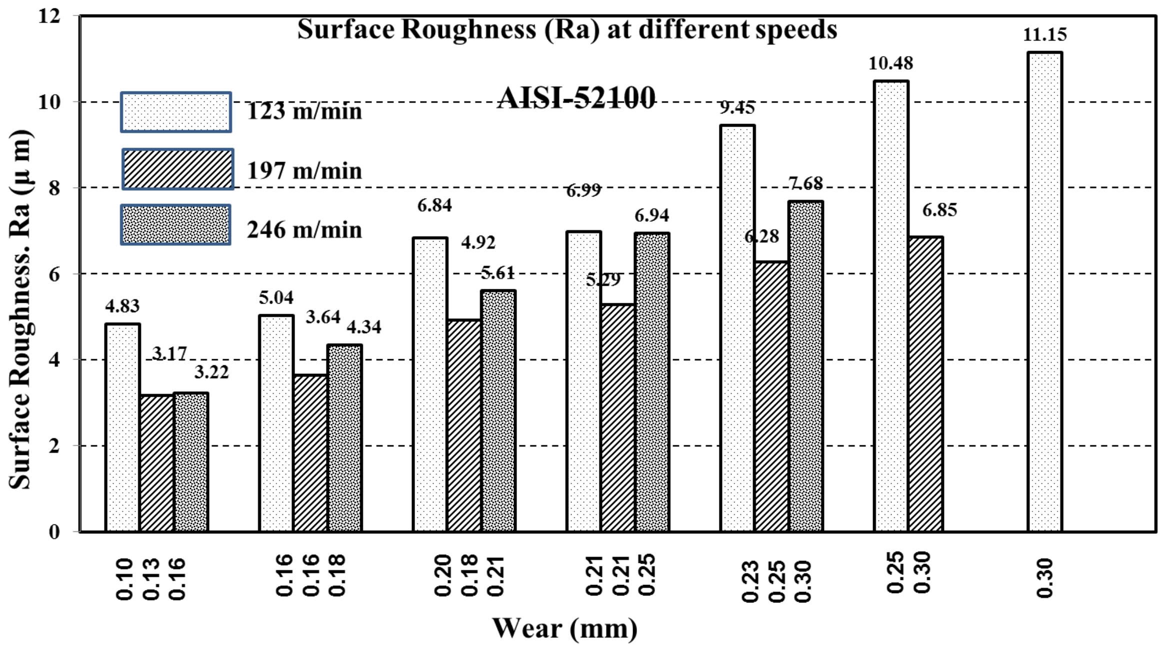


Figure 4.10: Surface Roughness values in µm obtained at regular intervals at different speeds for AISI-52100 work-material.

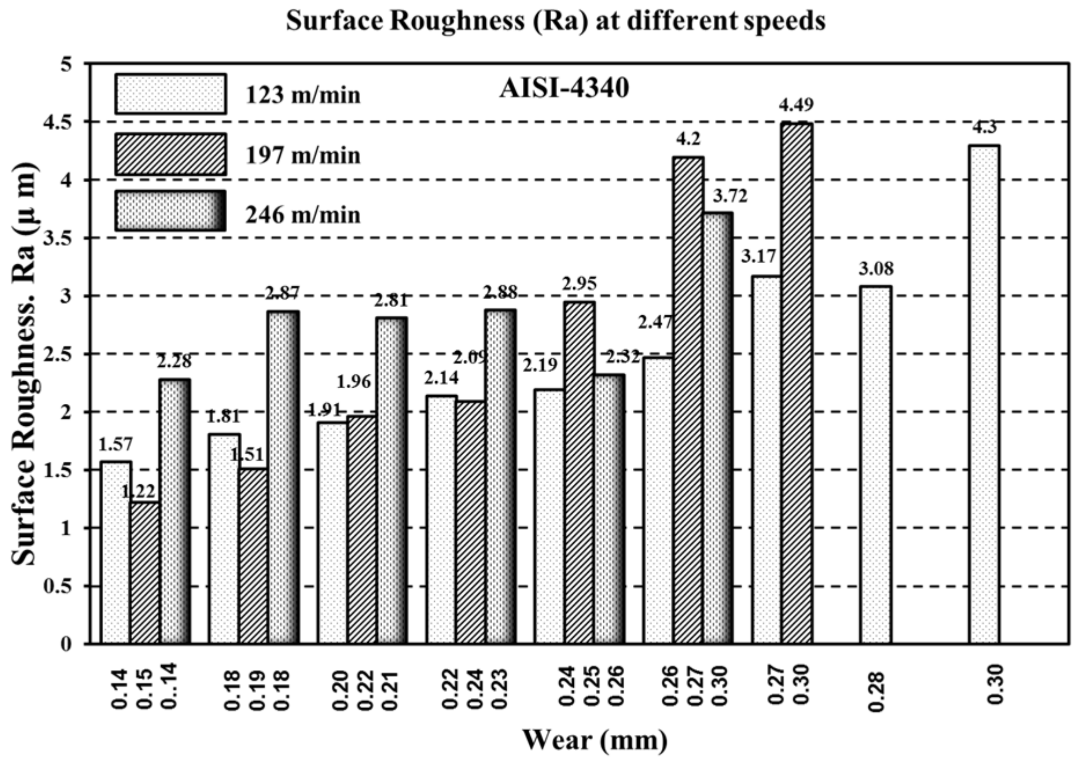


Figure 4.11: Surface Roughness in µm obtained at regular intervals at different speeds for AISI-4340 work-material.

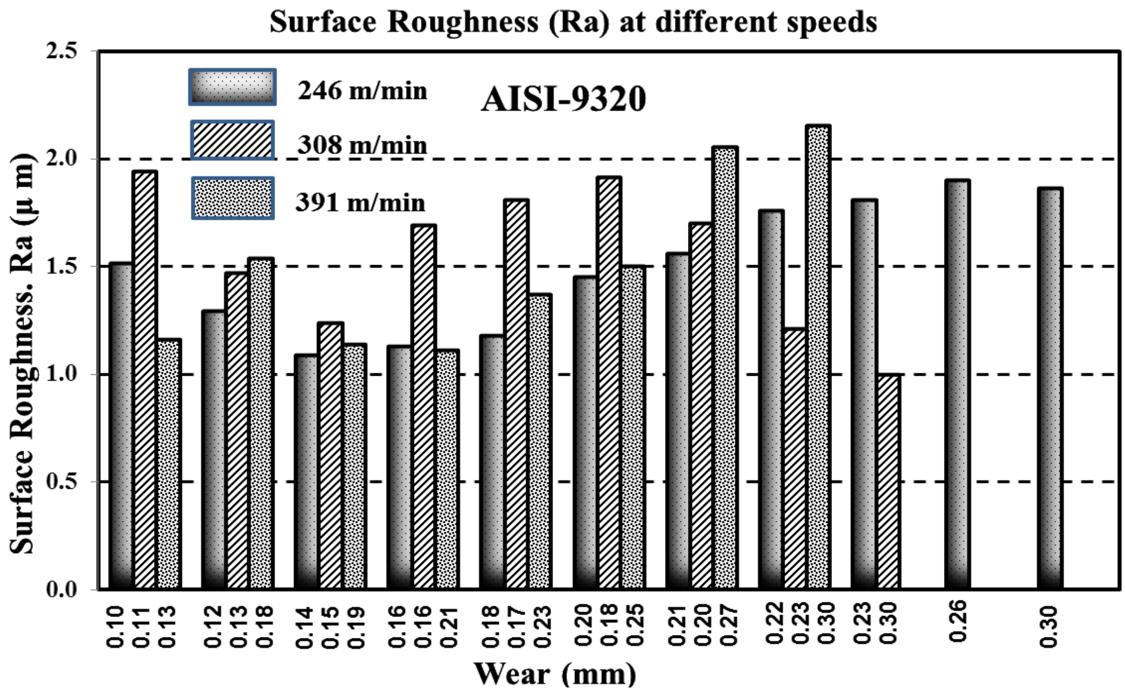


Figure 4.12: Surface Roughness values in µm obtained at regular intervals at different speeds for AISI-9320 work-material.

The present face turning investigation with respect to surface roughness and wear for all the work-materials is shown in the figure (4.8 to 4.12). The investigation is spread over the work on materials at three speeds: lower, medium and higher speed. It is very evident for all the cutting speeds that as the tool wear development progresses the surface roughness increase (i.e. surface finish deteriorates) to some extent and just before the tool fails (0.3mm) the surface finish may slightly improve and also this phenomena may not consistently not compliment tool wear (Islam 2013).

The figure 4.8 to 4.12 depicts that for a lower range of experimental speeds (197 m/min for AISI-1050 and AISI-51100; 123 m/min for AISI-52100 and AISI-4320; and 246 m/min for AISI-9320), the surface roughness values are spread over a broad range with a high Ra value at its wear. This is a case of abrasion wear. The formation of new cutting edges repeatedly is more until the final wear (Vb=0.3 mm) occurs. Thus it can be said that abrasion wear occurs at lower range of cutting speed with a broad range of surface roughness values and is dependent on the type/grade of work-material.

Table 4.5: Range of Surface roughness values in µm for the workmaterials

	Range of Roughness values(µ m) at		
	Lower speeds	Medium speeds	Higher speeds
AISI-1050	2.30 to 7.54 = 5.4	1.63 to 3.38 = 1.75	1.89 to 3.5 =1.61
AISI-51100	3.17 to 12.38 =9.21	2.41 to 8.74 = 6.33	2.01 to 3.5 =1.49
AISI-52100	4.83 to 11.15 = 6.32	3.17 to 6.85 = 3.68	3.22 to 7.68 = 4.46
AISI-4340	1.57 to 4.3 = 2.73	1.22 to 4.49=3.27	2.28 to 3.72 = 1.44
AISI-9320	1.51 to 1.86 = 0.35	1.00 to 1.94 = 0.94	1.14 to 2.15 = 1.01

Whereas at higher range of speeds (308 m/min for AISI-1050 and AISI-51100; 246 m/min for AISI-52100 and AISI-4320; and 391 m/min for AISI-9320), the surface roughness values lie in a narrow band and a comparatively lesser Ra value. Here the wear phenomenon may be due to mild diffusion/oxidation. Because of increased speed, the temperature at tool-chip-workpiece region is high. No newer cutting edges are formed. The cutting edge loses it sharpness into roundness quickly giving rise to a better surface finish. Table 4.5 shows the range of Surface roughness values obtained on each work-material tabulated at regular interval of time while machining at three different speeds.

