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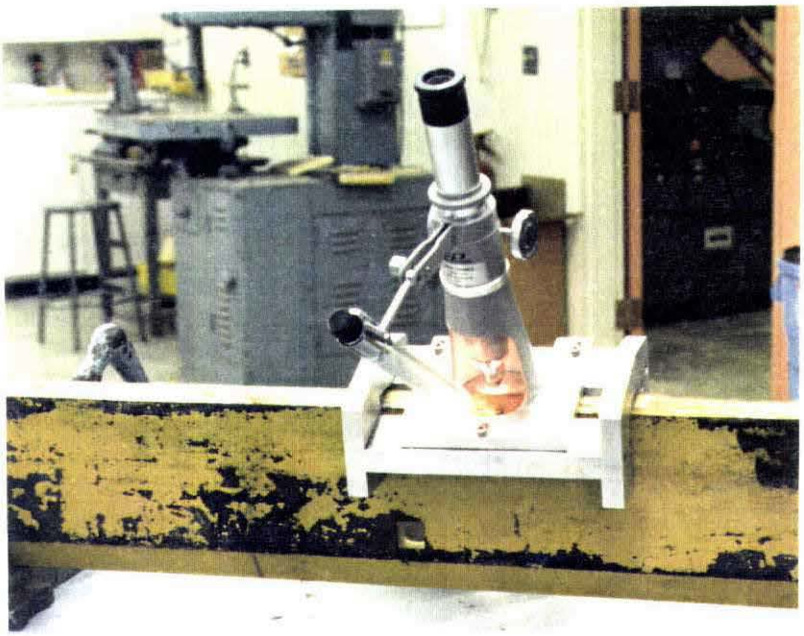

Snow Plow Cutting Edge Evaluation

Study SD95-14
Final Report

Prepared by
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April, 1996

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ACKNOWLEDGEMENTS

This study was performed under the supervision of the project technical panel of South Dakota Department of Transportation:

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. SD95-14F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Snow Plow Cutting Edge Evaluation		5. Report Date April 1996 6. Performing Organization Code
7. Author(s) Wilfred Nixon, PhD, YingChang Wei, PhD		8. Performing Organization Report No.
9. Performing Organization Name and Address Iowa Institute of Hydraulic Research The University of Iowa Iowa City, IA 52242		10. Work Unit No. 11. Contract or Grant No. 310368
12. Sponsoring Agency Name and Address South Dakota Department of Transportation Office of Research 700 East Broadway Avenue Pierre, SD 57501-2586		13. Type of Report and Period Covered Final; May 1995 to June 1996 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This study aimed at developing a specification to ensure that cutting edges meet the required durability and a test procedure to evaluate the cutting edges. A thorough review was carried out of all relevant SDDOT specifications for cutting edges and available literature pertaining to material test methods which might be used to measure cutting edge durability. A number of important materials properties which influence the durability of cutting edges were identified and discussed. Recommendations of specification changes of grain size and hardness were made.

The scratch test was identified as a simple and convenient testing method for the evaluation of cutting edges. A major outcome of this study is the development of the procedures and devices for the scratch test of cutting edges. A testing apparatus peculiar to the scratch test of cutting edges was designed and manufactured. Using this test apparatus, laboratory tests were conducted for three groups of existing cutting edges (referred to as Ken, Pacal, and Valks) provided by SDDOT. The highest scratch hardness was found for Kennametal blades, and the lowest scratch hardness for Pacal blades. This finding is consistent with the results of field tests performed by SDDOT under SD89-04 for the existing cutting edges where Kennametal blades were found to be more wear resistant than Pacal blades. Within the load range between 9.3N and 22N, the values of scratch hardness appeared to be fairly constant. This is an indication that the scratch hardness may be a promising parameter for evaluating wear resistance of cutting edges. It is recommended that the scratch test be used on a trial basis as a complementary means for cutting edge evaluation.

17. Keywords Cutting edge specification, scratch test, scratch hardness, carbide evaluation	18. Distribution Statement No restrictions. This document is available to the public from the sponsoring agency.		
19. Security Classification (of this report) Unclassified	Security Classification (of this page) Unclassified	21. No. of Pages 26	22. Price

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1. EXECUTIVE SUMMARY

The cutting edge specifications for snow plows, motorgraders, and underbody blades are not generic but tend to be based on a specific manufacturer's product. Whether these specifications can ensure the required durability of cutting edges is often found questionable. South Dakota Department of Transportation (SDDOT) experienced significant problems in using the cutting edges which were manufactured according to the current specifications. The cutting edges provided by contractors appeared to meet the required specifications but did not perform satisfactorily when used to plow snow and ice. Questions were raised as to whether the specifications of cutting edges were appropriately written, and how to test quickly if the cutting edges purchased meet the required specifications. These concerns led to the development of a Request for Research Proposal by SDDOT for snow plow cutting edge evaluation.

The purposes of this study are: to develop a specification which will ensure that cutting edges meet the required durability, to develop a test procedure for durability of cutting edges on the basis of which they may be accepted or rejected, and to develop a procedure to evaluate new cutting edge materials.

A review of all relevant South Dakota Department of Transportation (SDDOT) specifications for cutting edges was made to determine which material properties were currently required and specified. A review of literature on wear resistant materials also identified a number of material properties which most closely relate to cutting edge durability. It is obvious that the selection of cemented carbide as cutting edge inserts, as is the practice of SDDOT, is justified by the superior abrasive wear resistance of the material. The durability of the carbide inserts is determined by a number of important material properties, including **hardness, transverse rupture strength, fracture toughness, grain size, thermal expansion, density, porosity, and corrosion resistance**. The SDDOT specifications gave a clear description of dimensions of the cutting edges and specify some important material properties, such as density, hardness, transverse rupture strength, and porosity. These properties are commonly used to evaluate cemented carbides, and there is no good reasons to exclude any of them from the specifications. The ranges of values of these properties, except for the hardness (see below), seem to be reasonable, and should remain the same. Other material properties and parameters, such as fracture toughness, grain size, thermal expansion, and corrosion resistance, were assessed in detail by this study and summarized as following.

Fracture Toughness, Thermal Expansion, and Corrosion Resistance: The fracture toughness may be a better material property for characterizing the fracture strength of carbide inserts, but its measurement would pose great difficulties. Thermal expansion is an inherent problem of steel/tungsten carbide (WC) composites because of the significant difference in the thermal expansion coefficients of these two materials. Specifying the thermal expansion of the carbide insert is not meaningful in controlling this problem. While it is desirable to know the corrosion behavior of the carbide in salt media, this is not possible without an extensive series of tests and further study. Therefore, these three parameters are not recommended to be used in the specifications.

Grain Size: The grain size of tungsten carbide is an important factor influencing the hardness and abrasion resistance of tungsten carbide/cobalt (WC-Co) materials. For example, the hardness of a 88WC-12Co cemented carbide decreases from 91 HRA to 84 HRA as its tungsten carbide grain size increases from $1.5X10^{-6}$m to $5.5X10^{-6}$m. Since the measurement of grain size is relatively simple, to ensure that the carbide inserts possess the required hardness, it is desirable to specify the grain size of the tungsten carbide. Referring to the data reported in literature, it is recommended that the grain size be specified as between 2 to 6 micrometers. Further, it may be important to specify the percentage of the grains whose sizes lie within a particular range, e.g. 2 to 3, 3 to 4, and 4 to 6 micrometers. This graded specification, however, should be based on a thorough examination of grain sizes of existing cutting edges, which was not pursued in this study. It should be noted that while larger grains, in general, give higher toughness they also, in general, give lower hardness and less wear resistance.

Hardness: The specification of hardness also needs consideration. Based on the results of literature review, the field tests conducted by SDDOT (SDDOT, SD89-04), and the laboratory tests of this study, it is recommended that the hardness of carbide inserts be specified as 88.0 minimum to 90.0 maximum on the Rockwell A scale (HRA). Carbide inserts with higher HRA values will improve the wear resistance of cutting edges, but are also more brittle and prone to shock failure. Therefore, a maximum hardness of 90.0 HRA is suggested.

