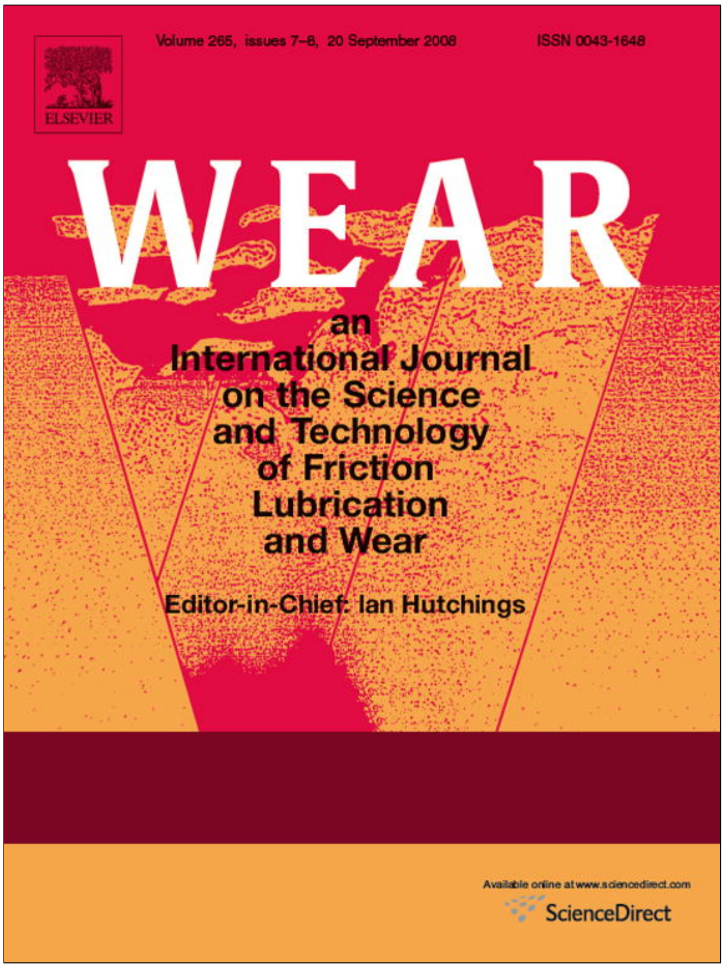
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Wear tests of steel knife blades

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ABSTRACT

A study is presented on the relative wear rates of two carbon steels, a Damascus steel and a stainless steel, using the Cutlery and Allied Trades Research Association (CATRA) of Sheffield England cutting test machine. The carbon steels and stainless steel were heat treated to produce a fine array of carbides in a martensite matrix. Tests were done at hardness values of HRC = 41 and 61. At HRC = 61 the stainless steel had slightly superior cutting performance over the carbon steels, while at HRC = 41 the Damascus steel had slightly superior cutting performance.

1. Introduction

The ability of a knife to hold an edge during use is an important subject for both professional and amateur knife makers. The loss of edge radius during use is basically a wear problem which is often ill defined because it is evaluated by qualitative tests that involve cutting speeds, applied forces and test material that are not consistently held constant. The Cutlery and Allied Trades Research Association (CATRA) of Sheffield England has developed a cutting test machine that holds these variable constant and allows a relative quantitative measure of cutting performance. The test is described in an international standard, reference number: ISO 8442-5:2004(E). This paper presents a study of two historical questions on knife cutting utilizing the CATRA machine for evaluation.

1.1. Study I

Recent experiments of the authors have been successful at reproducing the Damascus blades of antiquity [1]. A considerable lore developed around these blades because of their supposed superior cutting ability over other steel blades available at the time. The AISI steel 1086 is a common high carbon steel representative of the other steels available in the past. Therefore, in Study I the cutting performance of the reproduced Damascus blades is compared to 1086 blades of identical geometry at hardnesses of both HRC = 41 and 61. Modern bladesmiths often make carbon steel knives from the common bearing steel AISI 52100 (ISO 683-17) heat treated to contain fine arrays of carbides to enhance wear resistance. Therefore this high carbon steel was also used in Study I at the hardnesses of HRC = 41 and 61.

1.2. Study II

It has long been taught and remains a widely held view that stainless steel blades cannot hold an edge as well as a high carbon steel blade. The second study addresses this question by comparing the cutting performance of stainless blades made from AEB-L to 52100 and 1086 at a hardness of HRC = 61. The AEB-L stainless steel is recognized as one of the better stainless compositions that allows optimization of corrosion resistance at this high hardness level while minimizing the presence of large primary carbides, which are prone to pull-out along the knife edge.