4.4.1 Surface finish validation results

The alloying elements like C, Cr and Ni always hardens the workmaterial which do affect the surface roughness while machining. The roughness of machined surface is correctly revealed by Rz and Ra values in the studies made by Kopac, J and Bahor,M (2001). For assessing the possible effect of the carbon, chromium and nickel composition the roughness of the machined surface Ra and Rz values are shown in the figure.4.13. The roughness of a machined surface is a result of interaction of the

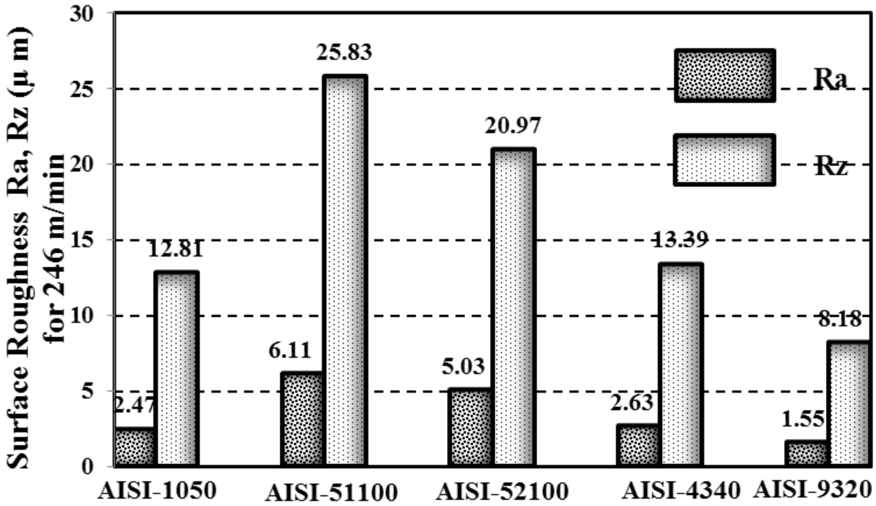


Figure 4.13: Surface Roughness Ra and Rz (µm) after face turning at 246 m/min

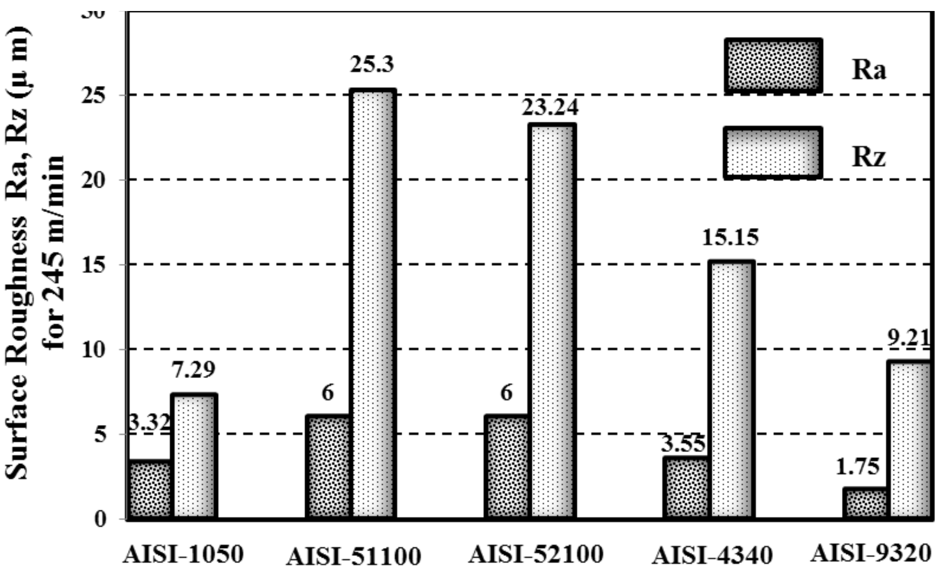


Figure 4.14: Surface Roughness Ra and Rz (µm) after face turning at 245 m/min

workmaterial properties and the tool material and the geometry under the cutting condition used.

There is always the influence of the base workpiece properties on the roughness which may be used for defining the machinability vide surface finish. Thus it was found from the experiments that for higher cutting speed better surface finish is produced for longer cutting time of active tool life. Also better surface finish was observed as the cutting edge of the tool worn out. Built up edge was observed on the tool rake face while machining at 123 m/min for AISI-1050 and AISI-9320 work-materials. The built-up edge has formed due to high temperature and diffusion of work-material (Thamizhmani et al. 2007)

Though most of the results altogether on surface roughness do compliment the tool wear, still in some instances it fairly compliments. This is because surface roughness by itself is not a reliable indicator of machinability, due to non-optimal cutting conditions and interaction effects of additional factors (Islam 2013).

4.5 Critical Volume

Total volume of the material removed for the investigation is shown in detail here in figure 4.15 and figure 4.16. The critical volume is the volume of material removed from the start of the test till the tool reaches its tool life .criterion of flank wear of 0.3mm. The calculation of the total volume removed is shown with the illustration at the end of this section 4.5. The details of volume of material removed for each work-material at different speeds is shown in figure 4.15. However the total volume of the material removed as in figure 4.16 gives an idea of the material consumed and

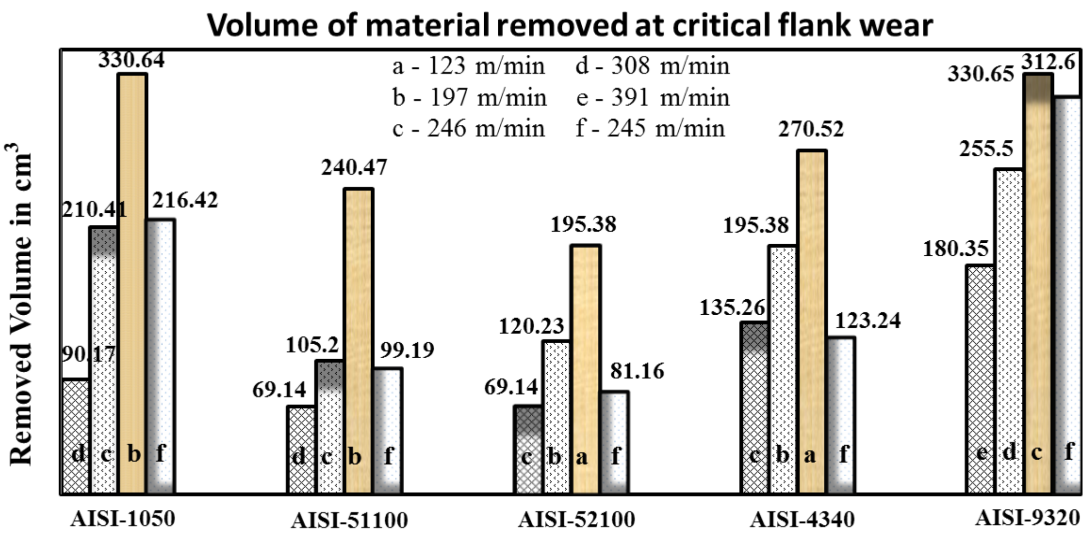


Figure 4.15: Removed volume at critical flank wear at various cutting speeds for the work-material.

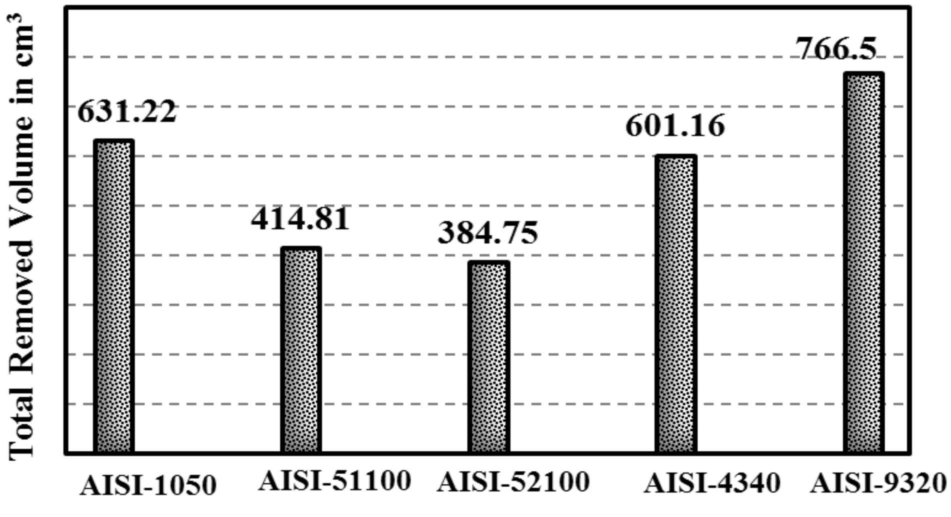


Figure 4.16: Total removed volume at critical flank wear of work-materials.

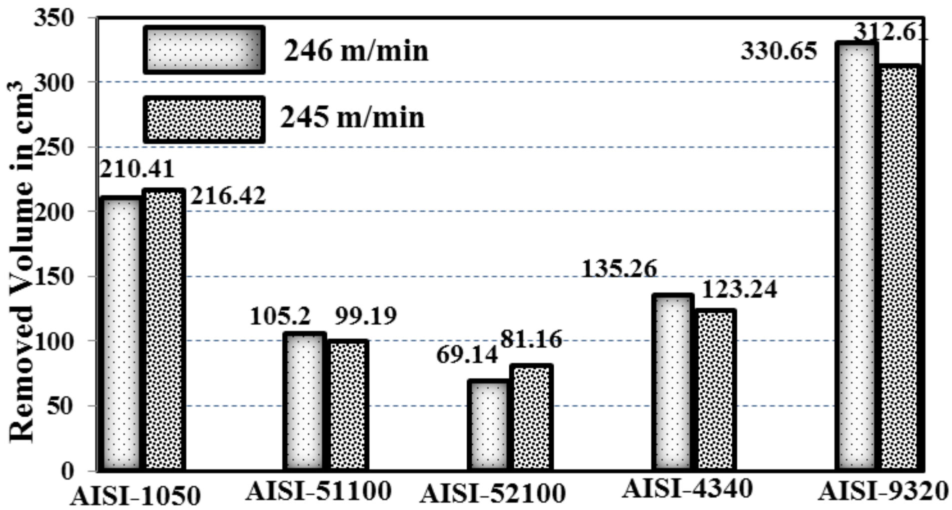


Figure 4.17: Removed volume at critical flank wear for all the work-material at 246 m/min on HMT-Lathe and 245 m/min on Panther

material required for the experimentation of the machinability ranking using face turning method.

Figure 4.17 shows amount of material removed for two different speeds. All the work-materials are machined at 246 m/min on a sturdy HMT lathe to rank their machinability. To check the reproducibility of this result, the work-materials are tested at speed of 245 m/min on another machine (Panther lathe) with the same cutting parameters. The machinability ranking for the volume of material removed results are in close agreement with each other. The repeatability and reproducibility test even for the removed has proved consistent machinability ranking as I, II, III, IV, and V of the work-material, AISI-9320, AISI-1050, AISI-4340, AISI-51100 and AISI-52100 respectively. Thus the highest machinable work-material AISI-9320 is subjected to maximum material removal till the tool reaches its failure criterion.