To develop a test procedure to evaluate cutting edges, a thorough review was carried out of available literature pertaining to material test methods which might be used to measure cutting edge durability. Numerous testing methods for measuring wear and abrasive resistance of various materials were found through the literature search. Among these methods, four types of testing procedures may be considered suitable for cutting edge evaluation. They are ASTM G77-91, ASTM G65-91, ASTM B611-85, and the Scratch Test. While the three ASTM standard methods provide instructive guides for the determination of abrasion for a variety of materials, they require fairly complicated testing apparatus. The analysis of testing results from these methods is time consuming. The scratch test was identified as a simpler and more convenient testing method for the evaluation of cutting edges. Efforts were then concentrated on developing a simple and handy setup so that scratch tests on cutting edges can be performed quickly and easily.

A major outcome of this study is the development of the procedures and devices for the scratch testing of cutting edges. A testing apparatus peculiar to the scratch test of cutting edges was designed and manufactured. The testing apparatus comprises a polishing file mounted on a gliding frame, a scratching setup made of a diamond indenter and loaded by spring force, and an observing device consisting of a shop microscope and a guide frame. These simple test devices allow a scratch test to be easily performed on a cutting edge without breaking it, and reliable results can be obtained within 10 minutes. The testing procedures were outlined based on the experience gained from the laboratory tests of cutting edges using the testing apparatus. The procedures give a general description for preparing testing samples, conducting scratch tests, and examining scratch grooves.

Scratch Hardness: An important parameter that can be obtained from scratch test is the scratch hardness H_S which is very useful in evaluating the abrasion resistance of materials. The scratch hardness is a function of load and the width of the scratch groove. When scratch hardness is used to predict abrasion resistance, it usually correlates better than ordinary indentation hardness. This is supported by the experimental results of our laboratory tests conducted for three groups of existing cutting edges (referred to as Ken (Kennametal), Pacal, and Valks) provided by SDDOT. The highest scratch hardness was found for Kennametal blades, and the lowest scratch hardness for Pacal blades. This finding is consistent with the results of field tests performed by SDDOT under SD89-04 for the existing cutting edges where Kennametal blades were found to be more wear resistant than Pacal blades. Within the load range between 9.3N (2.1 pounds) and 22N (5 pounds), the width of scratch grooves showed a fairly linear dependence on load, and the values of scratch hardness of the blades appeared to be fairly constant. This is an indication that the scratch hardness may be a promising parameter for evaluating wear resistance of cutting edges.

As demonstrated in this study, the scratch test appears to be a feasible method for evaluating the wear resistance of cutting edges, and the application of the testing devices has been quite successful. This test methodology is suitable not only for testing the cutting edges purchased, but also for evaluating new cutting edge materials in principle. Nevertheless, while this test method appears to be very attractive, refinement in the testing procedures and improvement on the testing devices are certainly necessary. For example, continuous recording of both normal and tangent scratching forces by electronic means may be desirable. The use of a microscope with higher magnifications would improve the accuracy of the readings of scratch groove widths.

It is recommended that the scratch test be used on a trial basis as a complementary means for cutting edge evaluation. Using the testing devices developed in this study, it is appropriate for the loads to be controlled between 9 to 20N. In particular, a load of 15N may be used for the scratch test of purchased cutting edges. Whether the scratch hardness should be included in the specifications requires further consideration. It is recommended that a more thorough and systematic research on the scratch test be conducted before the implementation of scratch test for cutting edge evaluation.

2. PROBLEM STATEMENT

The cutting edge specifications for snow plows, motorgraders, and underbody blades are not generic but tend to be based on a specific manufacturer's product. Whether these specifications can ensure the required durability of cutting edges is often found questionable. South Dakota Department of Transportation (SDDOT) experienced significant problems in using the cutting edges which were manufactured according to the current specifications. The cutting edges provided by contractors appeared to meet the required specifications but did not perform satisfactorily when used to plow snow and ice. Questions were raised as to whether the specifications of cutting edges were appropriately written, and how to test quickly if the cutting edges purchased meet the required specifications.

The application of new types of cutting edges also requires a new approach in specification. New designs of cutting edges for use in the removal of snow and ice from roads have been forthcoming as a product from the Strategic Highway Research Program (SHRP) and also other sources. While the shapes of these new cutting edges are more efficient at removing ice and compacted snow from roads, as demonstrated by recent studies **[1-2]**, they place a higher demand on the cutting edge material. These new cutting edges must be more resistant to wear and shock loading than has previously been required for cutting edges. If not, they will lose their special shape and thus their effectiveness. The specification must be written in such a way that not only are the desired properties clearly specified, but also that these properties can be easily measured. Thus, a specification which stated "blades must perform for a minimum of 250 hours of continuous scraping" is not appropriate, because such performance cannot be adequately measured other than by using the blades and seeing how well they perform.

Accordingly, procedures must be developed such that the desirable properties of cutting edges are identified, and means of measuring these properties quickly and efficiently (i.e. at low cost, most probably in a laboratory) are determined. The identification and determination of these properties and the method of measuring them are the core of this study.

Changes in cutting edge design may also place new demands on cutting edges. As illustrated in Figure 1, the new cutting edge has both strengths and weaknesses. The sharp front edge provides for excellent ice removal, but is very prone to wear. The carbide insert on the leading face of the cutting edges is wear resistant, but is prone to damage due to shock loading from in-pavement objects. The carbide insert may even be poorly bonded to the steel matrix, with the result that it comes away from the steel under loading. There are in fact three materials which must be considered: the carbide insert, the steel matrix, and the interface or weld between these two. It would seem from Figure 1 that the strength of the steel matrix is not a major issue. It should be a relatively hard wearing steel, with adequate shock resistance, but not much more might be required of it. The weakness of the bond between carbide and steel is less simple to determine. But this kind of test is necessary only when the debonding failure is found to be frequent, which does not appear to be the case for these cutting edges.

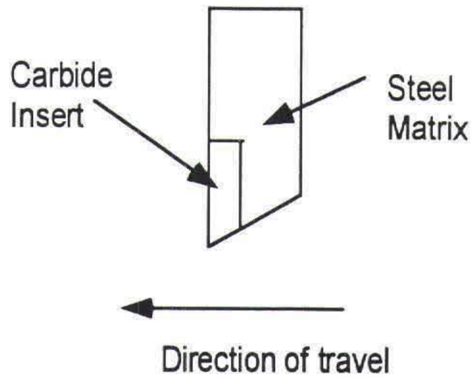


Figure 1 Schematic of SHRP cutting edge

The wear resistance of cutting edges is mainly determined by the carbide inserts. Therefore, the factors that influence the durability of the carbide inserts must be identified and appropriately specified. The carbide insert may fail due to excessive wear, especially if it is too soft, or it may undergo shock fracture, due to "sudden" loading. The wear issue is most simply addressed through a hardness test, which assumes that wear rates are directly proportional to load. This is not always the case. Further, the environment in which the blade meets the road and ice is rather a hostile one, with abrasives and corrosive agents (deicing salts) being present to a large degree. Accordingly, in addition to a hardness test, some sort of test of abrasion resistance or wear resistance would be appropriate. In this regard, some ASTM standard test methods to determine abrasive resistance of materials may be considered. Attention was also be paid to other test methods which would allow the wear resistance of the carbide to be quickly and easily evaluated.

3. OBJECTIVES

In responding to the problems described in Section 2, three objectives were undertaken for this research:

- to develop a specification which will ensure the required durability for cutting edges to be met;
- to develop a test procedure for cutting edges on the basis of which they may be accepted or rejected; and
- to develop a procedure to evaluate new cutting edge materials.

The first objective was accomplished with recommendations to the changes of the current specifications. In particular, the change in the range of hardness and the specification of grain size were suggested. The second and the third objectives were achieved with the development of a test methodology, the scratch test method, for cutting edge evaluation. The procedures for conducting scratch tests of cutting edges were developed, and the scratch testing apparatus was designed and manufactured. The results from the laboratory tests on the existing cutting edges using the testing apparatus developed by this study indicated that the scratch test is a promising method for evaluating cutting edges. This method is suitable for testing the cutting edges purchased and evaluating the new cutting edge materials. A more thorough and systematic research on the scratch test is needed before the implementation of this method for cutting edge evaluation. An important aspect of the future research is to investigate the relationship between the scratch hardness and the Rockwell hardness (A scale). In addition, an understanding of scratch mechanisms will provide a sound base for the application of the scratch test to the evaluation of cutting edges.