1.3. Experimental methods and materials

Fig. 1 presents a view of the CATRA machine as it tested a blade of this study at the Spyderco plant in Golden CO. The vice holding the blade moves back and forth in the direction of the arrow while a given force is applied downward on a bundled stack of card material causing the blade to cut through pieces of the card. As seen in the figure, the card material has the shape of thin strips stacked on top of each other into a bundle, and in a given cutting stroke a cer-

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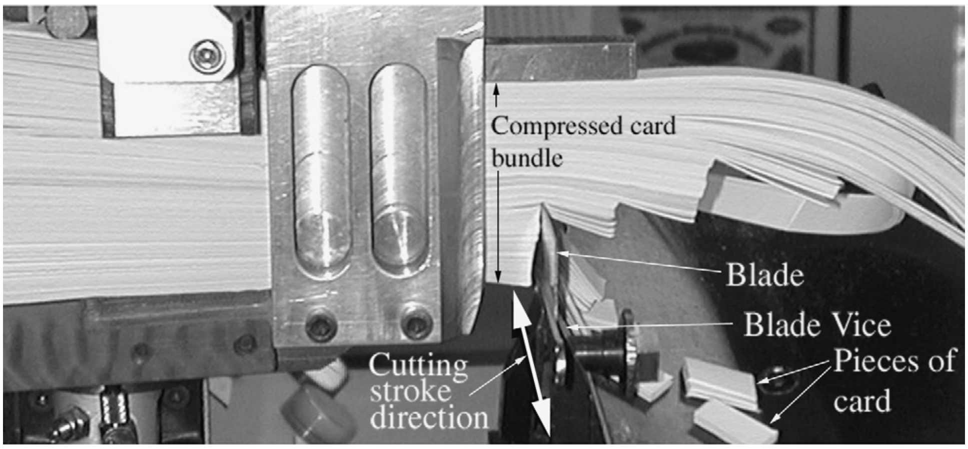

Fig. 1. The CATRA cutting test machine employed in this study.

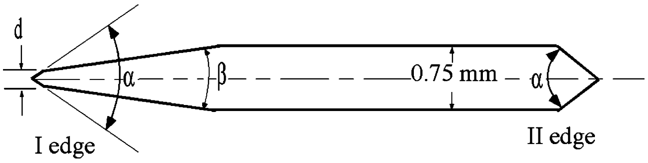

Fig. 2. The two different edge geometries studied.

tain number of strips are cut through and fall off from the stacked bundle. As may be inferred from Fig. 1, the vice table moves freely in the direction at right angles to the cutting stroke and which minimizes friction between blade and the compressed card bundle. A single cut is defined as one back and forth stroke of the vice table.

The experiments of this study were all carried out under the following operating conditions: test load = 50 N, Stroke length per cut = 40 mm, and cutting speed = 50 mm/s. The card material was supplied by CATRA and called a 5% quart paper having a width of 10 mm and thickness of 0.31 mm. It is specified as a chemical pulp containing 5% by weight of abrasive particles that are 99% SiO_2. Size distribution data supplied by CATRA on the particles show that 95% of the particles are less than 30 μm diameter and 57% less than 10 μm diameter. Software control of the machine provides printout of the cut depth for each stroke and the total number of strokes per blade can be varied, but a standard test is 60 strokes.

Fig. 2 presents a transverse section showing the target blade geometry for the two studies, with edge geometries labeled I for the Damascus blade study and II for the stainless blade study. The I edge utilized the common double bevel geometry. The blades were made from 10-cm long blanks that had been heat treated to the target hardnesses. The broad beta face was ground on the blades using a bevel cam grinder at Benchmade Knife Co., Portland OR. The target angle for the beta bevel was $\beta = 4.6^\circ$. Initial studies used a jig to produce a constant alpha angle on a belt grinder. This study, done with the type I edge on 52100 steel at HRC = 62, revealed two problems that limited consistent results with the CATRA machine. First, it is necessary to maintain the cutting edge exactly on the centerline of the width of the blade, which is a problem in hand grinding. Second, it was found that cutting performance is quite sensitive to the *d* dimension, which must therefore be held constant. Consequently all of the alpha edges, in both studies, were ground on the blades using a sharpening machine supplied by the Tru Hone Corp., Ocala, FL, USA. This machine utilizes two sets of intermeshed counter rotating grinding wheels rotating toward the blade edge which automatically tends to center the edge. By carefully dressing the wheels and using a mechanical jig to hold the blades and produce controlled movement through the wheels it was possible to maintain fairly accurate centering of the cutting edge along the blade width and a fairly constant value of the *d* dimension on the type I blades. The alpha tip angle averaged over all the type I blades studied was $40.8 \pm 0.6^\circ$. The average *d* dimension on these blades was measured as 191 ± 19 μm. The percent deviation of the cutting edge from the center of the blade width was also evaluated from the metallographic cross-sections of the blades and found to be $7.1 \pm 4.7\%$ of the blade width. These numbers illustrate that the alpha grinding operation with the Tru Hone machine produced fairly consistent tip geometries. The stainless steel was obtained as strip and the type II alpha angle was ground on one edge of the strip using the same conditions with the Tru Hone grinding machine.