Critical Volume Calculation

*Total Volume of material removed for one speed = [Cross-sectional area of work material * Depth of Cut] * No. of passes required till the tool failure criterion is reached (shown in appendix)*

Eg. Critical Volume Calculation for AISI-1050. (Please refer Table 5.1, 5.2 and 5.3)

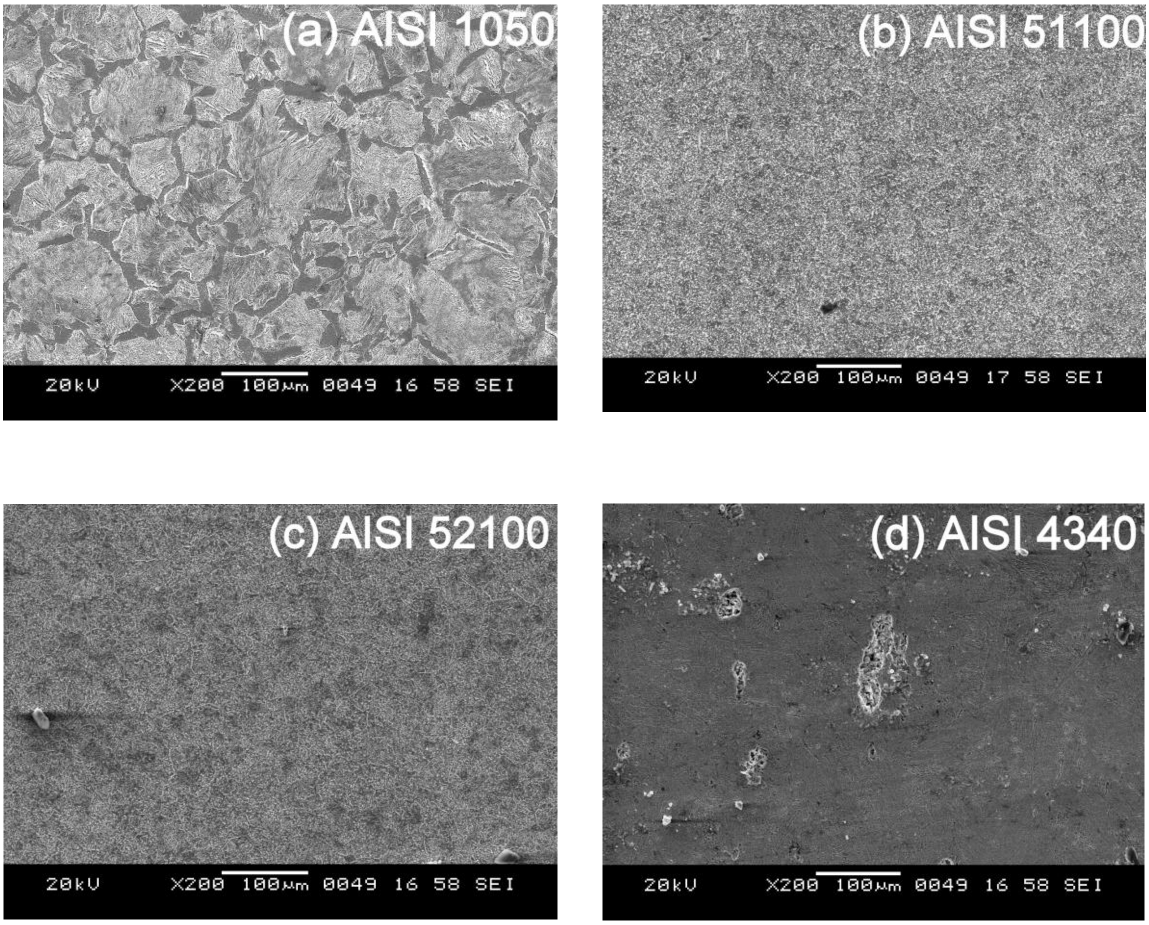
Volume of material removed for a speed of 197 m/min= $[\pi / 4(9.8^2 - 0.6^2) * 0.04] * 110 = 330.64\ cm^3$

Similarly Volume of material removed for a speed of 246 m/min and 308 m/min = $210.4\ cm^3$ *and* $90.176\ cm^3$ *respectively. Since each work material is tested for three different speeds, the total volume of material removed for AISI- 1050 (Fig.4.16) =* $330.64\ cm^3 + 210.4\ cm^3 + 90.176\ cm^3 = 631.22\ cm^3$.

4.6 SEM investigations

The SEM images of each of the work-material are shown in figure 4.18. Whereas figure 4.19 shows SEM images of the machined surfaces of the work-material after the tool inserts have reached the tool life criteria of 0.3mm. From the images it is very evident that for the AISI-51100 the tool marks are dominant whereas for AISI-52100 the tool marks are unclear. The AISI-52100 is harder than 51100 .The AISI-52100 work-materials being harder has abraded the tool cutting edge. For the same cutting conditions and same tool, the effect of hardness is seen in the SEM images. The tool has penetrated more in AISI-51100 resulting in higher surface roughness value than AISI-52100 and this is evident from the values in figure 4.13 and figure 4.14. The hard material disallows the formation of newer tool edge in machining AISI-52100. This is clear from the increasing surface roughness values obtained in the table 4.6. Thus the tool wear for machining AISI-51100 steel material is mainly due to abrasion. Whereas the tools wear in AISI-52100 steel material is both, first due to abrasion and then due to adhesion.

AISI-52100 is harder than AISI-51100 mainly due to presence of more chromium. Chromium has positive effect on hardenability and is an important alloying element in steels. It is present as a solid solution in steels. In addition to hardenability and solid solution effects, chromium forms several important chromium carbides that are necessary for wear resistance in steels (Bruce L Brampitt 2002). The presence of chromium carbide is also seen in SEM image of AISI-52100 in figure 4.18 whereas in the same figure for AISI-51100 no evidences of any of the carbides are seen. Thus investigations from SEM also depict the ability of face turning test method to detect the effect of slight change in chemical composition.



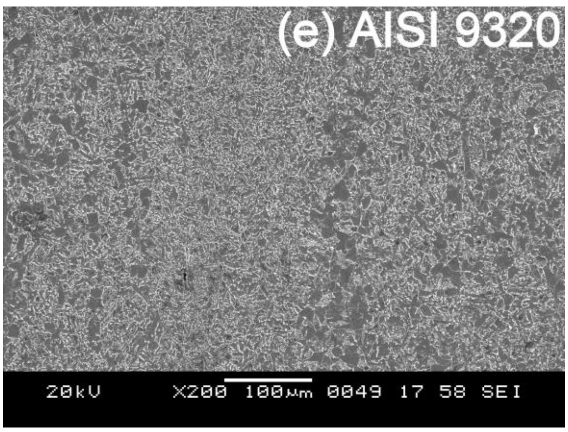


Figure 4.18: SEM microphotographs (Nital 3 % etched) of the work-materials

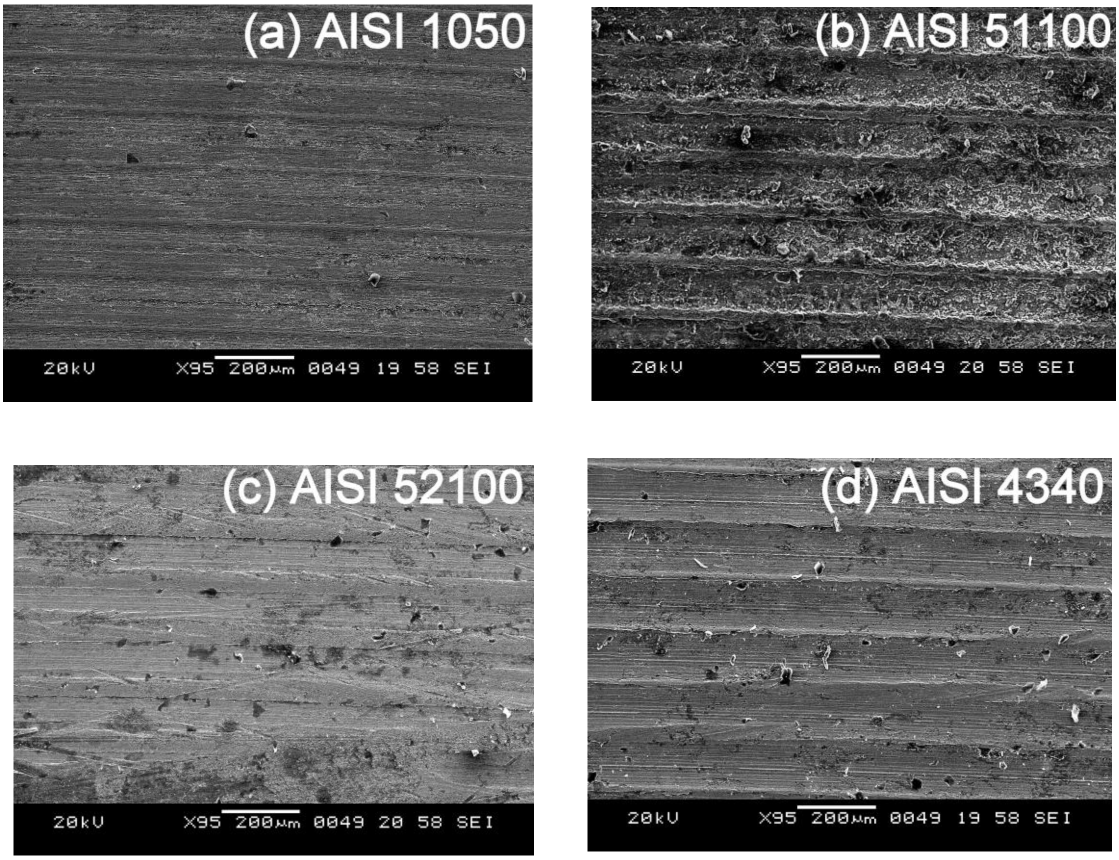
(a) AISI-1050

(b) AISI-51100

(c) AISI-52100

(d) AISI-4340

(e) AISI-9320



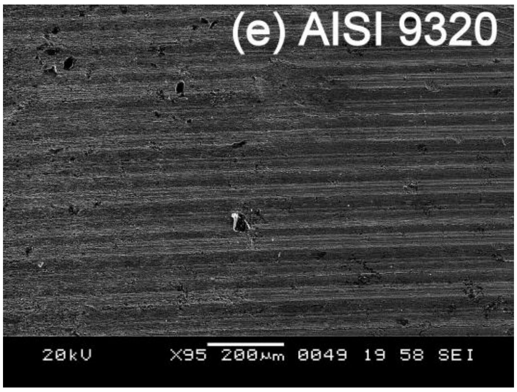


Figure 4.19: Machined surface images after tool wear of 0.3 mm has reached SEM microphotographs at 245 m/min
(a) AISI-1050
(b) AISI-51100
(c) AISI-52100
(d) AISI-4340
(e) AISI-9320

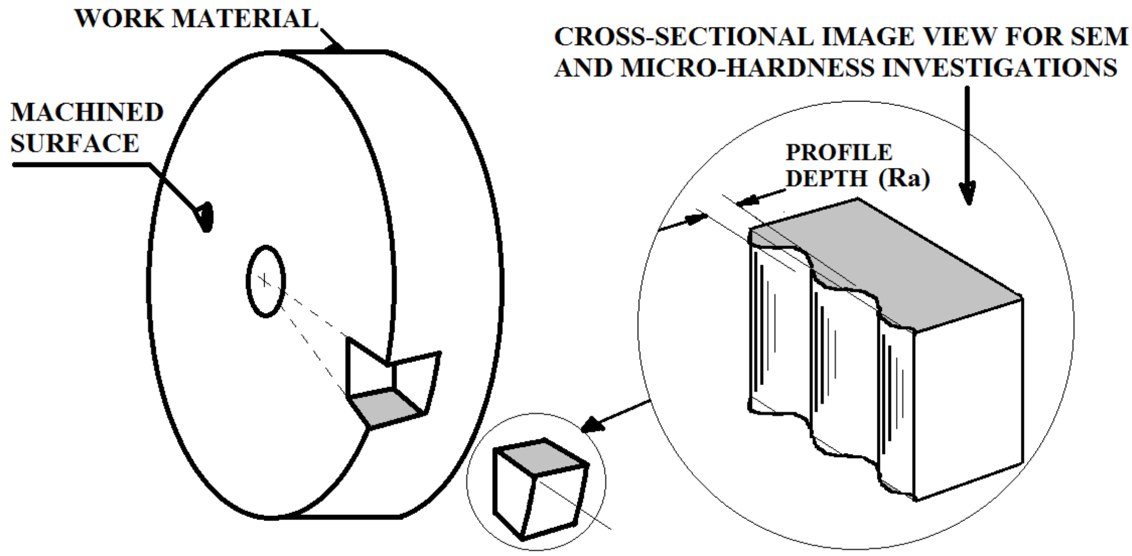


Figure 4.20: Line sketch showing how a sample is sliced out (after the tool life criterion is reached) from the work-material for SEM and Micro-hardness investigations.