4. TASK DESCRIPTION

4.1 Literature and Specification Reviews

4.1.1 Testing Methods

A thorough review has been carried out of available literature **[3-11]** pertaining to material test methods which might be used to measure cutting edge durability . Numerous testing methods for measuring wear and abrasive resistance of various materials have been found through the literature search. Among these methods, four types of testing procedure may be considered suitable for cutting edge evaluation. They are **[3-6]** ASTM G77-91, ASTM G65-91, ASTM B611-85 (reapproved 1991), and the Scratch Test (ASM Handbook, 1992). Of these four testing procedures, three are ASTM standard test methods. ASTM G65-91 is designed to determine the resistance of metallic materials to scraping abrasion by means of the Dry Sand/Rubber Wheel Test (Figure 2a). ASTM G77-91 utilizes a block-on-ring friction wear testing machine to measure the resistance of materials to sliding wear (Figure 2b). ASTM B 611-85 is designed to measure the abrasive wear of cemented carbides caused by a slurried abrasive on a rotating surface(Figure 2c). While these standard methods provide instructive guides for the determination of abrasion for a variety of materials, they require fairly complicated testing apparatuses. Also, the analysis of testing results from these methods is time consuming and far from straightforward. While the three ASTM tests may deserve future consideration, efforts have been concentrated on developing a simpler and more convenient testing method so that a quick evaluation of cutting edges can be conducted. In this context, the scratch test method is a good candidate.

Scratch testing is a method of mechanically testing a specimen surface. In this method, a hard scratching element (indenter and stylus) is used to generate a groove in the specimen surface **[6-10]**. Two typical scratch testing configurations are illustrated in Figure 3. As shown in Figure 3, these testing setups are quite simple and easy to operate. One of the general functions of scratch testing in materials research is to evaluate or rank the materials abrasion resistance, which matches well the requirement for the evaluation of cutting edges. Either testing configuration shown in Figure 3 may be considered for cutting edge evaluation. The setup in Figure 3a is a low-speed bench top scratching device working under fixed-load conditions. The penetration depth is determined by the load (deadweight or spring-controlled normal force) and the deformation resistance of the workpiece material. Since the load is known, the relative abrasion resistance of materials can be determined by measuring the groove shapes, the groove sizes, and the values of specific grooving energy (defined as the energy required to remove the unit volume of material) for different materials. The setup in Figure 3b is a high-speed scratching device which generates arc-shaped grooves. The applied normal force of this machine can not be preset and gages are needed for continuous monitoring of applied forces. A set-up of the type indicated in Figure 3a is more appropriate in terms of meeting the aims of this study.

4.1.2 Specification of Material Properties for Cutting Edges

A review of literature **[11-15]** also identified a number of material properties which most closely relate to cutting edge durability, including hardness, transverse rupture strength, fracture toughness, grain size, thermal expansion, porosity, and corrosion resistance. At the same time, a

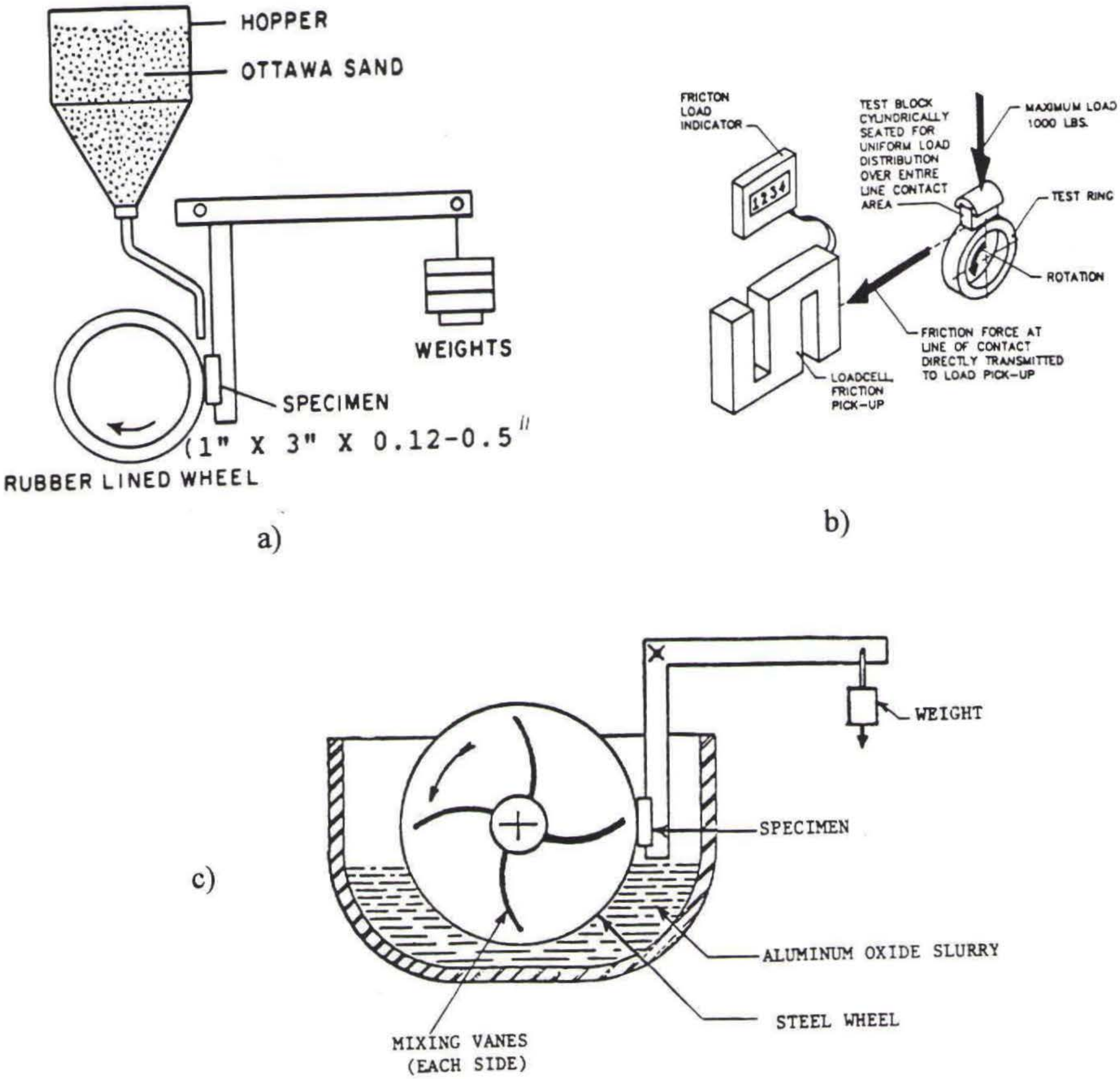
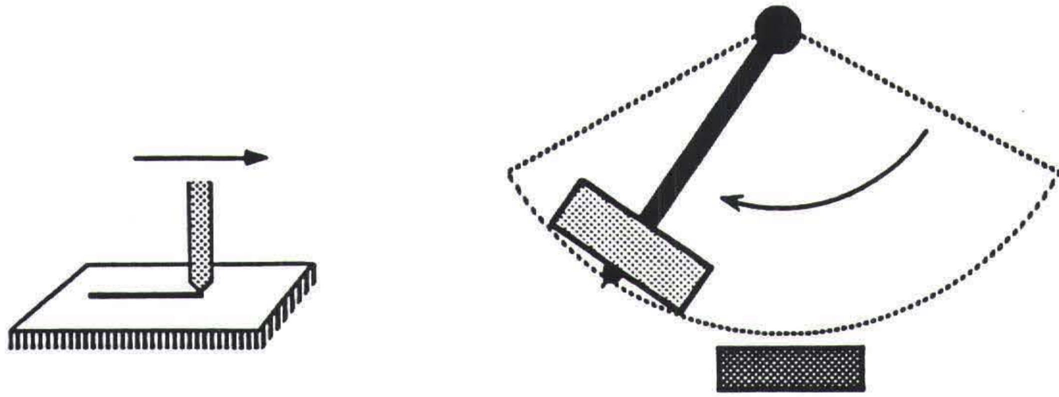


Figure 2 Standard test methods for measuring wear resistance. a) Dry Sand/Rubber Wheel test apparatus (ASTM G65-91 **[3]**), b) Block-on-ring friction wear test apparatus (ASTM G77-91 **[4]**), c) Abrasive wear resistance test apparatus (ASTM B611-85 **[5]**).



a) b)

Figure 3 The setups for scratch testing. a) Low-speed bench top scratching device, b) High-speed scratching device (modified Charpy pendulum) **[6]**.

review of SDDOT specifications of cutting edges has been conducted to check whether the material properties specified in the specifications are proper and adequate. It is believed that the information gathered from literature reviews has made an evaluation of the material property specifications and the testing methods of cutting edges possible.