1.4. Steels tested

The steels studied here were chemical analyzed using combustion analysis for C and emission spectroscopy for the other elements and the results are presented in Table 1. The three carbon steels were prepared by forging and grinding as will be described below but the AEB-L was received in finished strip form. The three carbon steels were all forged to blanks of around 2.3-mm thickness which were austenitized in salt and quenched in either oil or a polymer bath. The blades were then tempered to two different levels, HRC = 61 or 41. One batch of the Damascus steel was fast air-cooled which produced a hardness of around HRC = 41 to allow comparison between a fine pearlitic and a tempered martensite structure at the same hardness level. The 52100 steel was austenitized at the usual

Table 1
Chemical analysis of the steels studied

Steel	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	V	Nb	Ti
52100 (ISO 638-17)	1.04	0.30	0.02	0.021	0.24	0.05	1.34	0.02	0.16	0.017	0.004	<0.01	0.004
1086	0.87	0.42	0.007	0.006	0.18	0.10	0.16	0.02	0.19	<0.001	0.24	<0.01	0.003
Damascus	1.61	0.15	0.125	0.07	1.9	0.1	0.5	0.15	0.1	0.06	0.17	0.13	0.06
AEB-L	0.64	0.51	0.018	–	0.47	0.28	12.9	0.04	0.06	–	0.03	–	–

Values are in weight percent.

Table 2
Heat treat preparations

Steel	Austenitization temperature (°C)	Grain size
1086	790	12.8
52100	840	13.0
Damascus	800	Not measured

temperature of 840 °C for this steel which produces a fine array of carbides in the final structure. The 1086 was austenitized at the relatively low temperature of 790 °C using a short, 3 min, hold in order to produce fine carbides in the final structure.

The HRC values of all of the carbon steels were measured on the blanks after surface grinding from the as forged thickness of 2.3 mm to a thickness of 1.6 mm, in order to remove possible decarburization from the forging operation. The β bevel was then ground on to the blanks and surface grinding was used to produce the final blade thickness of 0.75 mm shown in Fig. 2 prior to grinding the alpha bevels on both edges.

The AEB-L strip was so thin that its hardness was determined with DPH microhardness testing on the sectioned samples and then converted to HRC. Similar measurements on the carbon steels reproduced the bulk HRC values within one point. (*Note*: The AEB-L strip had a thickness of 0.68 mm, slightly less than the 0.75 mm of the carbon steel blades shown in Fig. 2.)

Grain size measurements were made on the 1086 and 52100 steels using the technique presented by Grange [2]. As shown in Table 2, the final grain size was very fine. The Damascus steel had been forged to give the characteristic aligned bands of carbides that produce the surface patterns of this steel, and the low austenitization temperature was used to ensure a fine grain size, but measurements of grain size were not carried out on this steel or the AEB-L steel.

2. Experimental results

The final grinding of the α bevel on both the type I and II edges was done using 600 grit wheels. The edges were then given a final buffing treatment on a felt wheel that was loaded with Brownell's 555 White Compound. The abrasive in this compound is aluminum oxide, with an average particle size of under 1 μm. The buffing procedure produced an edge that appeared smooth and shinny to the eye. However, under SEM examination it was found that the final buffing operation produced a small bur at the edges of both type I and II blades as is illustrated for a type II edge on the stainless steel blade of Fig. 3 which presents a view looking at the tip along the center plane of the blade. Evaluation of the full shape of the bur formed along the edge requires the edge to be viewed both along the center plane, as shown here, and at right angles to this view from both sides of the blade. However, one may obtain a good qualitative idea of the size of the bur from the edge width dimension (EW) in Fig. 3. When no bur was present the value of EW was found to be around 0.5 μm and when burs were present the EW values generally ranged from 1 to 5 μm.

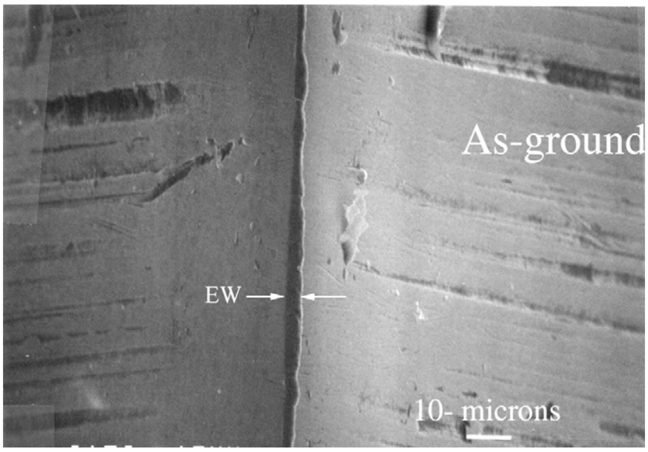

Fig. 3. SEM micrograph of as-ground type II edge.