4.6.1 Surface profile investigations

Machining is basically a finishing process with specified dimensions, tolerances and surface finish and thus the type of surface that a machining operation generates and its characteristics are of great importance in manufacturing. The surface profile investigation characterises the quality of machined surface (surface achieved) after the tool wear is reached. It shows the interacting effects of the each tool-work material pair. Here in the study conducted the carbide tool used is common for all the different work materials. The resultant work material properties due to its alloying elements affecting the tool wear is seen in this investigation.

The cross-sectional edge of the machined surface, SEM image, after the tool wear of 0.3mm is reached at cutting speed of 245 m/min is shown in figure 4.21. The line sketch of edge surface profile is shown in figure 4.20. Figure 4.20 shows how the sample for SEM and micro-hardness investigations was drawn from each of the work-material. While preparing the specimen, every care was taken to see that the cross-sectional edge was protected from mishandling. The specimen were encapsulated in an epoxy mould and then subjected to a series of soft polishing stages and then the micro hardness was measured.

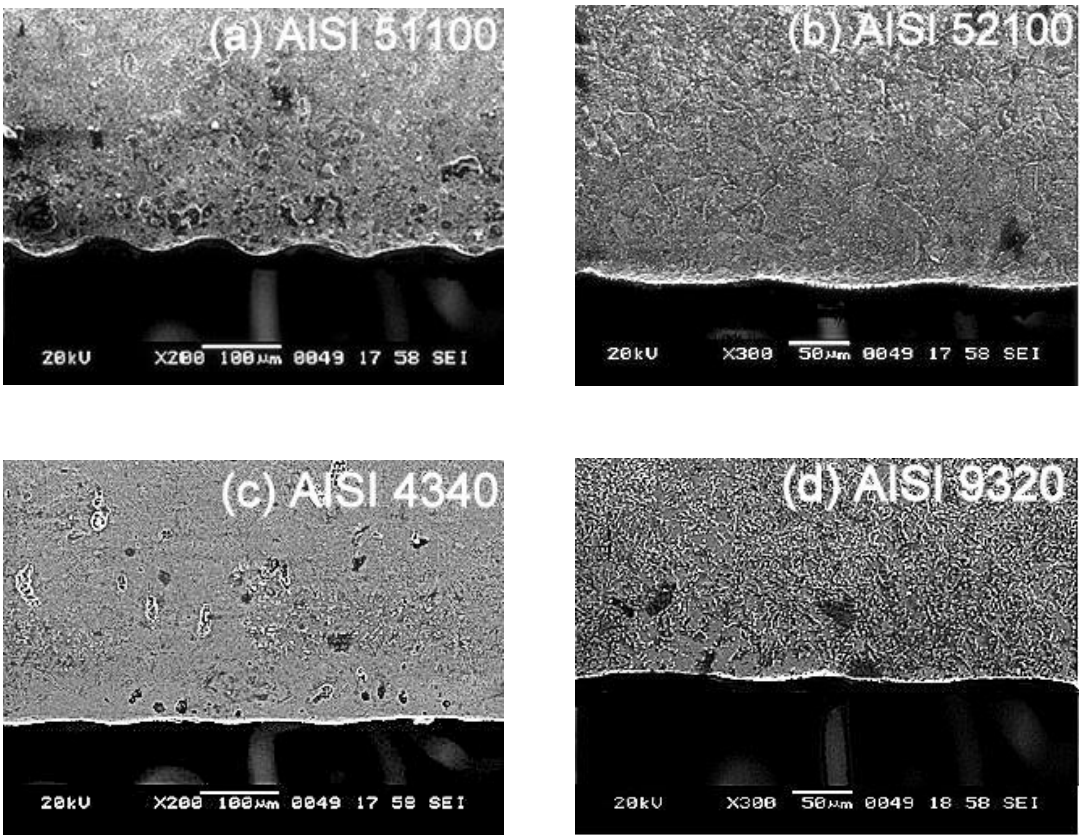


Figure 4.21: Cross-sectional Edge machined surface (SEM) images observed after tool wear of 0.3mm has reached at cutting speed of 245 m/min for work-materials (a) AISI-51100 (b) AISI-52100 (c) AISI-4340 (d) AISI-9320

The geometrical irregularities, feed marks and roughness depth of four samples are correctly depicted in the figure 4.21. The data in the table 4.6 for Ra values proportionately confirm with the corresponding profile feed marks of SEM in figure 4.21.The depth of profile (or average surface roughness) is as shown in table 4.6, the reasons explained in earlier section. The SEM investigations demonstrate the sensitivity and effectivity of face turning method at a greater depth. Thus face turning method can be used as a means of testing machinability of carbon and steel work materials.

Table 4.6: Surface Roughness (µm) after face turning at 245 m/min

	AISI-1050	AISI-51100	AISI-52100	AISI-4340	AISI-9320
Ra	3.53	8.44	7.99	3.25	1.3

4.7 Micro hardness investigations

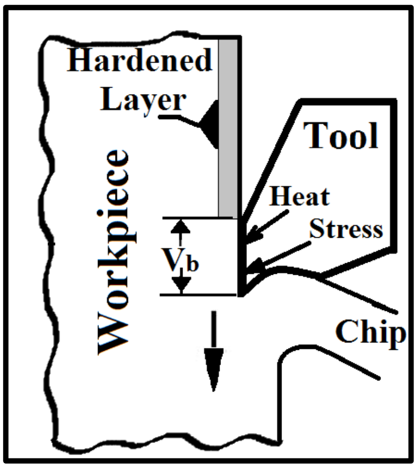


Figure 4.22: A typical hardened layer due to machining of work materials after flank wear is reached

Every machining process is subjected high stresses, high strain rate, high temperature and short interaction time (~ 0.1ms) with the work materials encountered during chip formation process. At high cutting speeds the machining process always result in some changes at work material surfaces in the form of microstructural alteration, microhardness changes and residual stresses which is categorically known as surface integrity. In machining all mechanical energy is converted in thermal energy, heat. The heat may increase local surface temperature dramatically. If the heat flux is high enough to reach the phase transformation temperature (ferrite + cementite = austenite) with subsequent rapid self-cooling by the bulk, the surface material will form martensite (Kevin Chou, Y. 2002).

Table 4.7: Microhardness at edge and center of cross-section of work-materials

Micro-hardness HV(50gm load)	Edge hardness (near machined surface)	Bulk material hardness
AISI-1050	279 HV	197 HV
AISI-51100	310 HV	215 HV
AISI-52100	263 HV	265 HV
AISI-4320	372 HV	263 HV
AISI-9320	309 HV	214 HV

At high speeds the work hardening effect on the machined surfaces were reported (Gaurav Bartarya et al 2012). Such work hardening effects influences the functional aspects of the work-material under consideration. Similar effects were observed while machinability testing of Powder Metallurgy steels (A.Salak et al 2006).

Machining normally induces a severe plastic deformation in the material. When the machining is done at higher cutting speed the thermal gradient plays an important role in inducing work hardening effect. The samples were encapsulated in an epoxy mold and then subjected to a series of soft polishing stages and then the micro hardness was measured. The changes in microhardness of the workpiece surface and subsurface (in the matrix) were measured normal to the machined surface using a Vicker's microhardness tester. The microhardness measurements for all the samples were repeated three times for each sample. Enough spacing between indents and from the edge of the sample was provided. Micro hardness is higher near the machined surface layer and decreases rapidly as the depth increases. This is due to the fact that the region confined to the surface is subjected to maximum workhardening. The microhardness near the surface was found nearly 1.5 times the bulk material micro hardness

The results are shown in the table 4.6. Except for AISI-52100, the work-hardening is prevalent on all work-materials. In AISI-52100 the hard particles of chromium disallow any significant work hardening effect (Rajshekhar. Lalbondre et al 2012). Thus the micro-hardness is almost same at the edge and center.

The increase in hardness of the machined surfaces at relatively low feed force (feed 0.145 mm/rev) causes significant work hardening on the machined surfaces. The materials were machined in dry and interrupted condition, which were also frequently cooled. Plastic deformation of the matrix was the prominent mode of the sub surface damage occurred under dry cutting conditions. It was found that the austenitic matrix phase affects the depth of plastically deformed zone beneath the machined surface. The degree of work hardening and its extent can be reduced by using properly optimized cutting parameters during high speed machining (Thakur, D.G et al. 2010).

4.8 Chip morphology and Crater wear

In the current study the cutting tools used were without chip breaker under dry cutting condition as indicated in the standard (ISO-3685:1993 E).The morphology of the chips formed when face turning the specimens was affected by the base alloy composition.

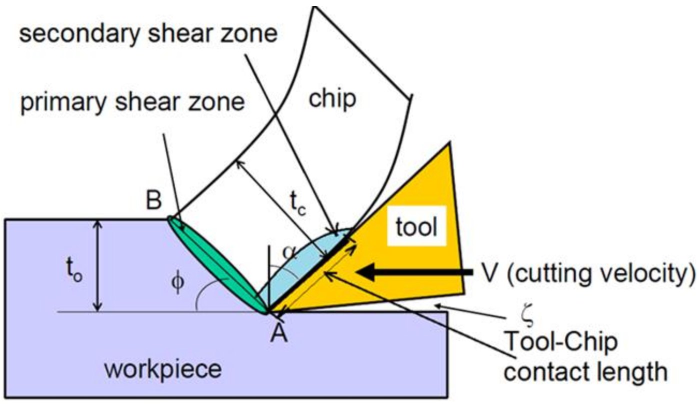


Figure 4.23: A typical chip-formation geometry

The main factors that affect the chip flow are the rake angle of the tool, the friction between the chip-tool and the work hardening of the work-material as it forms the chip (Ebrahimi .A, Moshkar MM 2009). The chip-tool contact length is shown in figure 4.23. The chip-tool contact length decreases with the increase in cutting speed causing decrease in the effect of contact forces. At high cutting speeds because of high temperature on contact zone. (Figure. 4.24), this effect shows the large damage and heat-affected area on the crater face during machining. Ye .G.G et al (2012) reported that increasing the cutting speed would lead to decrease of the finished surface temperature and increase of the tool-chip contact.

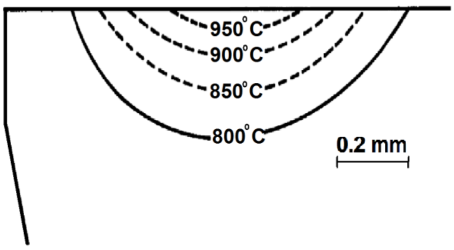


Figure 4.24: Temperature distribution on typical carbide tool (Trent. E M and Wright P K 2000)

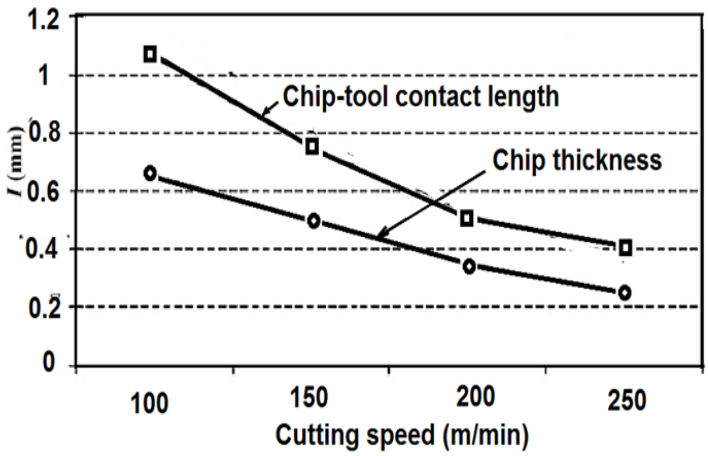


Figure 4.25: Chip-tool contact length & chip thickness v/s Cutting speed (Ebrahimi .A, Moshkar MM 2009).