The selection of WC-Co grade cemented carbide as cutting edge inserts, as is the practice of South Dakota DOT, is justified by the superior abrasive wear resistance of the material. The durability of the carbide inserts is determined by a number of important material properties which require appropriate specifications. For application as a cutting edge insert, these material properties may include hardness, transverse rupture strength, fracture toughness, grain size, thermal expansion, porosity, and corrosion resistance, as identified through the literature and listed above. The South Dakota DOT specifications **[15]** for cutting edges give clear description on the dimensions of the cutting edges and specifies some important material properties, such as density, hardness, transverse rupture strength, and porosity. There are some additional material properties, such as fracture toughness, grain size, thermal expansion, and corrosion resistance, that may need specifying. These are discussed in more detail below.

Fracture Toughness: To date, the most common method for determining the fracture strength of cemented carbides is to use the three-point bending strength test, or transverse rupture strength test(TRS). Technically, this does not actually measure the fracture toughness of the carbide thus tested, but it does provide what appears to be a reasonably good index of fracture resistance of the carbide. This method is sensitive to test bar size, surface finish, and other test parameters **[11]**. One of the reasons for this may be the defects existing in the specimen. These defects are mainly the tiny cavities formed during manufacture (this is why porosity is usually specified for a cemented carbide). The strength of such brittle materials (which might also include glass) is often found to be size dependent and surface finish sensitive. The failure of these materials usually takes place by nucleating cracks at the defect sites and propagating these cracks or pre-existing cracks through out the specimen. In this case, a fracture mechanics approach is particularly useful in characterizing the strength of the material, and the fracture toughness is a material parameter that should be pursued. Since WC-Co cemented carbides are extremely hard and contain a lot of tiny cavities, fracture toughness might be a better material property for characterizing the fracture strength of the material. However, against this must be set the fact that conducting fracture toughness tests on brittle ceramics such as carbides is notoriously difficult. While a true fracture toughness test would be desirable, it is probably not feasible at present. It is recommended that no further consideration is given to using fracture toughness in the specifications, at this time.

Grain Size: The grain size of tungsten carbide is an important factor influencing the hardness and abrasion resistance of the WC-Co materials **[11-12]**. For example, the hardness of a 88WC-12Co cemented carbide decreases from 91 HRA to 84 HRA as its tungsten carbide grain size increases from 1.5×10^{-6}m to 5.5×10^{-6}m. Experiments have shown that significant improvement in abrasion resistance could be achieved by reducing the tungsten carbide grain size**[12]**. When the amount of cobalt in a WC-Co material is decided, it is necessary to specify the tungsten carbide grain size to ensure a required hardness and abrasion resistance. It is recommended that grain size of the tungsten carbide phase of the cemented carbide should be specified.

Thermal Expansion: Since the carbide inserts are to be joined to the steel blades by brazing, it is important to take the thermal expansion of the materials into account. The coefficient of thermal expansion of SAE 1020 steel (the blade material, as specified in South Dakota DOT's specifications) is 11.7×10^{-6}m/m.K **[13]** which is more than two times greater than that of WC cemented carbide (5.2×10^{-6}m/m.K for WC carbide **[11]**). From the brazing temperatures to the cutting edge's operating temperatures, there is a considerable temperature change. The difference in the coefficients of thermal expansion of carbide and steel may cause excess residual stresses and contribute to the failure of the cutting edge. Under certain conditions, such a high thermal mismatch might give rise to very high strains at the interface between the two materials, which could in turn lead to failure of the interface, and separation between the insert and the steel matrix. However, such failures have not been at all common in the reported experience of SDDOT. Thus, it is not recommended that coefficients for thermal expansion of the constituent materials be specified to any greater degree than is currently the case.

Corrosion Behavior: The corrosion resistance of the carbide insert is a property that must be considered because the cutting edge experiences a corrosive environment (salts and abrasive sand particles on the roadways) during snow plowing and ice scraping. The corrosion resistance of carbides is limited by the susceptibility of the cobalt binder to chemical attack. The corrosive media typically dissolve the cobalt binder from the matrix, leaving behind a weak, unsupported skeleton of tungsten carbide grains, which are easily abraded away. Generally, the corrosion resistance of WC-Co materials is inversely related to their content of cobalt **[11]**. However, the corrosion resistance tests for WC-Co carbides have been performed mainly in acid media. No report on the corrosion behavior of WC-Co carbides in salt media has been found through our literature searching. Accordingly, to assess this problem fully, a separate study would be necessary. At this time, it is not recommended that corrosion resistance be made part of the specifications.

Once the pertinent material properties for a successful cutting edge have been identified, the specifications for these properties must be made. The operation of snow plowing and ice scraping requires a combination of abrasion resistance and impact strength for the cutting edges. To obtain the required material properties, choosing appropriate compositions and grain sizes for a cemented carbide is essential. Generally, the wear resistance of WC-Co carbides increases with decreasing cobalt content and decreasing grain size. Decreasing cobalt content, however, decreases the impact strength of the carbides. For the application of cutting edges, grade compositions ranging from 9 to 13% Co and tungsten carbide grain sizes ranging from 2 to $3.5X10^{-6}$m are recommended for WC-Co carbides**[12]**. The required cobalt content in South Dakota DOT's specifications is 11 to 12.5%, which appears to be in the desired range of cobalt content. When specifying the above identified material properties, care must be taken to decide a reasonable range for each of those parameters. The following parts of the project will deal with this issue.

4.2 Verification Procedures

To ensure appropriate performance of the cutting edges purchased, verification of material properties of the cutting edges is necessary. This involves a series of materials tests which would be performed on a random selection of cutting edges pulled from each batch supplied. Appropriate sampling is important for a good estimation of material properties. As a rule of thumb, a random sample of 10 specimens can be called a large sample. Larger samples will improve the reliability of test results, but may not be cost effective.

As indicated in Section 4.1, the durability of the cutting edges is determined by a number of material properties, including those specified in the South Dakota DOT specifications, such as hardness, density, transverse rupture strength, and porosity, and those identified so far by this study, such as fracture toughness, grain size, thermal expansion, and corrosion resistance. Obviously, it is not appropriate in terms of time and cost to conduct all of these materials tests for verification. Measurement should be made of those material properties which have a strong influence on cutting edge performance. In this context, the measurements of hardness and transverse rupture strength are desirable because these properties are among the most important properties in the specifications of cutting edges and are relatively easy to conduct.

An alternative form of verification is to seek a better material property for characterizing the wear resistance of cutting edge and a simpler and more effective testing method to measure it. A scratch test can be used to evaluate or rank materials abrasion resistance and to measure scratch hardness (see the definition and discussion below) of materials. These two functions of the scratch test match well the requirement for the evaluation of cutting edges. In particular, the scratch hardness seems to give better correlation with cutting edge performance, and is thus worth further consideration. This parameter and its determination (by scratch testing) are discussed in detail in the next section.