Table 3
List of blades tested

Blade test no.	Steel	HRC	No. of cuts
1–3	1086	41	2, 3, 60
4–6	1086	61	2, 3, 60
7–9	52100	42	2, 3, 60
10–12	52100	63	2, 3, 60
13–17	Damascus (P)	40	2, 3, 6, 60
18–22	Damascus	62	2, 3, 6, 60
23–25	Damascus	43	2, 3, 60
26–30	AEB-L	61	2, 3, 6, 60

The standard recommended CATRA test procedure measures a cutting depth after 60 strokes. It was found in initial studies that the cut depth decreased very rapidly in the first few cutting strokes and therefore the test procedure was modified to allow examination of the blade edge geometry after a small number of cuts.

Table 3 presents a list of the blades examined with the blades grouped by the steel type. The hardness values within each group fell within ±1 HRC unit of the value listed. The final column lists the number of cuts employed for individual blades. For example, most of the experiments examined three blades, removed from the machine after 2, 3 and 60 back and forth cutting strokes.

Fig. 4 presents the CATRA cutting data for the four steels studied with type II edges and a hardness of around HRC = 61. The vertical axis presents the depth of the cut versus the number of cutting strokes starting with cut 1 and going out to cut 15. The cut depth values shown in Fig. 4 are average values for all of the blades tested. Consider, for example, the group of 1086 blades numbered as 4–6 in Table 3. The cut depth data of Fig. 4 at cut numbers 1 and 2 are an average over 3 blades, at 3 they are an average over 2 blades and beyond 3 they are values for only 1 blade. One sees that there is a dramatic fall-off in the depth of a cut as the number of cuts increases. Values of cut depth beyond 15 cuts are not presented as there is little change beyond around the 12th cut.

Fig. 5 presents the CATRA cutting data for the three steels studied with the type I edges at an HRC value of around 61. The initial

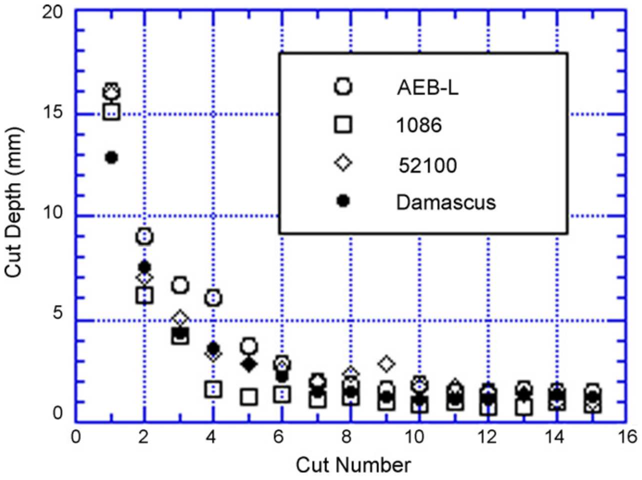

Fig. 4. CATRA data on type II edged blades with HRC around 61.

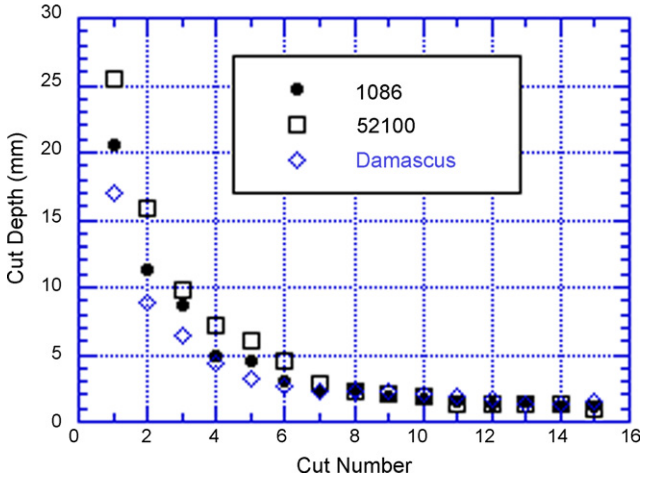

Fig. 5. CATRA data on type I-edged blades with HRC around 61.