Figure (4.26) to Figure (4.30) shows the chip morphology and corresponding crater wear image of the tool after tool life criterion has reached .for all the work-materials under consideration at different cutting speeds.

4.8.1 AISI 1050:

Since the base material is medium carbon steel the ductility effect on chips formation is seen by its continuous form. At lower range of 197 m/min speed the chip formed are continuous long tubular chip with uniform diameter a little under 2 mm as shown

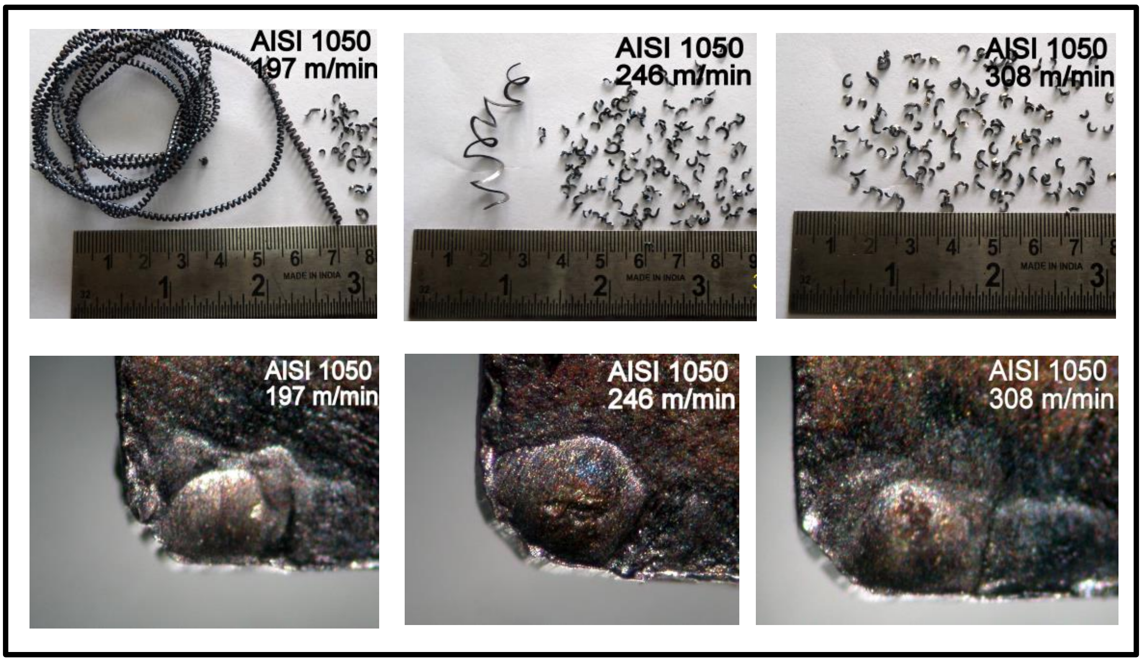


Figure 4.26: Chips obtained while machining AISI-1050 work-material and corresponding Crater wear recorded (at V_b=0.3) on the tool rake face at different speed of (a) 197 m/min (b) 246 m/min(c) 308 m/min.

in figure 4.26(a). This form of chip attracted continuous attention of the operator so as to avoid the chips to entangle around the rotating chuck and the work piece. This attention was needed to avoid: damage of the machined surface, injury to operator and abrupt load / hazard to the machine. The chips continually contact first the rake face of the tool and slide past from the crater area. Thus crater wear is spread over large area as such chips rub past the rake face as is evident in the figure 4.26(b)

At the speed of 246 m/min and 308 m/min the chips formed are segmental arched of 3mm -6mm in length. The size and shape is almost similar for both these speeds. However the crater wear at higher speed of 308 m/min is more concentrated than at speed of 246 m/min. At higher speed machining the heat dissipation is greater in the chip formation zone and thermal phenomena play a key role here. The area of crater wear is less but the depth of crater is comparatively more as the high speed impact of chip is more concentrated.

4.8.2 AISI 51100

This is high carbon steel. The expected chip is segmental at lower range of experimental speed, 197 m/min. The shape and sizes of chips at 197 m/min are longer and 6 – 8mm longer: and also the chip thickness is comparatively larger. At increased speeds 246 m/min the chips formed are of segmental but of very small size (2 to 5 mm as shown in Fig.4.27 (a) also the chips are of comparatively lower thickness (Ebrahimi .A, Moshkar M.M 2009). The crater wear formation at 197 m/min is stepped up in two regions as shown in Fig. 4.27 (b), which is a case of abrasion wear. The crater wear formation for all the speeds is almost similar to observations made for AISI-1050. .However the thickness of chips kept on decreasing as the experimental speed increased.

4.8.3 AISI 52100

This is a bearing steel with high chromium content. At lower range of its experimental speed (123 m/min) chips formed are short length, about 25mm, tubular chips with thickness of nearly 1mm.the crater is spread over large area with low depth.

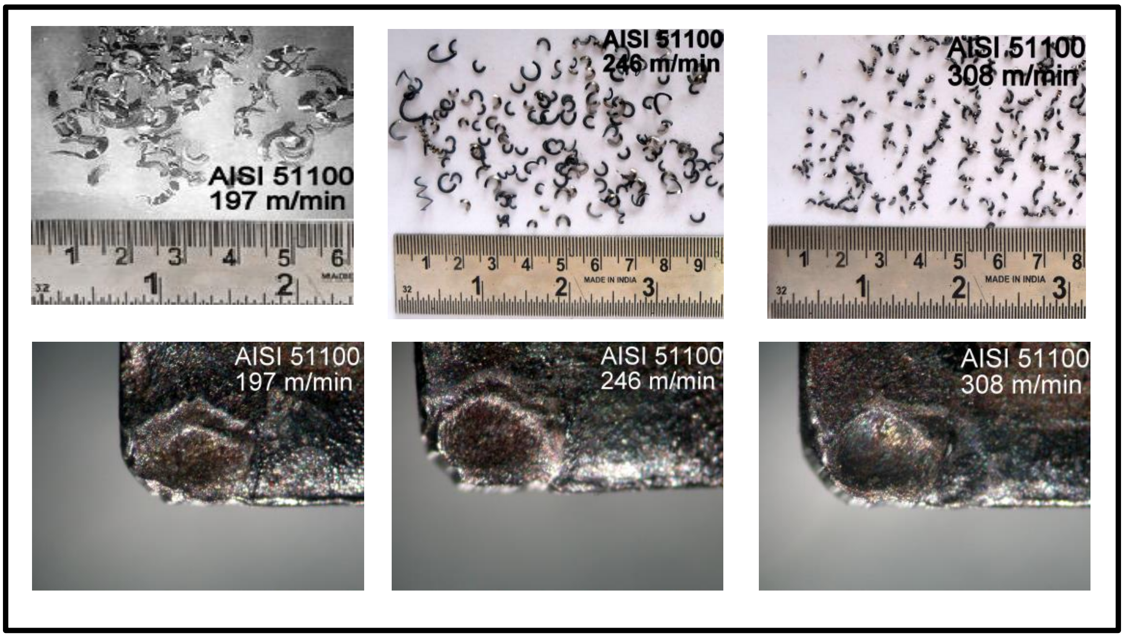


Figure 4.27: Chips obtained while machining AISI-51100 work-material and corresponding Crater wear recorded (at V_b=0.3) on the tool rake face at different speed of (a) 197 m/min (b) 246 m/min(c) 308 m/min.

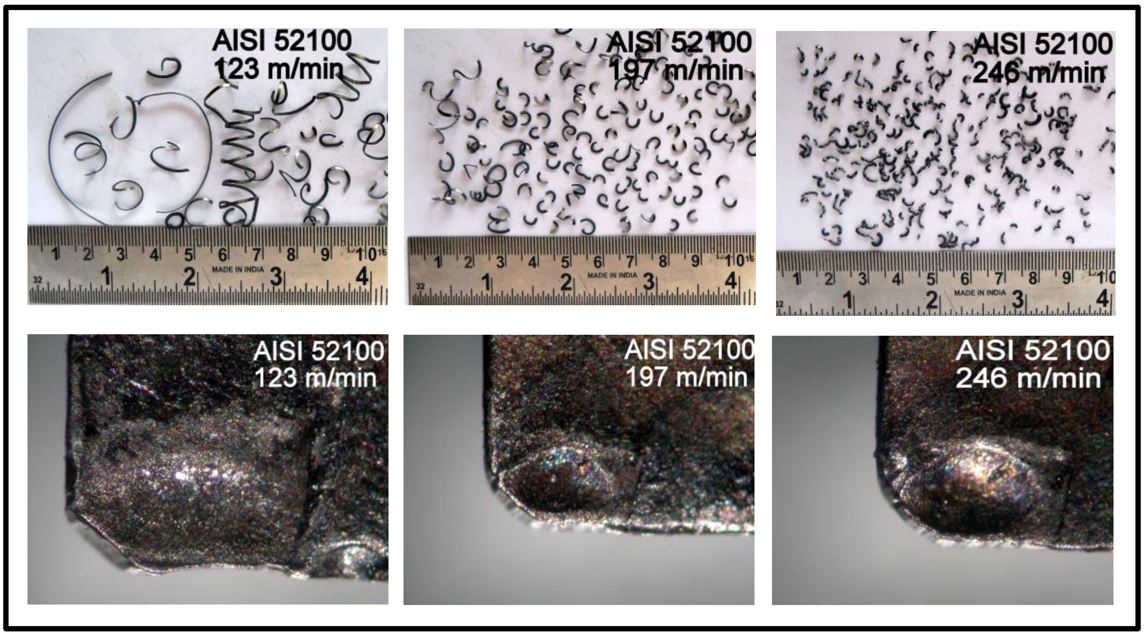


Figure 4.28: Chips obtained while machining AISI-52100 work-material and corresponding Crater wear recorded (at V_b=0.3) on the tool rake face at different speed of (a) 123 m/min (b) 197 m/min (c) 246 m/min.