4.3 Development of Wear Test -- Scratch Testing

4.3.1 Scratch Testing Setup

The scratch test was identified during the study as a promising method for evaluating wear and abrasion resistance of cutting edges. While there are a number of scratch testing devices commercially available, it is the purpose of this study to develop a simple and handy setup so that scratch test on the cutting edges can be performed quickly and easily. A configuration of such a

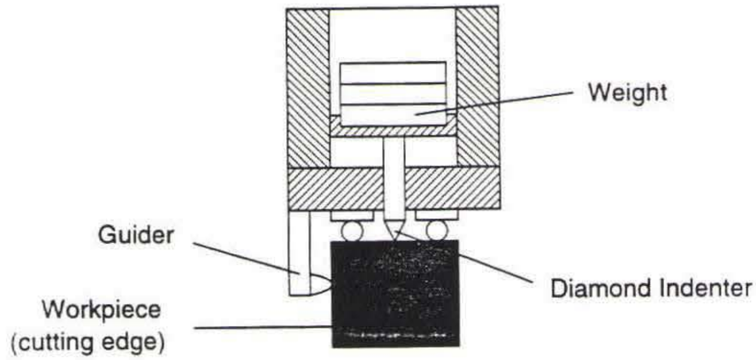


Figure 4 Schematical illustration of the proposed scratch testing device

scratch testing setup is thus proposed, as shown in Figure 4. This setup is a low-speed bench top scratching device and can be operated manually. By holding and displacing the device over the polished surface of the cutting edge (carbide insert), the scratching tip will generate a groove on the specimen surface. The guider (see Figure 4) is placed against the side of the cutting edge to ensure that a straight groove is produced. The shape and size of the groove are determined by the load and the shape of the indenter. It is necessary to choose an indenter with a well-defined shape, such as a Vickers or Rockwell hardness test diamond, to facilitate the determination of the dimensions of the groove. The load is readily applied by the use of standard weights. A microscope with micro-scale is needed to measure the width of groove. The manufacture of such a device does not pose great difficulties.

4.3.2 Important Parameters

While many parameters can be obtained from scratch testing **[6,7]**, two of them appear to be useful in the evaluation of cutting edges. These two parameters are shown in Fig. 5 **[6]**.

During scratching, there is a tangential force F_T and a normal force F_N acting parallel and perpendicular to the interface between the stylus and the material being scratched, respectively. The tangential force F_T can be divided into an adhesive component F_A and a plowing component F_P **[16,17]**, i.e., $F_T = F_A + F_P$. One of the two interesting parameters is the plowing stress H_P:

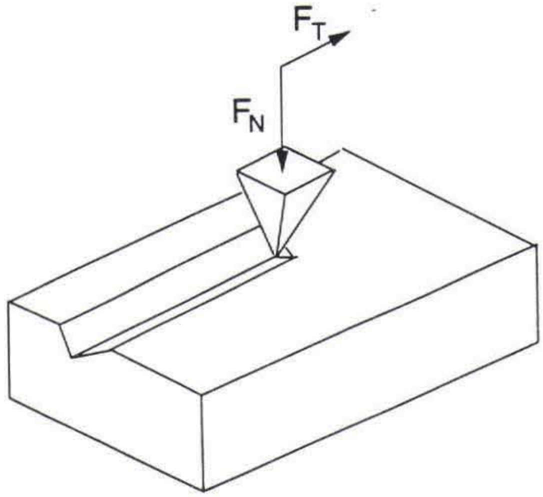
$$H_P = F_P/A_P,$$

the other is the scratch hardness H_S :

$$H_S = F_N/A_{LB}.$$

The plowing stress H_P is the mean pressure opposing the sliding movement of the stylus due to the plowing process only. The scratch hardness is the load per unit load-bearing area, i.e., the mean pressure resisting deeper penetration. Obviously, it is easier to measure H_S than to measure H_P because the normal force F_N and load-bearing area are readily obtained, while the plowing

(a)



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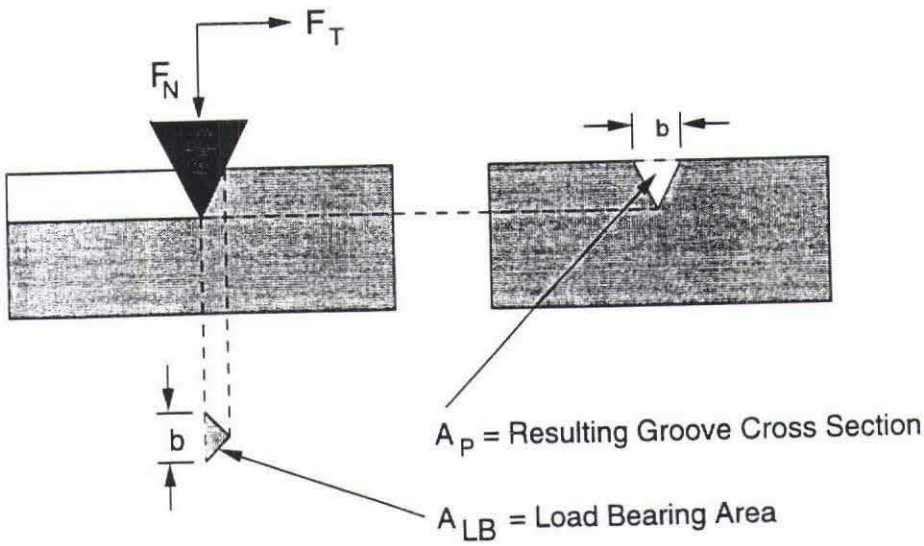


Figure 5 (a) Critical forces in scratch testing, (b) Resulting groove cross section and load bearing area.

component is more difficult to determine. However, in a non-work-hardening material the plowing stress should be approximately equal to the scratch hardness [6]. The carbide insert of cutting edges is a non-work-hardening material. Therefore, the measurement of scratch hardness would allow the plowing stress to be estimated at the same time.

Scratch hardness is an important parameter in evaluating the abrasion resistance of materials. When scratch hardness is used to predict abrasion resistance, it is believed to correlate better than ordinary indentation hardness [6]. Compared with ordinary indentation hardness tests, scratch hardness testing has a major advantage in its measuring procedure. It is much easier to accurately measure the width of a long scratching groove than to measure the diagonal of an indentation. It is therefore recommended that the scratch hardness test be considered as a method to evaluate cutting edges. Further details are given in Section 4.5, below.

4.4 Preliminary Consideration of Specification Changes

Based on the results from literature reviews and the above completed tasks , it is possible at this stage to screen the material properties with regard to which should be used in the specifications, and which properties can be excluded. The material properties specified in the SDDOT specifications include density, hardness, transverse rupture strength, and porosity. These properties are commonly used to evaluate cemented carbides and should remain in the specifications, although some changes in the ranges of their values have been recommended.

Additional material properties and parameters identified by this study include: thermal expansion, fracture toughness, corrosion behavior, grain size, and scratch hardness. Thermal expansion is an inherent problem of steel/WC carbide composites because of the significant difference in the thermal expansion coefficients of these two materials (see Section 4.1). Specifying the thermal expansion of the carbide insert is not meaningful in controlling this problem. It may be possible, however, to improve the brazing process to reduce residual stresses in the cutting edge. Although fracture toughness is a good parameter in evaluating fracture resistance of carbide, its measurement would pose great difficulties. While it is desirable to know the corrosion behavior of the carbide in salt media, this is not possible without a series of tests and study. Therefore, these three parameters are not recommended for use in the specifications.

The grain size of tungsten carbide is an important factor influencing the hardness and abrasion resistance of WC-Co materials; and its measurement is quite simple. The scratch hardness, as discussed above, is a promising parameter for cutting edge evaluation. These two parameters may be considered for use in the specifications to ensure appropriate performance of cutting edges. However, before the scratch test can be included in the specifications in any meaningful way, a series of tests (as indicated in Section 4.3.2) must be conducted to obtain benchmarking data. Such work forms an important part of the research activities for this project, as discussed below.