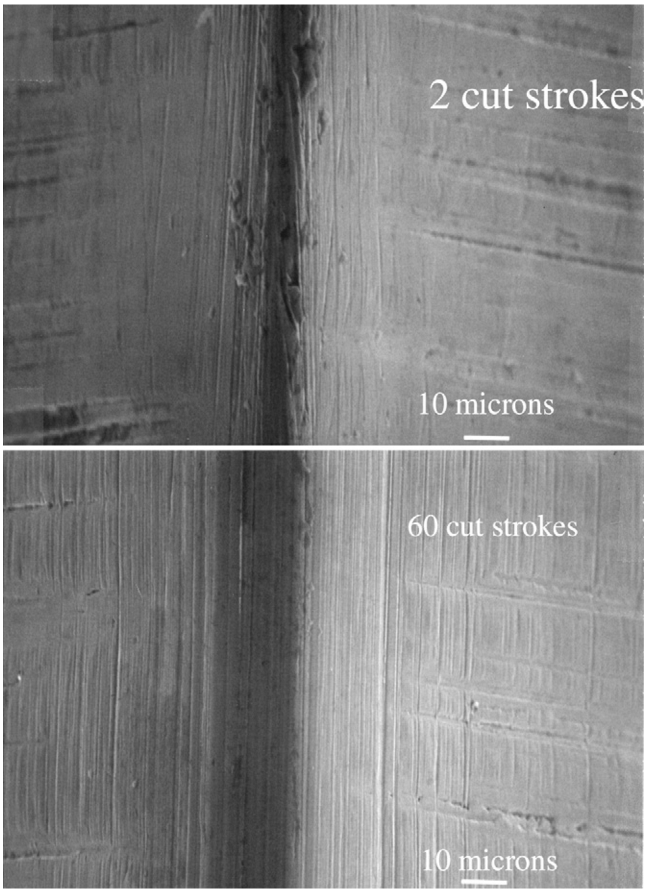

Fig. 6. SEM micrographs of type II edges on stainless blades after 2 and 60 cut strokes.

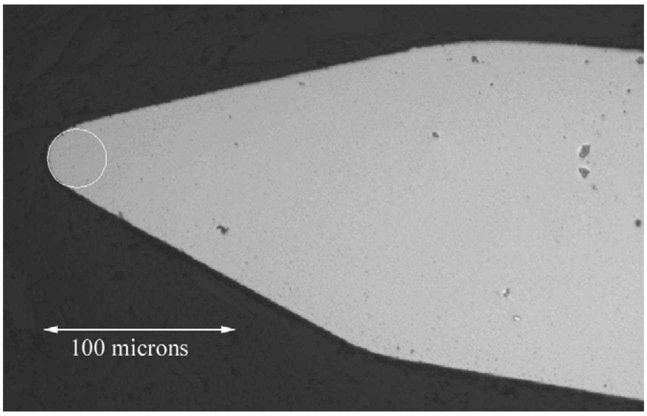

Fig. 7. Tip radius measurement. 1086 blade, 60 cuts, type I edge.

cut depths are seen to be generally larger than for the type II edges of Fig. 4, but again the cut depths fall off very rapidly as the number of cutting strokes increases. Examination of the cutting edge of the blades removed from the machine after 2, 3, 6 and 60 strokes revealed that the edge of blades were being rapidly worn by the cutting operation. Fig. 6(a) and (b) presents SEM micrographs of the cutting edge of a type II stainless steel blade after 2 and 60 cutting strokes, respectively. These micrographs are shown at the same magnification as that of the as-polished cutting edge of Fig. 3 and one sees that a significant rounding of the surface has occurred after only two cutting strokes.

In order to further characterize the wear at the cutting edge, blades were sectioned transversely and examined by standard metallurgical techniques. Micrographs were taken at 2 locations on each worn blade and at one location on an unworn portion near the end of the blade. As illustrated in Fig. 7, a circle was fit to the tip radius of the digital micrograph images with a software program and the tip radius determined from the magnification of the micrograph. The tip radius of curvature, *R*, for all of the unworn blades revealed the strong tendency for bur formation shown in Fig. 3, with over half of the sectioned samples showing burs. The unburred blades consistently gave a radius of curvature at the tip of less than 0.5 μm. The burred edges of the unworn blades showed a wide variation in R, generally in the 2–4 μm range, but up to 15 μm in a few cases. These values were consistent with the EW values measured in the SEM and shown for one blade in Fig. 3.

Fig. 8 presents the measured *R* values on worn blades with a type II edge and a hardness of around HRC = 61. The rapid increase of the tip radius with cut number is seen to roughly follow a logarithmic function. Data similar to Fig. 7 were also obtained for the type II blades with hardnesses of HRC = 41 and for the type I blades with hardness of both HRC = 41 and 61. In all cases the variation followed a logarithmic correlation similar to Fig. 7. These results, to be presented further in Section 3, show that the rapid drop in cut depth during the initial few cutting strokes is due to a rapid rounding of

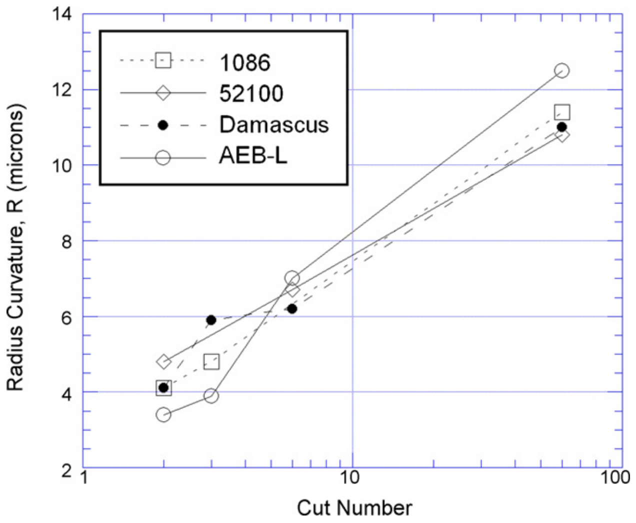

Fig. 8. Radius of curvature vs. cut number for type II blades with HRC around 61.

