Title of Publication *Edited by*
TMS (The Minerals, Metals & Materials Society), Year

FRICTION STIR PROCESSING OF D2 TOOL STEEL FOR ENHANCED BLADE PERFORMANCE

Carl D. Sorensen[1], Tracy W. Nelson[1], Scott M. Packer[2], Charles Allen[3]

[1]Brigham Young University, 435 CTB, Provo, UT 84602 USA
[2]Advanced Metal Products,2320 North 640 West, West Bountiful, UT 84087, USA
[3]Knives of Alaska, Inc., 3100 W. Airport Drive, Denison, TX 75020, USA

Keywords: Friction Stir Processing, Blade Testing, Microstructural Modification, D2 Steel

Abstract

Friction stir processing (FSP) has been applied to blade blanks made from D2 steel to improve blade performance. D2 blanks of moderate hardness (30-40 HRC) are subjected to FSP using a convex scrolled shoulder, step spiral pin (CS4) tool made from PCBN. The resulting microstructures are hard, tough, and corrosion resistant. Hardness on the order 65-68 Rockwell C are achieved consistently. The grain size is on the order of a micron or less. The chromium content remaining in the steel grains is higher than that in quenched and tempered D2. Knife blades manufactured from FSP D2 steel exhibit up to a 10 fold increase in edge life over traditional thermomechanically processed and heat treated D2 blades. Methods for repeatably testing blade edge performance are presented, along with a microstructural analysis of the FSP D2.

Introduction

Friction Stir Welding has received significant attention over the past few years as a revolutionary joining process. It produces a fine wrought microstructure with properties significantly better than the cast microstructure of fusion processes. More, recently the friction stirring process has been applied to materials where no joint is involved, as a means of changing the microstructure on a local scale. This application is termed Friction Stir Processing (FSP).

Because FSP is a relatively new metal working process, there are many applications yet to be explored. With the advent of new FSP tooling, applications in steels and other high softening temperature metals are becoming feasible. One of the most recent applications of FSP has been in processing of D2 tool steel for application to knives and other types of blades. This paper discusses preliminary results from this application.

Previous Work

FSP for Microstructural Modification.

FSP for microstructural modification has gained increasing interest during the last six years. A derivative of Friction Stir Welding [1], FSP locally alters the microstructure of a metal by the application of extreme plastic deformation under pressure and temperature. As a result, highly refined microstructures with enhanced mechanical and physical properties have been reported [2-5].

Properties obtained through FSP often exceed those obtainable by traditional metal working processes. Mahoney and co-workers successfully applied FSP to high-strength, low-density aluminum alloys in order to achieve thick section superplastic properties [2,3]. They demonstrated elongations greater than 600% in 5mm thick 7050-T7 without localized necking. Similarly, aerospace components which had been processed via FSP exhibited more complete forming at half the pressure and time than traditional superplastic material [6]. Previously, superplastic characteristics have been obtainable only in materials less than 2 mm thick because of limitations in the sheet production process.

Mishra and co-worker have successfully demonstrated increased mechanical properties in aluminum castings processed via FSP. The FSP material showed tensile strengths and elongations almost double those of the casting [4].

Blade Testing

The leading organization for standardizing test methods for blades is the Cutlery and Allied Trades Research Association (CATRA). CATRA has defined a number of standard tests and associated testing equipment for use in testing commercial blades. Many of these tests have become ISO or EU standards. For testing durability of knife edges, CATRA developed the CATRA Edge Retention Tester (ERT)[7]. This equipment is used to perform cutting tests according to ISO 8442.5-2004, which is specified for food preparation knives. The ERT tests the ability of a knife edge to cut through standard media, consisting of silica-impregnated paper. The paper is cut by means of knife strokes of fixed length and velocity, under the effects of a constant normal force. Typically, the test is run with a normal force of 50 N, with a stroke of 40 mm and a speed of 50 mm/s. When necessary, the media is lifted off the knife edge, and advanced automatically to provide new media to cut.