4.5 Scratch Tests of Cutting Edges

A series of scratch tests have been conducted on existing cutting edges provided by the South Dakota Department of transportation. These tests serve two purposes. One is to check if the scratch test method and the testing equipment comprise a feasible method for evaluating the wear and abrasion resistance of cutting edges. The other is to determine if the parameters sought, e.g. the scratch hardness H_S, can be related to the results of the field tests of cutting edges conducted under SD89-04.

4.5.1 Scratch Testing Setup

Based on a configuration of a scratch testing setup proposed during the last phase of the study (see Figure 4), a testing device peculiar to the scratch test of cutting edges was designed and manufactured (Figure 6). The operation of this device is demonstrated by the photograph in Figure 7b and will be discussed further in Section 4.5.2.

The indenter is a Rockwell hardness test diamond with a vertex angle of 120°. Instead of using standard weights to apply the load to the diamond tip, a spring is installed to ensure a better contact between the diamond stylus and the polished surface of the cutting edge (carbide insert). The guider has dual functions: To ensure that the load is applied in a direction perpendicular to the surface of carbide inserts and to allow a straight scratch groove to be produced.

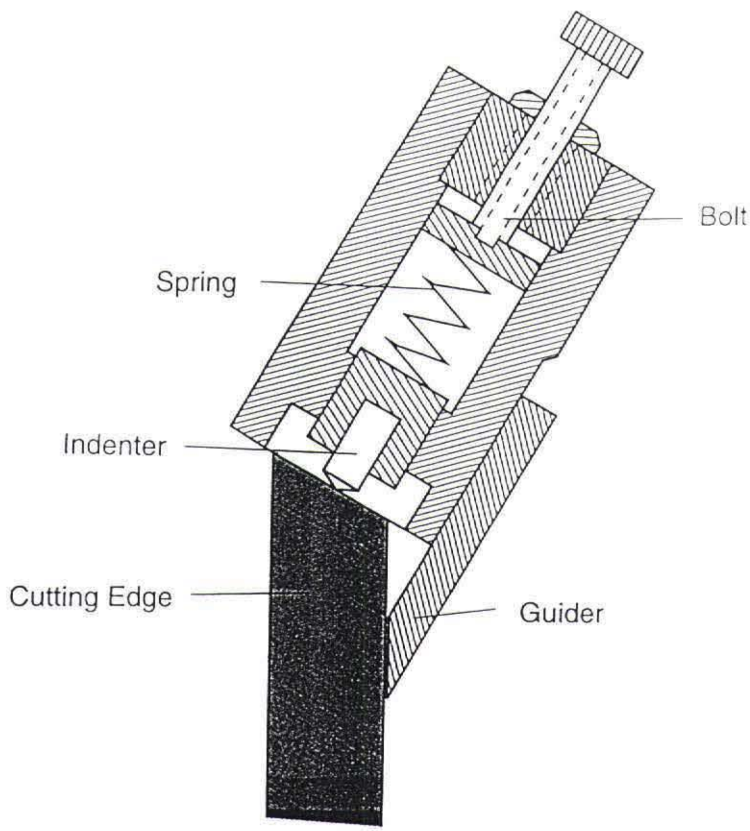
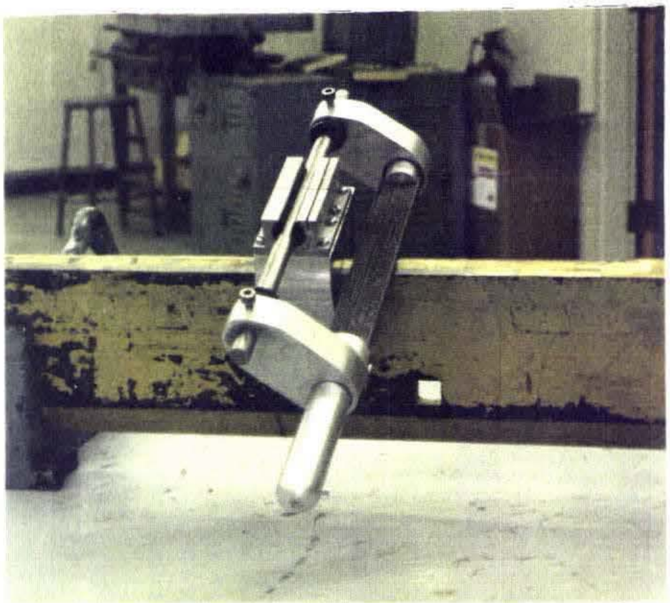


Figure 6 Configuration of the scratch testing device

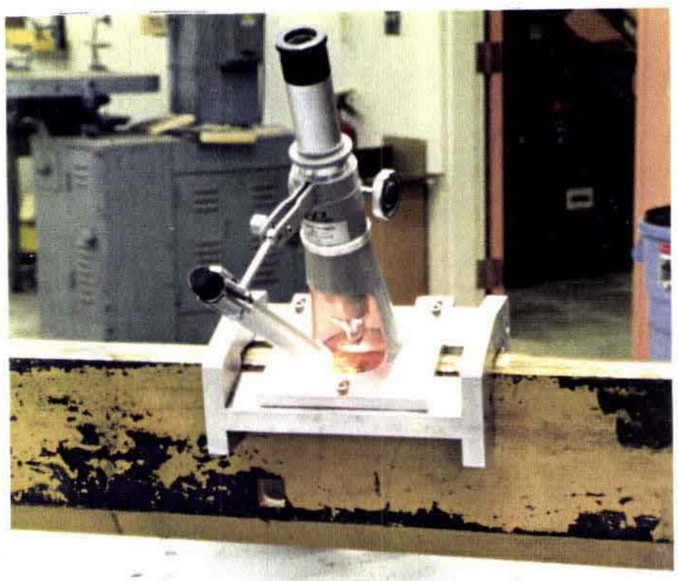
4.5.2 Testing Procedures

The testing procedures include: preparing testing samples, conducting scratch tests, and examining scratch grooves. These procedures are illustrated by the photographs in Figure 7 and are discussed below.

(a)



(b)



(c)

Figure 7 Illustration of experimental procedures for the scratch test of cutting edges.
a) filing carbide surface with a diamond file; b) Performing scratch test;
c) Examining scratch grooves.

Preparation of testing samples: The section of carbide insert to be scratch tested is randomly selected from a cutting edge. The surface of the selected carbide insert is filed to a smooth finish using a diamond file (see Figure 7a). One side of the file is coated with coarse diamond particles with which the top layers of a carbide insert can be removed quickly. The other side of the file is coated with fine diamond particles with which the filed surface can be polished to become smooth enough for scratch testing. To facilitate filing, the file is coupled with a sliding bar, gliding in a direction parallel to the surface of the cutting edge (carbide inserts). This mechanism ensures that the file is moving within the same plane so that a smooth flat surface can be obtained. Some difficulty was experienced in achieving a desired shiny finish, but no other simple methods were found in this study.

Scratch Tests: As shown in Figure 7b, the scratch test is performed by pressing and displacing the scratching device over the polished surface of the cutting edge, forcing the diamond indenter to generate a groove on the specimen surface. To produce a uniform scratching groove, the device has to be pressed firmly against the surface of the cutting edge and to be moved at low speeds, between 2--5mm/second. The load to be applied is preset before testing by adjusting the bolt and is calibrated using a Wagner digital force gage.

Examination of Scratching Grooves: The scratch grooves are examined using a shop microscope at 100X magnification (see Figure 7c). The microscope is equipped with a micro-scale with graduation of 0.01mm. This allows the width of a scratch groove to be read out at a scale of 0.005mm. Keeping the line of sight normal to the scratched surface is a necessity for accurate measurement of groove width. To facilitate this measurement, the microscope is mounted onto a guide frame with its carrier base parallel to the polished surface of the cutting edge (Figure 7c). Under this configuration, the line of sight is perpendicular to the scratched surface, and the focusing operation becomes straightforward. The guide frame can be adjusted in the X-direction, and the carrier base in the Y-direction. Thus, any point on the surface of the cutting edge can be easily examined.