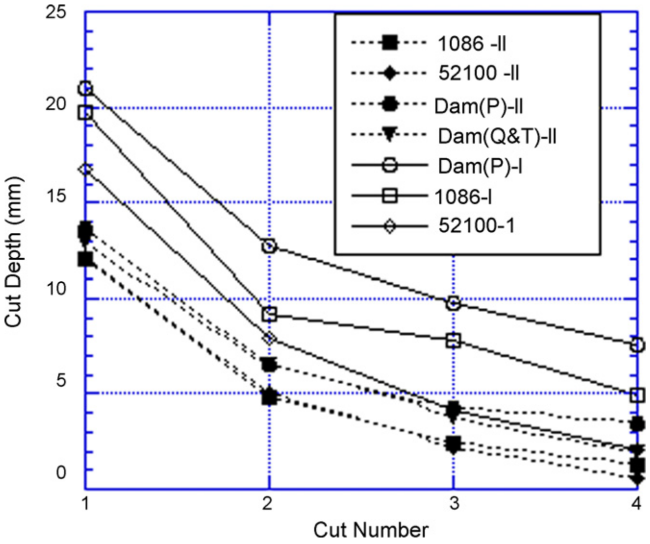

Fig. 9. CATRA data on steels with HRC around 41.

the cutting edge. Hence the ability of the CATRA test as performed here to evaluate relative edge retention of different steels is most sensitive at the first few cutting strokes.

Because of this result the data collected for the steels at HRC values of around 41 are presented in Fig. 9 only for the first 4 cutting strokes. Data for blades with type II edges are shown with the solid symbols and those with type I edges with open symbols. One sees the somewhat surprising result that for both type of edges at this lower hardness the Damascus steels have superior edge retention than either of the carbon steels.

3. Discussion

3.1. Microstructure

All of the steels of this study except the Damascus steel were heat treated to produce fine arrays of carbides to enhance wear resistance at the cutting edge. The size range of the carbide arrays were too small to be resolved well in the optical microscope so a series of micrographs was taken using the SEM. After standard metallographic polishing the AEB-L steel was etched with Viella's etch and the 1086 and 52100 steels were etched with 5% nital to reveal the carbide particles. The carbides in the AEB-L displayed a fairly uniform distribution with an average particle diameter of 0.5 μm and an average particle distribution of 0.3 particles/μm^2. The 52100 steel was heat treated with the standard heat treatment recommended for this bearing steel as described above. This heat treatment is designed to produce a fine carbide array. Literature data show that the carbides of the standard heat treatment have a bimodal distribution with typical diameters of 0.2 μm for the small range and 0.6 μm for the large range [3,4]. The SEM micrographs of the 52100 steel displayed such a bimodal distribution with particle diameters close to this size range and a total average particle distribution of 0.2 particles/μm^2. As explained above the 1086 steel, which is not generally heat treated to produce carbides in a martensite matrix, was given a special heat treatment to produce small carbides. The carbides displayed an average diameter of 0.2 μm with a particle distribution of 0.5 particles/μm^2.

Damascus steel contains bands of carbides that produce the characteristic surface patterns of these steels. The carbides in these bands range in size from 3 to 20 μm and the band spacing ranges from 30 to 100 μm [5]. Fig. 10 shows that in the Damascus steel of this study the band spacing is on the order of 30 μm and the carbide sizes in the bands is in the range of 2–6 μm. The matrix between the carbide bands contains scattered carbides having a much lower density than in the other steels and a larger average diameter. Fig. 10 presents a section view of a typical cutting edge to illustrate the location of the carbide bands relative to the tip. It is apparent that even with the broadened radius of a worn blade, such as that of Fig. 10, the carbide bands will often not lie along the cutting edge of a Damascus blade.

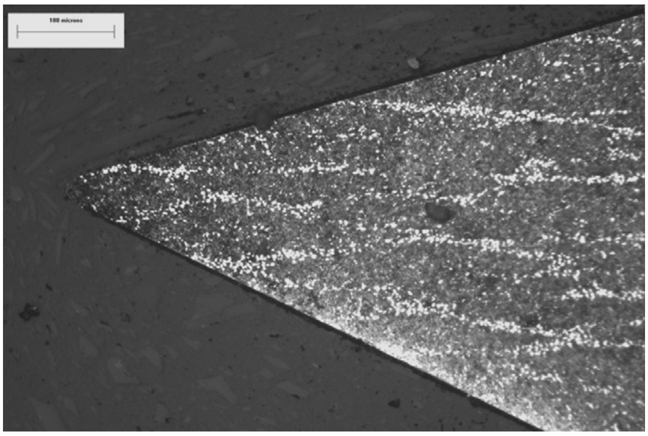

Fig. 10. Tip region of typical Damascus blade 5% picral etch.