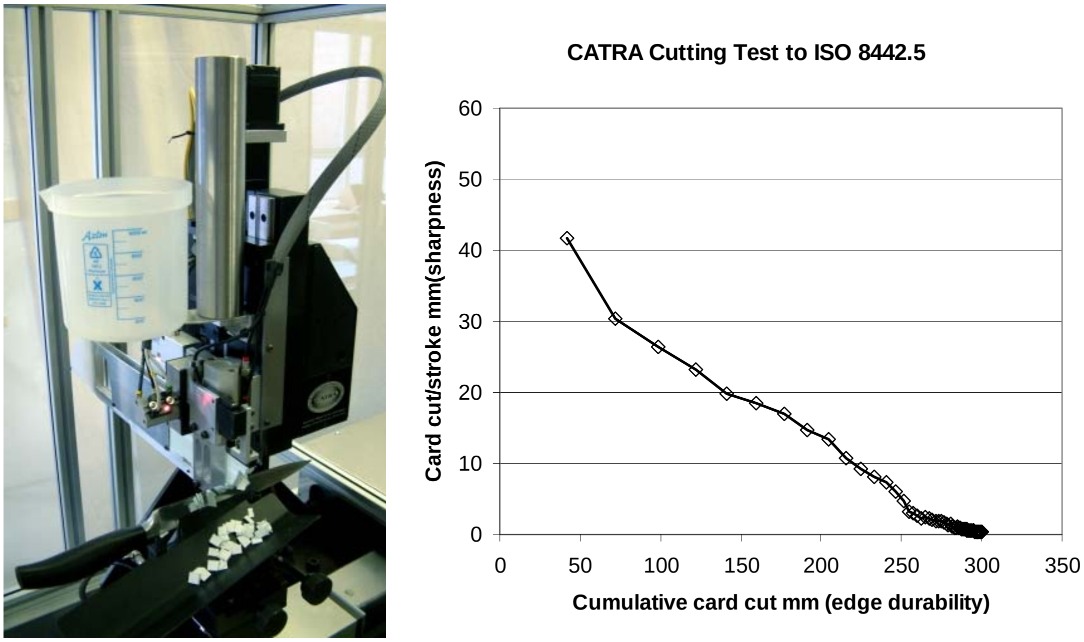


Figure 1: The CATRA Edge Retention Tester, along with a sample data plot from ERT Testing (from [7]).

The ERT measures two important data values for each blade tested. The initial cutting performance (ICP), calculated as the total media cut in the first three strokes, measures the initial sharpness of the blade. The total card cut (TCC), calculated as the total media cut during a test of 60 strokes, measures the life of the blade edge.

For extremely sharp blades such as razors and scalpels, CATRA has developed a different machine for measuring blade sharpness, called the Razor Edge Sharpness Tester (REST)[7]. The REST machine pushes a blade a fixed distance into a silicone medium similar to weatherstripping. During the test, the force required to push the blade into the material is recorded. In contrast to the ERT test, there is no slicing or motion parallel to the blade edge. The REST value is recorded as the peak force during the cutting cycle, measured in N. The lower the peak cutting force, the sharper the blade.