4.5.3 Test Results and Discussion

Following the above testing procedures and using the devices presented, scratch tests were carried out for the existing cutting edges provided by SDDOT. Three groups of cutting edges, originally supplied to South Dakota DOT by Kennametal, Pacal, and Valks, were tested. These different edges are referred to as Ken, Pacal, and Valks in Table 1 and Figure 8. Each group tested had two identical samples. Scratch tests were performed under different loading levels, with normal forces of 2.1 pounds (9.3N), 3.5 pounds (15.4N), 5 pounds (22N), and 7 pounds (30.9N). Two groove width readings were taken for each sample, giving four readings for each group. The test results are listed in Table 1 and plotted in Figure 8a.

The values of scratch hardness H_S were calculated using

$$H_S = (8F_N)/(3.14b^2),$$

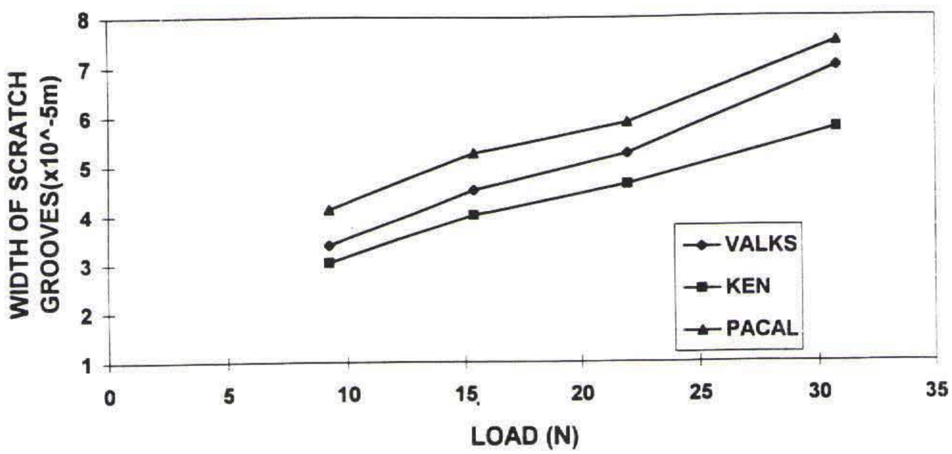
where F_N is the normal force and b is the groove width**[6]**. It is obvious from Table 1 and Figure 8b that the highest scratch hardness is found for Ken blades, and the lowest scratch hardness for

Table 1 The groove width b and the scratch hardness H_S of carbides

Sample	9.3 N			15.4N			22 N			30.9N		
	b	Mean	Hs	b	Mean	Hs	b	Mean	Hs	b	Mean	Hs
VALKS	3.5			4			5			7		
	3			4.5			5.5			7		
	3.5			4.5			5			7		
	3.5	3.4	20.8	5	4.5	19.4	5.5	5.3	20.3	7	7	16
KEN	3			4			4.5			5.5		
	3.5			4.5			5			6		
	2.6			3.5			4.5			5.5		
	3	3	25.9	4	4	24.5	4.5	4.6	26.2	6	5.8	23.8
PACAL	4.5			5			5.5			7		
	4			5.5			5.5			8		
	4			5.5			6			7.5		
	4	4.1	13.9	5	5.25	14.2	6.5	5.9	16.2	7.5	7.5	14

Note: The unit is (10^{-5}m) for groove width b and (GPa) for scratch hardness H_S.

(a)



(b)

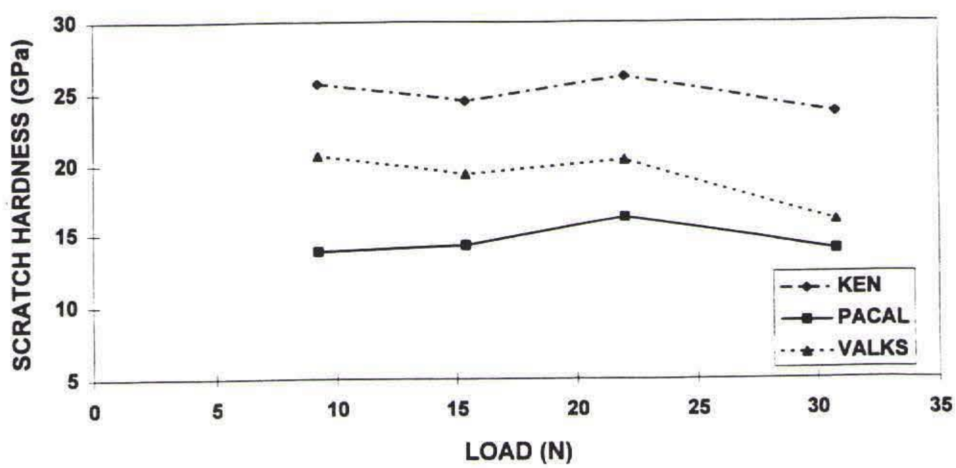


Figure 8 (a) Plots of scratch groove width versus normal force,
(b) Scratch hardness of cutting edges.

Pacal blades. Equivalently, at the same load the smallest values of groove width is observed for Kennametal blades , and the largest values of groove width for Pacal blades(see Table 1 and Figure 8a). This finding is consistent with the results of field tests performed by SDDOT under SD89-04 for the existing cutting edges where Kennametal blades were found to be more wear resistant than Pacal blades **[14]**. Furthermore, within the load range between 9.3N and 22N, the width of the scratch grooves shows a fairly linear dependence on load. This evidence is an indication that the scratch hardness may be a useful parameter for evaluating wear resistance of cutting edges.

It is reasonable to expect that the scratch hardness is a material property and its value should be constant for a given material. Arguably, this appears to be the case for the blades tested (Figure 8b). At the load of 30.9 N, however, the values of scratch hardness for Ken and Valks blades dropped. Whether this truly corresponded to a material property change or it was caused by experimental errors is not known yet. Therefore, loads higher than 22N are not recommended.

It was found that the testing procedures required for conducting the scratch test could be easily performed with the assistance of the testing devices. The surface of the carbide inserts could be treated by the diamond file to become smooth enough for scratch testing. The scratching set-up (see Figure 6) proved to be very effective in producing straight scratch grooves with different widths under different loading. The use of the shop microscope was found to be adequate for the observation and measurement of scratch grooves, although higher magnification would be desirable.

In general, the scratch test is believed to be a feasible method for evaluating the wear resistance of cutting edges, and the application of the testing devices appears to be quite successful. In particular, the simple test set-up allow a scratch test to be conducted on a cutting edge without breaking it, and reliable results can be obtained within 10 minutes. Nevertheless, while this test method appears to be very attractive, refinement in the testing methodology and improvement on the testing devices are certainly necessary. For example, continuous recording of both normal and tangent forces by electronic means may desirable. The use of a microscope with higher magnifications would improve the accuracy of readings of scratch groove widths. It is believed, however, that the purpose of utilizing the scratch test to evaluate cutting edges can be achieved by appropriately operating the existing testing devices.

4.6 Recommendations to Specification Changes and Test Procedures

The cutting edge specifications were examined with reference to the results of the field tests conducted by SDDOT under SD89-04, the findings of this study, including the information acquired from literature reviews and laboratory tests (scratch tests), as well as the property data provided by cutting edges manufacturers. Two specific issues were addressed. First, what material properties or parameters should be specified? Second, what ranges of values should be defined for the specified properties?

The material properties specified in the SDDOT cutting edge specifications include density, hardness, transverse rupture strength, and porosity. These properties are commonly used to evaluate cemented carbides, and there is no good reasons to exclude any of them from the specifications. The ranges of values for density (14.1 minimum to 14.6 maximum), transverse rupture strength (350 ksi minimum), and porosity (A06 B00 C00) are consistent with the values found in the literature **[12], [18]**; and there seems no problems resulted from the definition of these ranges of values in application of cutting edges. Therefore, the specifications of these properties and their values should remain the same.