3.2. Characteristics of the CATRA wear test

As discussed above in reference to Fig. 8 the radius of curvature at the edges increased rapidly with cut number in all of the tests carried out here. These results are summarized broadly in Table 4 which lists the range of tip radii measured over all the blade sets after 2 and 60 cutting strokes. If the burs on the as-ground blades are neglected, the radius of curvature increases from an initial value of less than 0.5 μm to values ranging from 3.4 to 6 μm in the first 2 cuts. Hence, the initial rate of increase of radius is on the order of 3 μm/cut. This initial rapid increase of the edge radius accounts for the initial rapid loss of cut depth which is characteristic of the wear test data.

The combination of the hard silica particles in the 5% Quartz board and the 50 N load leads to this very rapid wear at the fine edge. The silica particles are harder than the HRC 61 blades (silica HRC = 67–75 [6]) and would be expected to cause severe wear. Generally, steel knives are used to cut materials with hardnesses much less than HRC 61 so that in normal usage the edge radius would remain fine. Therefore, the CATRA test approximates the normal use of steel knives only for the conditions where the edge radius remains small. Hence, the most important parameter measured by the CATRA test for evaluating the cutting performance of knives in normal use is the initial cutting rate. One would expect the longer 60 stroke CATRA wear rates would be useful for evaluating knives made from materials that have hardnesses closer to that of silica. A study of blades coated with various types of hardfacing materials using the CATRA machine has shown this to be the case [7].

Table 4
Range of measured *R* values

Blade type	HRC	2 cuts (μm)	60 cuts (μm)
II	61	3.4/5	11/12.5
II	41	5.5/6	12.2/14.5
I	61	4/5.5	12.5/15.8
I	41	4.5/6	14.5/18

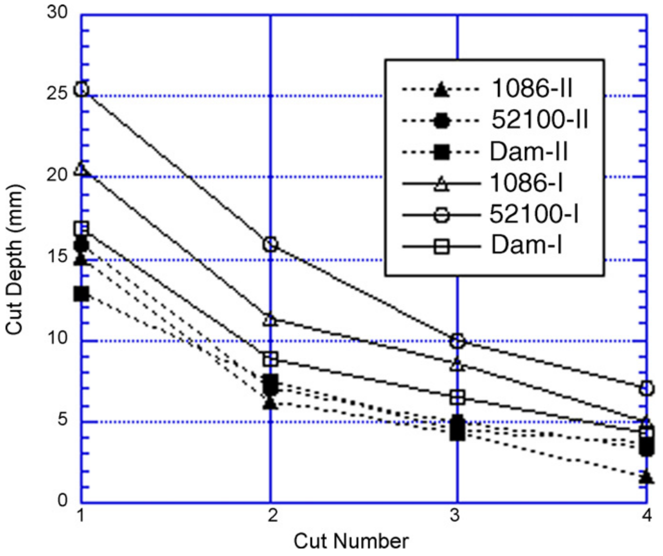

Fig. 11. CATRA data on steels with HRC around 61.

3.3. Relative edge retention of the steels studied

Because of the rapid loss of cutting depth and corresponding broadening of tip radius with the number of cutting strokes, the most useful information for evaluation of edge retention is the record of cut depth versus cut number for the first few cutting strokes. Such data is presented for the carbon steel and Damascus blades at the lower hardness of HRC = 41 in Fig. 9. Fig. 11 presents a similar plot for the data for the carbon steel and Damascus blades at the higher hardness of HRC = 61, and Fig. 12 compares the stainless steel AEB-L blades to the carbon steel and Damascus blades, all with the type II edges.

The data of Fig. 11 compare the cutting performance of the two high carbon steels with the Damascus steel at HRC = 61. For both types of edges it is seen that the 52100 has the best performance. These data, as well as those of Fig. 9 at HRC = 41, also illustrate that the type I blade edges produce larger cutting depths than the type II edges for all of the steel types. This result is expected since, even though the both edges have the same α angle, the type I edge is much thinner near the cutting edge and should offer less resistance during cutting. For example, the effective d dimension for the type II edge is the width of the blade, 0.75 mm, whereas the d dimension of the type I blade averaged 0.19 mm.