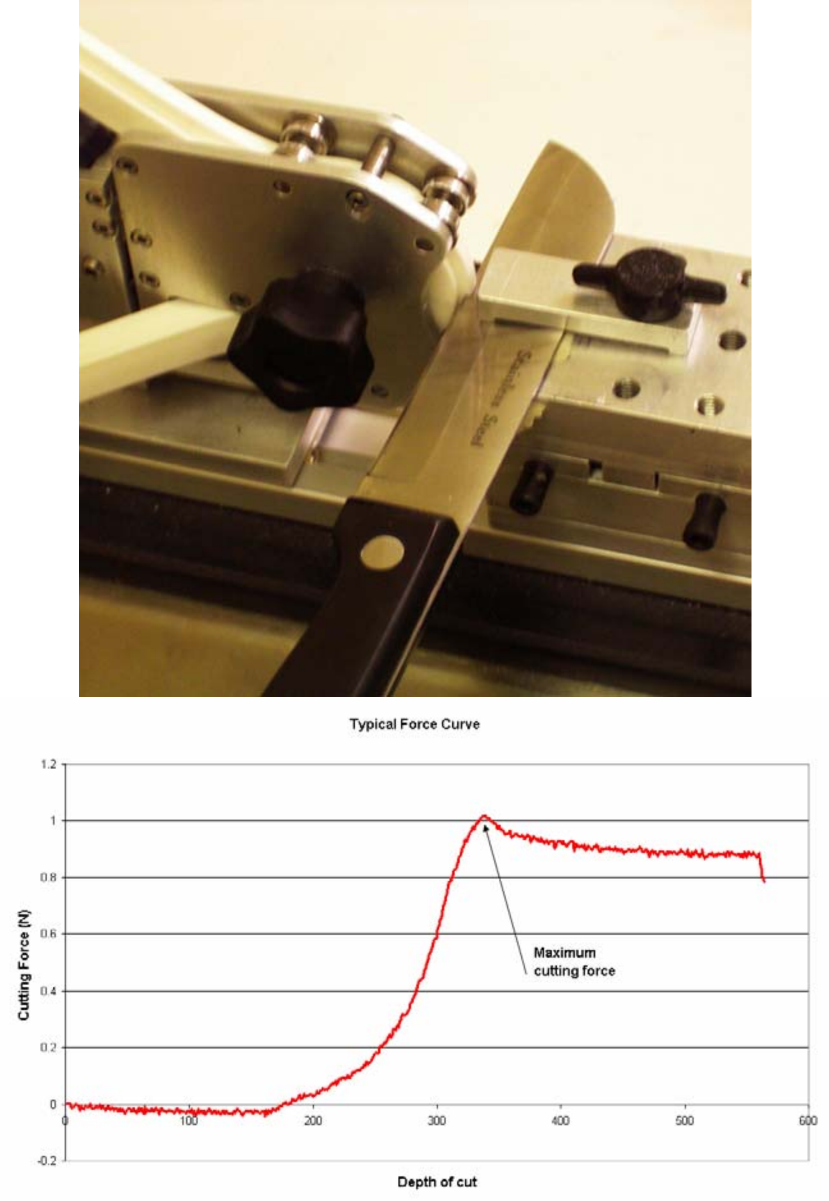


Figure 2: The CATRA Razor Edge Sharpness Tester in action, along with a typical REST plot (from [8]).

D2 Steel

D2 is an air-hardenable high carbon, high chromium cold work tool steel [Ref ASM]. Primary strengthening is attributed to the high carbon (C), chromium (Cr) and vanadium (V) content. The high carbon contributes to higher hardness in the martensite that forms during quenching from the austenitic temperature. Cr and V slow the transformation kinetics of the austenite to pearlite, increasing the hardenability. Cr and V also act as secondary hardening agents by forming carbides thought the microstructure.

Typical applications of D2 tool steel include tool and dies for cutting, forming and shaping of materials. However, the D-series tool steels also exhibit excellent wear resistance because of their higher carbon and vanadium, making them suitable materials for knife blades. Table 1 shows the specified composition for alloy D2 [Ref. ASM Handbook].

Table 1 Nominal composition of D2 tool steel.

Steel/Comp.	C	Cr	Mn	Si	Ni	Mo	V
D2	1.4-1.6	11.0-13.0	0.6 max	0.60 max	0.30 max	0.70-1.20	1.10 max

Despite the high Cr content, D2 is not considered “stainless”. D2 is not considered stainless because much of the chromium in D2 is tied up in the form of chromium carbides, which form during cooling from the austenitic temperature in the range of 650-800C. The carbides obtain their high Cr levels by absorbing Cr from the surrounding steel. This Cr depletion greatly reduces corrosion resistance; in the steel surrounding the carbides the Cr concentration is less than 12%. Thus, D2 is not considered stainless steel.