The specification of hardness does need consideration. The carbide inserts of cutting edges are a grade of tungsten carbide with 11 to 12.5 percent cobalt. Typical values of hardness of this grade of carbides are found in the literature to be 88.5 to 90.0 HRA **[12]**. The hardness in SDDOT specifications is specified as 87.5 minimum to 89.0 maximum HRA. The nominal hardness of carbides used in Kennametal cutting edges is 88.5 HRA**[18]**. Considering that Kennametal cutting edges have been proved by field tests (SDDOT, SD89-04) and laboratory tests (scratch tests of this study) to be the most wear resistant, it is recommended that the hardness be specified as 88.0 minimum to 90.0 maximum HRA.

It has been emphasized previously that the grain size of tungsten carbide is an important factor influencing the hardness and abrasion resistance of WC-Co materials. To ensure that the carbide inserts possess the required hardness, it is desirable to specify the grain size of the tungsten carbide. Referring to the data reported in the literature **[12], [18]**, it is recommended that the grain size be specified as 2 to 6 micrometers. It would be desirable to specify further the percentage of the grains whose sizes lie within a particular range, e.g., 2 to 3, 3 to 4, and 4 to 6 micrometers. This graded specification, however, should be based on a thorough examination of grain sizes of existing cutting edges, which was not pursued in this study. It should be noted that while larger grains, in general, give higher toughness they also, in general, give lower hardness and less wear resistance. Nevertheless, the measurement of grain size is quite simple, the implementation of this specification will not pose much difficulty. Therefore, it is reasonable to require a manufacturer to supply the information of grain size with each cutting edge shipment, along with a representative photomicrograph.

As demonstrated in this study, the scratch hardness is a promising parameter for cutting edge evaluation, and the scratch test is a feasible and reliable method. While it seems reasonable to include scratch hardness in the specification, in order for this to occur, a more thorough and systematic research on the scratch test would be necessary. At this stage, however, it is recommended that the scratch test be used on a trial basis as a complementary method for cutting edge evaluation. Using the testing devices developed in this study, it is appropriate for the loads to be controlled between 9 to 22N. In particular, a load of 15N may be used for the scratch test of purchased cutting edges. As illustrated in Figure 8a, within this load range, the widths of scratch grooves seems to show a linear dependence on load. In an attempt to provide an estimate for the widths produced under given loads, a table giving the calculated values of groove widths is generated for reference, assuming a linear relationship between the load and the scratch groove width (Table 2). It should be kept in mind that the calculation was based on a regression equation derived from the experimental data which comprised of only three datum points (9.3N, 15.4N, and 22N) for each type of blade. Nonetheless, the estimate still gives a 95% level of confidence. It is recommended that the scratch hardness for the cutting edge should lie in the range 24.5 to 26.5 GPa. The scratch hardness is calculated from the load and scratch groove width, using the equation given in section 4.5.3.

Table 2 Estimated values of groove widths for scratch test of cutting edges

LOAD (N)	WIDTH OF SCRATCH GROOVES(x 10^-5m)		
	VALKS	KEN	PACAL
9.0	3.4	3.1	4.2
10.0	3.6	3.2	4.3
11.0	3.7	3.3	4.5
12.0	3.9	3.4	4.6
13.0	4.0	3.6	4.7
14.0	4.1	3.7	4.9
15.0	4.3	3.8	5.0
16.0	4.4	3.9	5.1
17.0	4.6	4.1	5.3
18.0	4.7	4.2	5.4
19.0	4.9	4.3	5.6
20.0	5.0	4.4	5.7
21.0	5.2	4.6	5.8
22.0	5.3	4.7	6.0

5. CONCLUSIONS

This study was instigated by South Dakota DOT to investigate some important issues relating to the evaluation of snow plow cutting edges. The development of an appropriate specification and a test procedure for cutting edges was the core of the project. The research tasks have been accomplished through extensive literature reviews and laboratory tests. The findings and conclusions of this study are summarized as follows.

- The relevant SDDOT specifications were reviewed to determine which material properties were required and specified. A thorough review of literature identified a number of material properties and parameters which affect the durability of cutting edges(carbide inserts). These material properties and parameters include hardness, transverse rupture strength, fracture toughness, grain size, thermal expansion, density, porosity, and corrosion resistance. The hardness, transverse rupture strength, density, and porosity are included in SDDOT specifications, and the ranges of their values, except for hardness, seem to be appropriately specified and should remain the same.

- The grain size of tungsten carbide is an important factor determining the hardness and abrasion resistance of carbide inserts. To ensure that the cutting edges possess the required durability, it is desirable to specify the grain size of the carbide. It is recommended that the grain size of tungsten carbide be specified as 2 to 6 micrometers, and that the manufacturers supply the information of grain size with each cutting edge shipment, along with a representative photomicrograph.

- Based on the results of literature reviews, the field tests (SDDOT, SD89-04), and the laboratory tests of this study, it is suggested that the hardness be specified as 88.0 minimum to 90.0 maximum. Carbide inserts with higher HRA values are more brittle and prone to shock failure (although it may improve wear resistance), therefore, a maximum hardness of 90.0 HRA is suggested.

- Scratch test was identified as a promising method for evaluating the wear and abrasion resistance of cutting edges. The testing procedures and devices for the scratch test of cutting edges were developed. The laboratory tests have shown that application of these procedures and devices to cutting edge evaluation is feasible. This method is suitable not only for testing the cutting edges purchased, but also for evaluating new cutting edge materials in principle.

- Scratch hardness was found to be a very useful parameter in evaluating the abrasion resistance of cutting edges. This was demonstrated by the results from the laboratory tests conducted for three groups of existing cutting edges (referred to as Valks, Ken, and Pacal). The highest values of scratch hardness were found for Ken blades, and the lowest values of scratch hardness for Pacal blades. This finding is consistent with the results of field tests (SD89-04) where Ken blades were found to be more wear resistant than Pacal blades.

While the scratch test appears to be an attractive test method for evaluating wear resistance of cutting edges, and the application of the testing devices developed in this study has been quite successful, it is imperative that some problems of this approach be mentioned.

The magnification of the shop microscope is not high enough to examine fine scratch grooves. For example, grooves generated using loads less than 8.8N (2 pounds) are difficult to distinguish. This impedes the examination of fine details of the grooves and limits the accuracy of measurement. The use of a diamond file to polish the surface of carbide inserts is not fully satisfactory, and the desired shiny surface finish is difficult to obtain. This, again, may cause reading errors in the measurement of grooves. Obviously, refinement in the testing procedures and improvement on the testing devices are necessary if this method is to be implemented.

6. RECOMMENDATIONS

(1). Specification Changes

- **Hardness:** The hardness is an important material property determining the wear resistance of carbide inserts, appropriate specification of its value is a necessity. As justified in Section 4.6, it is recommended that the value of hardness be specified as 88.0 minimum to 90.0 maximum HRA. A maximum hardness of 90.0 HRA is suggested because carbide inserts with higher values of hardness are more brittle and prone to shock failure.
- **Grain Size:** Since the grain size of tungsten carbide has a significant effect on the hardness and wear resistance of the carbide inserts, to ensure the carbide inserts possess required hardness, it is recommended that the grain size of tungsten carbide be specified in the specifications of carbide inserts, and that the range of the grain size be limited to 2 to 6 micrometers.

(2). Trial Use of the Scratch Test Method

It is recommended that the scratch test (and scratch hardness) be used on a trial basis as a complementary means for cutting edges evaluation. This method may be used to test the cutting edges purchased to see if they can meet the required specifications. If the scratch hardness is too low, it may be an indication that the cutting edges might not meet the required specification. Using the testing devices developed in this study, it is appropriate for the loads to be controlled between 9 to 22N. In particular, a load of 15N may be used for the scratch test of purchased cutting edges. The estimated values of scratch grooves under given loads for Ken cutting edge may be used as a reference. A tentative specification of scratch hardness between 24.5 and 26.5 GPa is recommended.

(3). Further Research

Since the scratch test appears to be a promising method for cutting edge evaluation, it is recommended that a more thorough and systematic research program be carried out in order for this method to be fully implemented. An important aspect of the future research may be to investigate the relationship between the scratch hardness and the Rockwell hardness (A scale).
An understanding of scratch mechanisms will provide a sound base for application of scratch test for cutting edge evaluation.

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