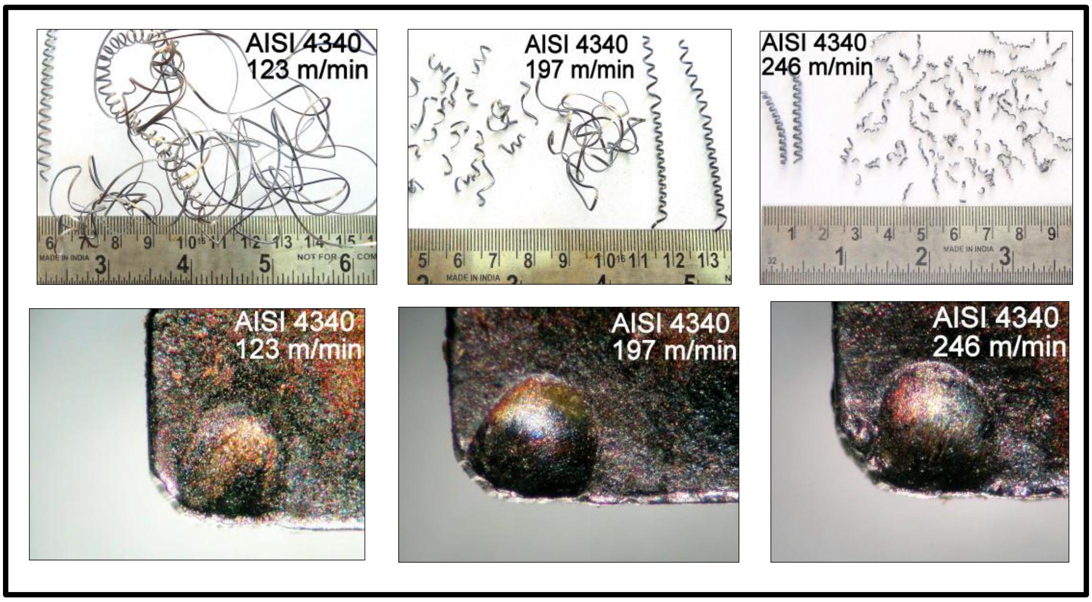


Figure 4.29: Chips obtained while machining AISI-4340 work-material and corresponding Crater wear recorded (at V_b=0.3) on the tool rake face at different speed of (a) 123 m/min (b) 197 m/min (c) 246 m/min.

At 197 m/min the chips formed are arched loose of uniform size around 5 mm. This has given rise to a small area of crater on the rake face.

At still higher speed of 246 m/min chips formed are loose arched but smaller in size, shape and thickness than the earlier one. The crater area is concentrated, clear having good reflecting surface because of the thermal effect arising out higher cutting speed.

4.8.4 AISI 4340

At 123 m/min the chips are snarled continuous ribbon chips therefore the crater formed though concentrated but low depth.

At next higher speed of 197 m/min the chips formed are tubular and snarled chips. However the crater is clear, reflective and good depth.

At further higher speed of 246 m/min the chips are small, consistent tubular chips. The crater is similar to earlier but the cutting edge is burred.

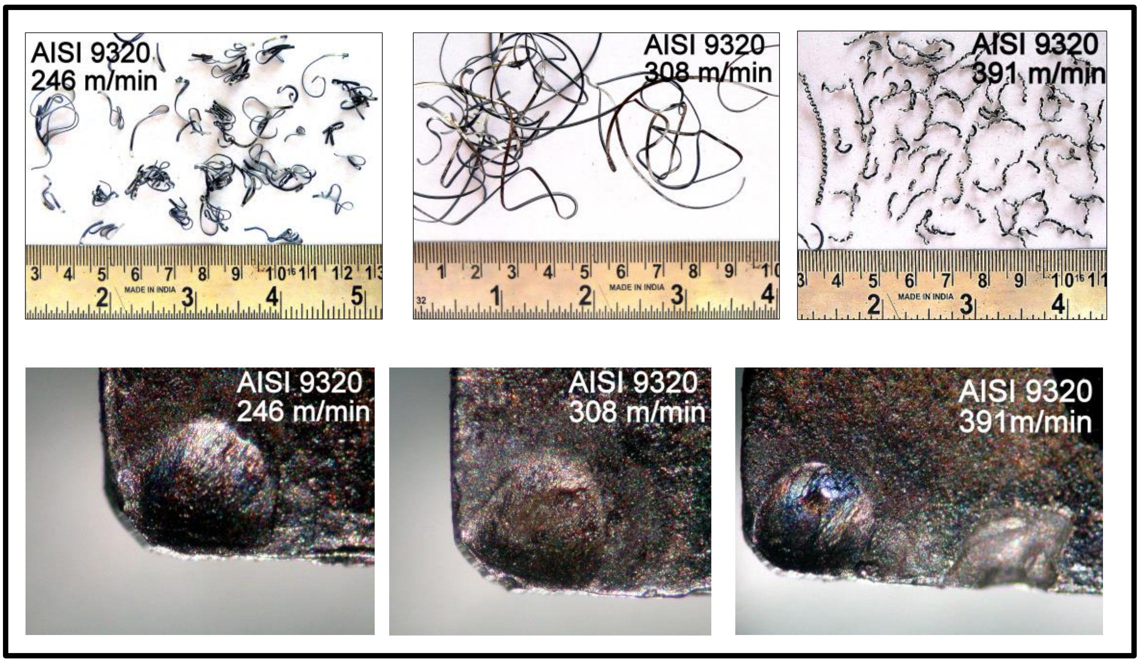


Figure 4.30: Chips obtained while machining AISI-9320 work-material and corresponding Crater wear recorded (at V_b=0.3) on the tool rake face at different speed of (a) 246 m/min (b) 308 m/min (c) 391 m/min.

4.8.5 AISI 9320

At lower range of experimental speed of this alloy steel, 246 m/min, the chips produced are snarled accumulated in small bunch which is repetitive in nature. The chips flows on the rake face at one particular area giving rise to a cleat and reflective surface of crater.

For the next level of higher speed 309m/min, the chip produced are continuous ribbon type snarled which entangled into a big bunch and piled on the rake face. The chips needed to be hand disposed after every pass. Obviously the chip piling on the rake face created a comparatively large crater area with low depth.

At the speed of 391 m/min, the highest experimental speed in the current study, the chips are thinner but tubular with very small diameter, less than 0.6 mm, with the uniform tube length from 9mm to 16 mm. The chip disposal over the rake face of the tool was very easy. Therefore the crater produced as expected was very clear and reflective with better depth.

4.8.6 General observations

All the cutting parameters (cutting speed, feed and depth of cut) have significant effect on the chip formation and tool wear. The plastic deformation of material, rate of tool wear and chip formation types vary with cutting conditions (Bhuiyan, M.S.H et al 2012). The chip formation is mostly affected by the change of cutting speed followed by the depth of cut and the feed rate. The rate of tool wear and plastic deformation of work-material increases with the increase of cutting speed, feed rate and depth of cut until the chip breakage. The tools wear decreases with the increase of chip breakage**.**

In this case of dry and high speed machining, the heat dissipation in the chip formation zone is much greater. Thus the thermal phenomenon plays a key role in the tool wear and surface integrity (Grzesik. W and Niestory. P 2000). The most significant factor influencing the crater wear is the temperature at the tool-chip interface.

It has been thus observed that the chip morphology under different cutting speed is different. The chips thickness kept on decreasing as the cutting speed is increased to the next level. The formation of different chips results in different shape and size of crater on the tool. This is quite prevalent in current study. Daymi. A et al (2009) reported that generally a continuous chip is formed at lower speeds of 50 m/min, flow chip for speeds ranging around 100 m/min and shear localized chip starting from the transition speed of 125 m//min and above. Further he concluded that chip segmentation by shear localization is an important process (observed at certain range of cutting speeds) which is desired as it reduces the level of cutting forces by improving chip's evacuation. Here in the current study the commencement of shear localization of chip with transition speed was observed somewhere near the middle range of experimental speed for each of the work-material.

CHAPTER 5

CONCLUSIONS AND SCOPE FOR FUTURE

5.1 Conclusions

Based on the detailed discussions made in the previous chapter, the current study with the objectively identified: tool-work material pair with its grade and geometry; machining parameters and experimentation resources has arrived to the following conclusive remarks.

- The face turning operation represents a contemporary interrupted machining mode which in reality is found very commonly in manufacturing industry. The related machinability tests conducted is close to shop floor conditions and can be used to monitor engineered changes in industries, as the behavior of wear mechanism of the carbide tool for the said steels is in line with traditional machining methods.
- This test demonstrated the ability to detect the effect of slight change in chemical composition of carbon, manganese, and chromium in these steels. The SEM and surface profile investigations reveal varying effect of alloying elements (namely carbon, manganese, and chromium) on machinability. The SEM investigations and analysis is successfully used for machinability characterization of the work-materials under consideration.
- The machinability ranking of the work-materials is in the order of I-AISI-9320, II-AISI-1050, III-AISI-4340, IV-AISI-51100 and V-AISI-52100 considering tool wear; the surface finish and chip morphology studies being complimentary to the results.
- The tool life equation presented for the work-materials lies within a permissible limit of ±5%. The model equation follows a polynomial quadratic equation $f(x) = \text{Intercepts} + B1*x+B2*.x^2$ with 95% confidence level.
- Effect of chip formation over the crater wear was also demonstrated. The chip morphology studies revealed that the shear localization of the chip occurs near the middle range of experimental speed used for the work-materials under consideration.

The face turning method of determining the machinability of steels is easy and simple, as it can be performed in a locally available machine tool laboratory with a proper combination of tool-work material grade and geometry. The time taken to derive the machinability results by this method is comparatively less. This method is effective as the machinability characterization aspects: tool wear development and wear mechanisms involved in machining; tool life studies and machinability indices of the work-material; surface roughness and micro hardness investigations (SEM) of the machined surfaces; and chip morphology and crater wear, are in close agreement with the available literature. This methodology of determining machinability can be considered as a step towards creating a local data base.

5.2 Scope for future

The following recommendations shall be made as the scope for future work

- The experiments in present work were conducted for dry cutting conditions. A lot of research work has been conducted to determine the effect of wet cutting conditions and Minimal Quantity Lubrication (MQL) which resulted in considerable influence on tool wear/life, surface finish/integrity and chip formation during machining. Thus an attempt can be made to further study on wet and/or minimal quantity lubrication and compare it with its corresponding dry conditions for tool wear/life, surface finish and chip formation under different cutting conditions.
- The present study involved machinability studies on as rolled work materials of carbon and alloy steels. Considerable research on the heat treated materials for its improvement in mechanical and metallurgical properties has been made. Hence the ensuing work material can be suitably heat treated as per the required application and its influence on machinability characterisation can be attempted for further investigations.
- The current investigation of machinability on carbon and alloy steels is made using a single point uncoated tungsten carbide tool, P-30. A lot of published literature is available on the influence of coating on tool wear/life. An attempt

to investigate machinability of harder steels using a coated tool is suggested. Further the study can also be compared with its uncoated tool counterpart.

APPENDIX

The appendix is categorized in two sections, the first one consists of tabulated data and the second one consists of micro-hardness figures.

Tables

The entire data of the experimental work undertaken has been systematically tabulated individually for each of the work-material, from table 1 to table 20. For the stipulated number of passes the wear on the tool was progressively recorded and simultaneously surface finish parameters Ra, Rz and Rq on work-materials was recorded. The details of such recordings for the work-materials under consideration at different speeds are given in the tables ahead.

Table 5.1: Tool wear and surface finish recorded periodically while machining work-material AISI 1050 at speed of 197 m/min.

AISI 1050 197 m/min [640 rpm]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	4.96	0.12	3.72	19.39	4.16	1.12
20	9.91	0.14	3.01	15.67	3.46	1.16
30	14.87	0.15	2.30	11.95	2.75	1.20
40	19.83	0.18	3.45	17.30	4.15	1.20
50	24.78	0.20	4.6	22.64	5.55	1.21
60	29.74	0.23	6.12	21.86	6.39	1.04
70	34.70	0.25	7.54	38.29	9.13	1.21
80	39.66	0.26	6.51	29.88	6.07	0.93
90	44.61	0.28	6.78	31.03	8.08	1.19
100	49.57	0.29	6.38	29.18	7.53	1.18
110	54.53	0.30	5.65	27.22	6.74	1.19

Critical Volume of material removed = 330.64 cm3

Table 5.2: Tool wear and surface finish recorded periodically while machining work-material AISI 1050 at speed of 246 m/min.