FSP Methods

FSP was performed on 6.5mm thick D2 steel with nominal composition shown previously in Table 1. Two different heat treatments were used in this investigation. Both were austenitized and quenched then tempered to Rc 30 and 40. Plates were cut 15cm in width and 60 cm in length. The processed sides of the plates were ground and cleaned with acetone prior to processing.

Table 2: Parameters used in DOE

Weld Side Next to Blade Edge	Spindle Speed, RPM	Feed, IPM	Hardness	Pin	Blade IDs
Retreating	300	3	40	Stepped Spiral	2-1, 2-2
Retreating	450	3	30	Stepped Spiral	4-1, 4-2
Advancing	300	5	30	Stepped Spiral	5-1, 5-2
Advancing	450	5	40	Stepped Spiral	7-1, 7-2
Advancing	300	3	30	Tri-flat	1-1, 1-2
Advancing	450	3	40	Tri-flat	3-1, 3-2
Retreating	300	5	40	Tri-flat	6-1, 6-2
Retreating	450	5	30	Tri-flat	8-1, 8-2

FSP was performed using two different tool designs. Both tools had a convex scrolled shoulder that was 25.4 mm in diameter and a convex radius of 90 mm. The diameter at the base of the pin was 6mm, with a pin half-angle of 15 degrees, and a pin length of 2.2 mm. One tool had a simple truncated cone pin and the other featured a step spiral.

FSP was performed at 300 and 450 RPM and 3 and 5 IPM (1.3 and 2.1mm/s). During processing, the center of the tool was 12 mm from the edge of the plates. The edge of the knife blade was placed between the center of the processed zone and the edge of the plate. For some blades, the advancing side of the processed zone was closest to the edge of the plate; for others the retreating side was closest to the edge. All plates were processed under position control. Table 2 shows the parameters for each of the blades produced in this study.

Transverse samples were removed from each parameter set. These were mounted, polished, etched, and examined via optical microscopy (OM) for weld quality and microstructure. Each sample was etched with 10% Nital for up to 8 minutes. Optical microscopy images were examined to determine grain structure and carbide distribution in the processed zone.

Vickers microhardness was performed on each set of conditions. Microhardness tests were performed with an automatic microhardness tester using a Vickers diamond indenter, a 300 gram load, and an 8 second dwell. A line trace along the plate centerline through the processed zone was performed on each sample.

Blade Testing Methods

Following microhardness testing, a waterjet cutter was used trim the plates to the intended blade edge at a distance of 3 mm from the process zone centerline. Microhardness testing showed that the hard zone would be included in the blade if the cut were made at this location. The blades were then ground with a bevel angle of 20 degrees to an edge thickness of 0.75 mm (0.030 in). The final sharpening was performed on an abrasive belt using a fixture to hold a constant edge angle, followed by a cardboard wheel to remove the wire edge.

The blades created by the process described above were then tested using a combined test sequence based on CATRA testing principles. Blade sharpness was measured using the CATRA REST tester. Blade durability was measured by a test similar to the CATRA ERT test, but using a different cutting medium.

The ERT-style testing used in this study used manila rope ¾ inch in diameter. Rope was used instead of CATRA test media because the CATRA test media was too aggressive, and not indicative of the typical use of outdoor knives.