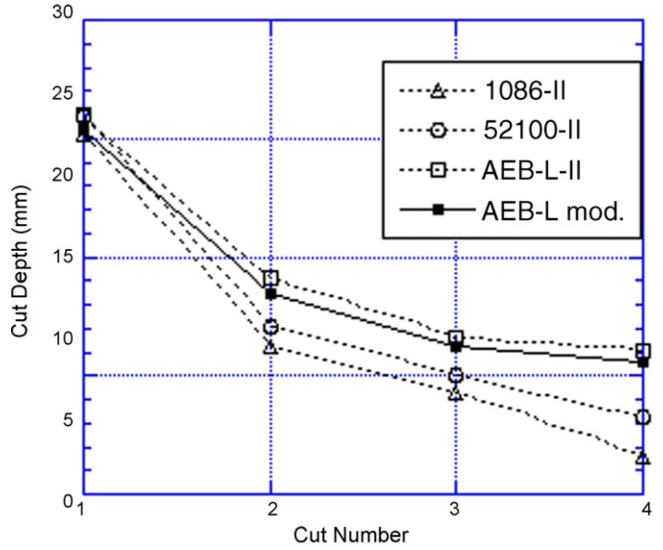

Fig. 12. Comparison of AEB-L stainless with and without modification for smaller thickness to the two carbon steels.

The data of Fig. 9 at HRC = 41 present the surprising result that the Damascus blades at HRC = 41 give better cutting performance than the two carbon steels. This result is probably due to the higher volume fraction carbide in the Damascus steel which results from its higher carbon content. At the relatively low matrix hardness of HRC = 41 the higher volume fraction of the hard carbides must improve the wear resistance more than it does at the higher matrix hardnesses of HRC = 61. Because the carbide hardness is very much harder than the pearlite matrix present at HRC = 41 and it is only slightly harder than the martensite matrix at HRC = 61 it seems logical that the increased volume fraction carbide would have more effect on wear at the HRC = 41 level.

Most all Damascus steel blades from antiquity that we have been able to examine [1] contain a pearlitic matrix structure. The reputation of Damascus steel being superior in cutting ability to European steels was established in the 16 to 18th centuries. During this time period when the Damascus steel reputation was made the European steel blades were made from carburized bloomery or wrought iron. It seems likely that these European blades were inferior to the Damascus blades for two reasons. First, the bloomery and wrought irons contained slag inclusions which would lead to lack of toughness in the blades. Second, lack of control of the carburizing process at this time made it difficult to consistently produce a uniform high carbon level in the steels, which could lead to hardness levels in the HRC = 40 and below range even in a well heat treated blade.

When comparing the cutting performance of the AEB-L stainless steel to the carbon steels one must be concerned about the fact that the width of the stainless steel blades were thinner than the carbon steel blades by 9.3% (0.68 mm vs. 0.75 mm). One may make a rough estimate of how much this reduction in thickness would have increased the cutting depths by assuming that the cutting depth reductions going from the type I edges of Fig. 11 to the type II edges of Fig. 9 are proportional to the increase of the effective d dimension going from 0.19 to 0.75 mm; and that the corresponding reduction in the AEB-L data if its width had been 0.75 mm was proportional to an effective d dimension going from 0.75 to 0.68. The average % reduction for the first 4 cuts of the 1086 and 52100 blades between the type I and II blades at HRC = 61 were calculated. Then the corresponding reduction in the AEB-L data was calculated from these averages by reducing them by the ratio of the effective d change of (0.75–0.68)/(0.75–0.19) and the reduced values are given in Fig. 12 by the line labeled AEB-L-mod. The AEB-L stainless blades appear slightly superior to the carbon steels except for the first cut versus the 52100. Hence, the data support the conclusion that the stainless steel cutting performance is as good or better than the high carbon steels. The composition of the Uddeholm steel, AEB-L and the Sandvik steel 12C27 are essentially the same and the manufactures report [8] that these steels, when properly heat treated to produce a fine array of chromium rich carbides in martensite matrices with hardnesses in the low HRC 60s range, give superior cutting performance over carbon steel blades at the same hardness levels. The present results are consistent with these claims. Because the chrome carbides in the stainless blades are known to be harder than those in high carbon steels one might expect better wear resistance for these stainless blades. It seems probable that the common reputation of carbon steel blades being superior to stainless steel blades might have arisen because stainless cutlery is often not optimized for hardness. In addition, the popular AISI martensitic stainless steels such as 440C which are often used for stainless cutlery contain large primary carbides that are prone to pull-out of the cutting edge during wear.

4. Conclusions

(1) Use of the CATRA machine with their standard board to evaluate cutting performance of steel blades is best carried out at small stroke numbers.
(2) These experiments support the view that martensitic stainless steels optimized for hardness and fine carbide distributions have slightly superior cutting performance than high carbon steels.
(3) At a hardness of HRC = 61, 52100 steel has a better cutting performance than 1086 steel and both are generally better than Damascus steel. However, at HRC levels of 41 obtained with fine pearlite or quenched and tempered conditions the Damascus steel has slightly superior cutting performance than high carbon steels.

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