AISI 1050 246 m/min [800 rpm]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
5	1.98	0.11	3.38	15.32	3.97	1.17
10	3.97	0.17	3.21	15.49	3.77	1.17
20	7.93	0.20	3.54	16.72	4.17	1.18
30	11.90	0.23	2.13	11.69	2.65	1.24
40	15.86	0.25	1.63	9.82	2.08	1.28
50	19.83	0.26	1.69	7.6	2	1.18
60	23.79	0.28	1.95	11.89	2.48	1.27
70	27.76	0.30	2.24	13.97	2.92	1.30

Critical Volume of material removed = 210.41 cm3

Table 5.3: Tool wear and surface finish recorded periodically while machining work-material AISI 1050 at speed of 308 m/min.

AISI 1050 308 m/min [1000 rpm]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
5	1.59	0.2	2.56	10.02	3.08	1.20
10	3.17	0.23	2.88	15.61	3.48	1.21
15	4.76	0.25	1.89	10.24	2.31	1.22
20	6.34	0.27	2.34	12.11	2.82	1.21
25	7.93	0.28	3.26	16.47	3.91	1.20
30	9.52	0.3	3.51	18.11	4.26	1.21

Critical Volume of material removed = 90.176 cm^3

Table 5.4: Tool wear and surface finish recorded periodically while machining work-material AISI 1050 at speed of 245 m/min.

AISI 1050 245 m/min [796 rpm]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	4.1	0.13	3.35	2.53	3.86	1.15
20	8.21	0.16	2.86	3.74	3.28	1.15
30	12.31	0.19	3.48	5.33	4.01	1.15
40	16.42	0.22	3.82	6.82	4.44	1.16
50	20.52	0.24	3.23	8.00	3.74	1.16
55	22.57	0.26	3.08	8.64	3.60	1.17
60	24.62	0.27	3.17	9.35	3.78	1.19
65	26.68	0.29	3.36	10.11	3.88	1.15
72	29.55	0.30	3.53	11.13	4.12	1.17

Critical Volume of material removed = 216.42 cm3

Table 5.5: Tool wear and surface finish recorded periodically while machining work-material AISI 51100 at speed of 197 m/min.

AISI-51100 197 m/min (640 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
10	4.96	0.08	3.17	14.42	3.74	1.18
20	9.91	0.11	5.37	20.12	6.52	1.21
30	14.87	0.15	7.59	25.36	8.31	1.09
40	19.83	0.16	8.63	31.79	9.02	1.05
50	24.78	0.18	9	40.01	9.61	1.07
60	29.74	0.21	10.52	48.33	10.99	1.04
70	34.7	0.25	11.01	56.57	12.1	1.10
80	39.66	0.3	12.38	57.06	14.06	1.14

Critical Volume of material removed=240.47 cm^3

Table 5.6: Tool wear and surface finish recorded periodically while machining work-material AISI 51100 at speed of 246 m/min.

AISI- 51100 246 m/min (800 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	1.98	0.15	2.41	13.8	3.22	1.34
10	3.97	0.2	4	20.8	5.21	1.30
15	5.95	0.23	5.75	24	6.98	1.21
20	7.93	0.26	6.65	26.9	7.92	1.19
25	9.91	0.27	7.01	28	8.36	1.19
30	11.90	0.28	8.23	33.3	9.74	1.18
35	13.88	0.3	8.74	34.1	10.24	1.17

Critical Volume of material removed=105.20 cm3

Table 5.7: Tool wear and surface finish recorded periodically while machining work-material AISI 51100 at speed of 308 m/min.

AISI- 51100 308 m/min (1000 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	1.59	0.19	2.01	13.26	2.73	1.36
8	2.54	0.22	2.48	14.11	2.88	1.16
10	3.17	0.24	2.72	15.73	3.25	1.19
13	4.12	0.25	2.98	16.02	3.98	1.34
18	5.71	0.27	3.21	17.57	4.1	1.28
23	7.30	0.3	3.5	18.81	4.38	1.25

Critical Volume of material removed=69.14 cm3

Table 5.8: Tool wear and surface finish recorded periodically while machining work-material AISI 51100 at speed of 245 m/min.

AISI-51100 245 m/min (796 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	1.99	0.12	2.3	13.4	3.07	1.34
10	3.99	0.15	4.07	20.3	5.06	1.24
15	5.98	0.21	5.65	23.8	6.84	1.21
20	7.97	0.23	6.58	26.8	7.78	1.18
25	9.96	0.24	6.92	27.3	8.22	1.19
30	11.96	0.25	8.07	32.3	9.59	1.19
33	13.15	0.3	8.44	32.9	10.09	1.20

Critical Volume of material removed=99.19 cm3

Table 5.9: Tool wear and surface finish recorded periodically while machining work-material AISI 52100 at speed of 123 m/min.

AISI 52100 123 m/min (400 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
10	7.93	0.1	4.83	23.97	6.03	1.25
20	15.86	0.16	5.04	24.44	5.85	1.16
30	23.79	0.2	6.84	31.37	8.32	1.22
40	31.72	0.21	6.99	33.29	8.08	1.16
50	39.66	0.23	9.45	36.61	11	1.16
60	47.59	0.25	10.48	39.08	11.69	1.12
65	51.55	0.3	11.15	43.75	12.39	1.11

Critical Volume of material removed= 195.38 cm^3

Table 5.10: Tool wear and surface finish recorded periodically while machining work-material AISI 52100 at speed of 197 m/min.

AISI 52100 197m/min (640 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	2.48	0.13	3.17	14.42	3.74	1.18
10	4.96	0.16	3.64	17.98	4.47	1.23
20	9.91	0.18	4.92	22.02	5.91	1.20
30	14.87	0.21	5.29	22.28	6.25	1.18
35	17.35	0.25	6.28	23.91	7.15	1.14
40	19.83	0.3	6.85	25.21	7.93	1.16

Critical Volume of material removed=120.23 cm^3

Table 5.11: Tool wear and surface finish recorded periodically while machining work-material AISI 52100 at speed of 246 m/min.

AISI 52100 246 m/min (800 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	1.98	0.16	3.22	15.5	3.9	1.21
10	3.97	0.18	4.34	19.79	5.27	1.21
15	5.95	0.21	5.61	23.34	6.5	1.16
20	7.93	0.25	6.94	27.59	7.99	1.15
23	9.12	0.3	7.68	30.62	8.81	1.15

Critical Volume of material removed= 69.14 cm^3

Table 5.12: Tool wear and surface finish recorded periodically while machining work-material AISI 52100 at speed of 245 m/min.

AISI 52100 Validation 245 m/min (796 RPM)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq/Ra**
5	1.99	0.2	4.36	17.43	4.62	1.06
10	3.99	0.22	4.2	15.28	4.64	1.11
15	5.98	0.23	5.01	21.71	6.20	1.24
20	7.97	0.27	6.65	26.48	7.94	1.19
25	9.96	0.29	7.82	29.08	8.76	1.12
27	10.76	0.3	7.99	29.48	9.73	1.22

Critical Volume of material removed= 81.16 cm^3

Table 5.13: Tool wear and surface finish recorded periodically while machining work-material AISI 4340 at speed of 123 m/min.

AISI 4340 123 m/min [400 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	7.93	0.14	1.57	7.08	1.72	1.10
20	15.86	0.18	1.81	9.73	2.17	1.20
30	23.79	0.20	1.91	9.37	2.26	1.18
40	31.72	0.22	2.14	9.49	2.54	1.19
50	39.66	0.24	2.19	10.22	2.57	1.17
60	47.59	0.26	2.47	10.4	2.87	1.16
70	55.52	0.27	3.17	13.74	3.61	1.14
80	63.45	0.28	3.08	15.64	3.65	1.19
90	71.38	0.30	4.30	19.47	4.74	1.10

Critical Volume of material removed=270.52 cm3

Table 5.14: Tool wear and surface finish recorded periodically while machining work-material AISI 4340 at speed of 197 m/min.

AISI 4340 197 m/min [640 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	4.96	0.15	1.22	7.44	1.52	1.25
20	9.91	0.19	1.51	9.09	1.88	1.25
30	14.87	0.22	1.96	11.03	2.43	1.24
40	19.83	0.24	2.09	11.11	2.52	1.21
50	24.78	0.25	2.95	13.15	3.43	1.16
60	29.74	0.27	4.20	22.23	4.96	1.18
65	32.22	0.3	4.49	19.7	4.96	1.10

Critical Volume of material removed= 195.38 cm3

Table 5.15: Tool wear and surface finish recorded periodically while machining work-material AISI 4340 at speed of 246 m/min.

AISI 4340 246 m/min [800 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
5	1.98	0.14	2.28	9.5	2.58	1.13
15	5.95	0.18	2.87	11.73	3.25	1.13
25	9.91	0.21	2.81	11.23	3.38	1.20
30	11.90	0.23	2.88	11.84	3.31	1.15
40	15.86	0.26	2.32	10.53	2.72	1.17
45	17.84	0.30	3.72	18.26	4.39	1.18

Critical Volume of material removed=135.26 cm^3

Table 5.16: Tool wear and surface finish recorded periodically while machining work-material AISI 4340 at speed of 245 m/min.

AISI 4340 245 m/min (796 rpm)						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
5	2.05	0.12	3.67	14.47	4.22	1.15
10	4.10	0.13	3.92	15.97	4.50	1.15
17	6.98	0.16	4.41	18.66	5.17	1.17
20	8.21	0.20	3.79	16.75	4.53	1.20
25	10.26	0.21	3.78	16.66	4.50	1.19
30	12.31	0.22	2.86	14.66	3.60	1.26
35	14.36	0.24	3.25	13.09	3.66	1.13
40	16.42	0.29	2.99	13.27	3.54	1.18
41	16.83	0.3	3.25	12.83	3.51	1.08

Critical Volume of material removed= 123.24 cm3

Table 5.17: Tool wear and surface finish recorded periodically while machining work-material AISI 9320 at speed of 246 m/min.

AISI 9320 246 m/min [800 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	3.97	0.10	1.51	9.66	1.9767	1.31
20	7.93	0.12	1.29	7.63	1.59	1.23
30	11.90	0.14	1.09	7.11	1.38	1.27
40	15.86	0.16	1.13	6.68	1.38	1.22
50	19.83	0.18	1.18	7.9	1.46	1.24
60	23.79	0.20	1.45	8.94	1.8	1.24
70	27.76	0.21	1.56	8.7	1.87	1.20
80	31.72	0.22	1.76	10.21	2.15	1.22
90	35.69	0.23	1.81	10.02	2.19	1.21
100	39.66	0.26	1.9	11.21	2.32	1.22
110	43.62	0.30	1.86	11.78	2.42	1.30

Critical Volume of material removed= 330.65 cm^3

Table 5.18: Tool wear and surface finish recorded periodically while machining work-material AISI 9320 at speed of 308 m/min.

AISI 9320 308 m/min [1000 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	3.17	0.11	1.94	8.64	2.23	1.15
15	4.76	0.13	1.47	6.86	1.70	1.16
25	7.93	0.15	1.24	7.42	1.54	1.24
35	11.10	0.16	1.69	9.52	2.09	1.24
45	14.28	0.17	1.81	9.63	2.18	1.20
55	17.45	0.18	1.91	9.8	2.32	1.21
65	20.62	0.20	1.7	8.31	2	1.18
75	23.79	0.23	1.21	7.31	1.52	1.26
85	26.97	0.3	1	6.12	1.27	1.27

Critical Volume of material removed= 255.50 cm^3

Table 5.19: Tool wear and surface finish recorded periodically while machining work-material AISI 9320 at speed of 391 m/min.