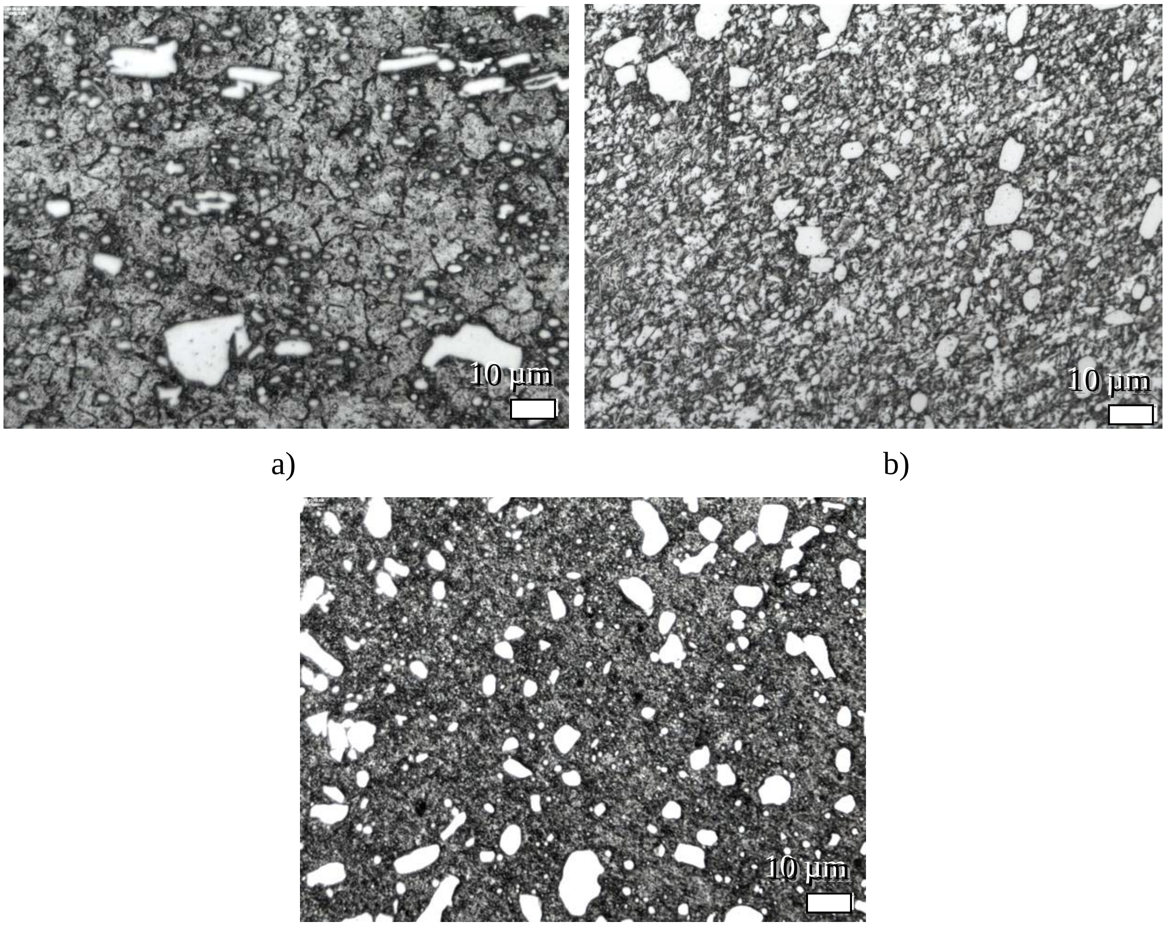
After being tested in the REST tester, the sharpened blade was placed in the ERT tester. 20 strokes were made on the ERT tester. The blade was removed and tested in the REST tester. The blade was returned to the ERT tester for 40 strokes, then tested on the REST. The cycle of 40 strokes on the ERT followed by REST testing was repeated until the blade was too dull to shave.

Results and Discussion

Microstructure Evaluation

Grain Size Reduction. As shown in the photomicrographs in Figure 3, the grain size of the FSP D2 (Figure 3 b and c) has been reduced significantly over that of the base metal (Figure 3 a).

The grain size of the base metal (traditionally processed) D2 ranges from 5 to 15 µm. Figure 3 b and c show that the grain size for the FSP D2 is significantly smaller than that of the as-received material. Grain sizes of the FSP D2 range from submicron to a few µm. In addition to grain size, carbides appear to be smaller on average compared to those in the base metal.



a) b)

c)

Figure 3: Optical micrographs of FSP D2 showing changes in grain size. a) Normally heat-treated D2, b) FSP at 600 RPM and 4 in/min, and c) FSP at 250 RPM and 4 in/min

Figure 3 also demonstrates that FSP processing parameters can also have a significant effect on grain size. The microstructure shown in Figure 3 b was processed at 650 rpm and 4 in/min. The grains in this image appear to be between 1 and 5 µm in size. At 250 RPM and 4 in/min (Figure 3 c) the grains are so fine that, even at 1000X, the interior of the grain cannot be resolved.