AISI 9320 391 m/min [1270 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	2.50	0.13	1.16	6.91	1.42	1.22
20	5.00	0.18	1.54	8.35	1.86	1.21
25	6.24	0.19	1.14	6.71	1.39	1.22
30	7.49	0.21	1.11	6.95	1.38	1.24
35	8.74	0.23	1.37	8.22	1.54	1.12
40	9.99	0.25	1.5	8.91	1.93	1.29
50	12.49	0.27	2.05	10.91	2.51	1.22
60	14.99	0.3	2.15	11.05	2.75	1.28

Critical Volume of material removed= 180.35 cm^3

Table 5.20: Tool wear and surface finish recorded periodically while machining work-material AISI 9320 at speed of 245 m/min.

AISI 9320 245 m/min [796 RPM]						
No of Passes	**Time (min)**	**Wear (mm)**	**Ra**	**Rz**	**Rq**	**Rq / Ra**
10	4.10	0.15	1.61	9.33	2.02	1.26
20	8.21	0.16	1.78	9.51	2.22	1.24
30	12.31	0.18	1.74	9.62	2.22	1.27
40	16.42	0.20	1.73	9.25	2.15	1.24
50	20.52	0.21	1.90	10.41	2.33	1.22
60	24.62	0.23	2.07	9.43	2.42	1.17
70	28.73	0.24	1.74	8.89	2.05	1.18
80	32.83	0.26	2.10	9.14	2.42	1.15
90	36.93	0.28	1.89	8.55	2.16	1.14
100	41.04	0.29	1.35	8.65	1.72	1.28
104	42.68	0.30	1.29	8.56	1.64	1.27

Critical Volume of material removed= 312.61 cm^3

Figures

After machining and when the tool life criterion of 0.3 mm is reached the micro hardness test is done for each of the workmaterials under consideration. The edge-

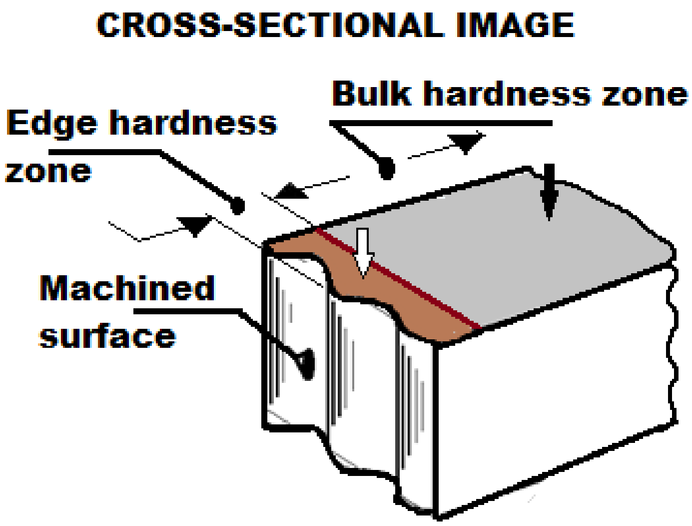


Figure 5.1: Cross-sectional image of the work-material showing how the edge-hardness and bulk-hardness are safely tested.

hardness and the bulk-hardness zones are identified as shown in the figure 5.1. The edge hardness zone is the one which is susceptible to workhardening affects by machining and is generally under 200µ adjacent to the machined surface. Whereas the bulk hardness zone is the one which is safely located 200µ away from the machined surface. The bulk hardness is inherent to work material property and is unaffected by machining. Both the edge hardness and bulk hardness is done to know the relative effect of machining on the edge surface.

The actual micro-hardness testing done for the machined work-materials, at the edge and bulk, is shown in the images from figure 5.2 to figure 5.10. After the tool wear criterion is reached, 0.3mm, the work-materials were systematically prepared for microhardness testing. The images in the figure 5.2 to figure 5.10 show the point (red cross hair) where the micro hardness was recorded.

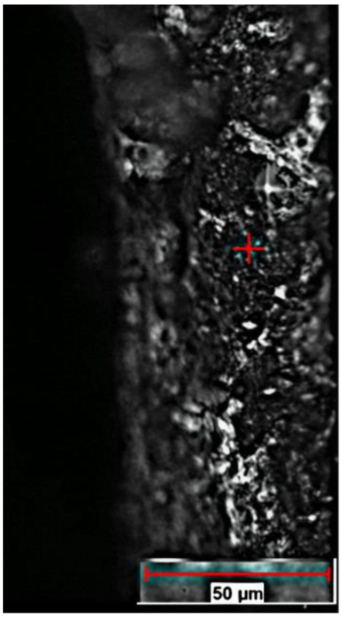


Figure 5.2: AISI 1050 Edge Hardness-279 HV

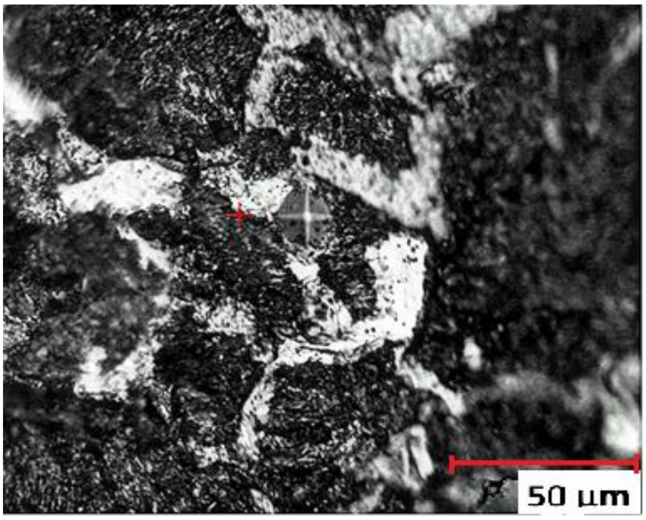


Figure 5.3: AISI 1050 Bulk Material Hardness-197 HV

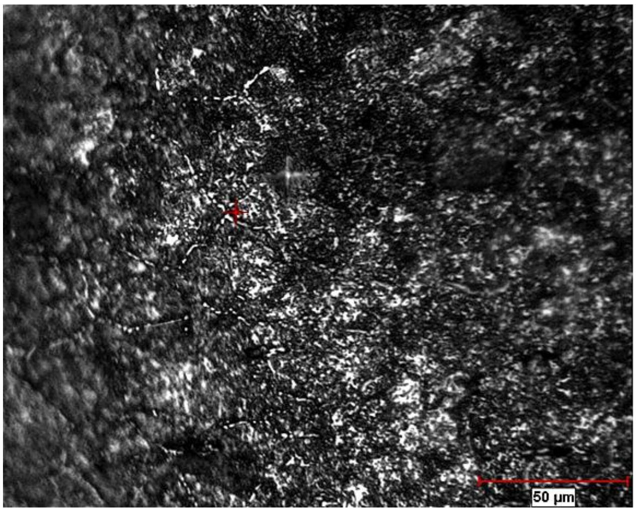
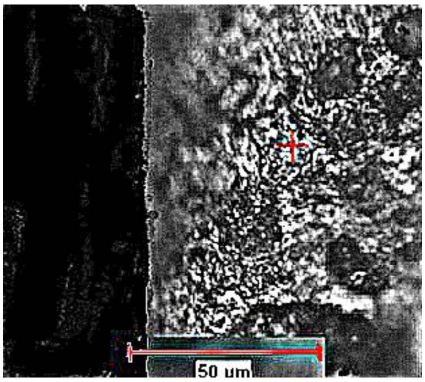


Figure 5.4: AISI 51100 Bulk Material Hardness-215 HV



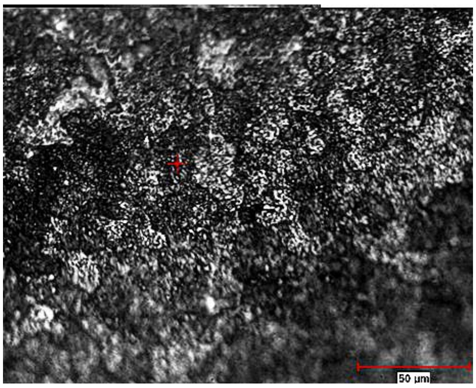
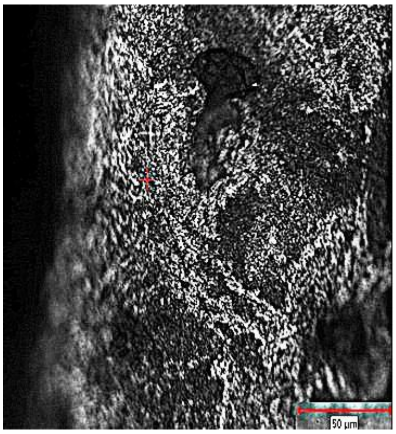


Figure 5.5: AISI 52100 Edge Hardness-263 HV

Figure 5.6: AISI 52100 Bulk Material Hardness- 265 HV



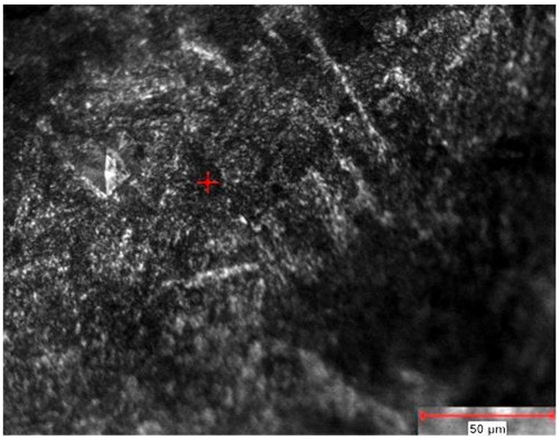


Figure 5.7: AISI 4340 Edge Hardness-372 HV

Figure 5.8: AISI 4320 Bulk Material Hardness- 263 HV

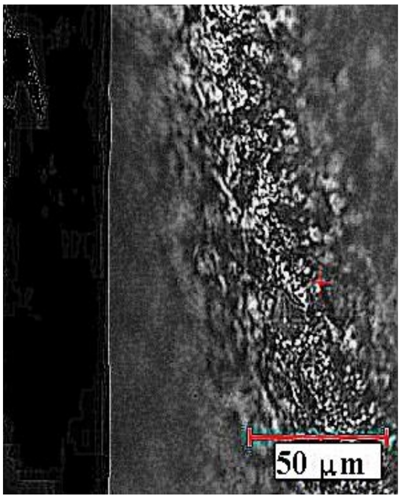


Figure 5.9: AISI 9320 Edge Hardness-309 HV

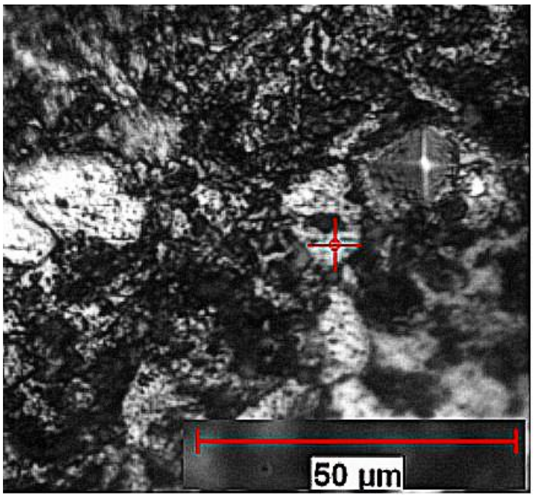


Figure 5.10: AISI 9320 Bulk Material Hardness- 214 HV

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