Transmission electron microscopy (TEM) was used to analyze the grain size of the FSP D2 at 250 RPM and 4 IPM. Figure 4 shows a TEM micrograph of this material at a magnification of 80,000X. The average grain size in this figure is about 500 nm.

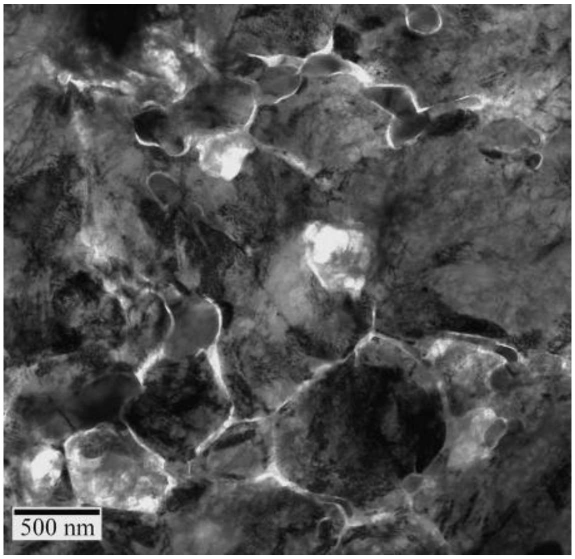


Figure 4: Transmission electron micrograph of FSP D2 at 250 RPM and 4 in/min showing typical grain sizes of 500nm.

Grain sizes of this magnitude in tool steels are unobtainable by traditional metal working processes. Perhaps the most promising candidate would be powder metallurgy (PM) processing. PM processing may be capable of attaining grain sizes of this magnitude, but the strength and toughness of the material is severely compromised by the presence of oxide inclusions and voids inherent to the process. As an example, a photomicrograph of S30V, a powder metallurgy processed steel, is shown in Figure 5. The grain sizes here are on the order to 5-10 µm, which is about 30% smaller than traditional D2, and approximately 5 times larger than the coarsest FSP D2. Although this process leads to smaller grains than traditional D2, the void and oxide content (seen as darker region in Figure 5) result in very poor fracture toughness.

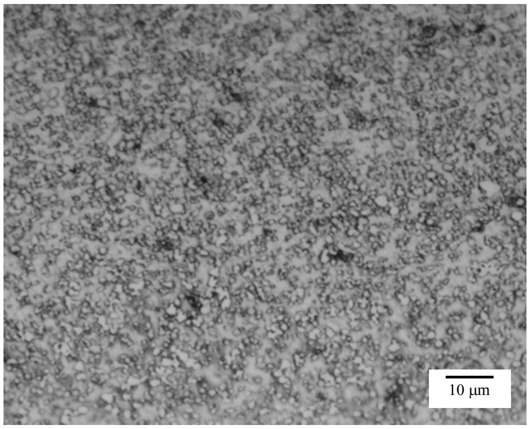


Figure 5: Photomicrograph of powder metallurgy processed S30V steel.

Greater Levels of Alloying Elements in the Matrix In addition to the reduction in grain size, FSP D2 gets a second bump in hardness from the addition of chromium (Cr) and carbon (C) to the martensite matrix. Under the elevated temperature and strain rates present during FSP, the Cr rich carbides in the D2 steel begin to dissolve, with the Cr and C diffusing into the austenite matrix. During post-processing cooling, these elements are retained in solution, thus increasing the steel’s hardenability and martensitic hardness. This leads to strength not typically reached in traditional D2 processing.

The increased level of Cr in the matrix is demonstrated by the increased corrosion resistance of the FSP D2. The material processed by FSP exhibits excellent corrosion resistance when subjected to a nitric acid solution as shown in Figure 6. The FSP region (in the middle of the figure) shows no indication of attack by nitric acid implying that the processed zone is "stainless". In contrast to the undisturbed FSP region, the base metal is severely attacked by the etchant, leading to a dark grey color.

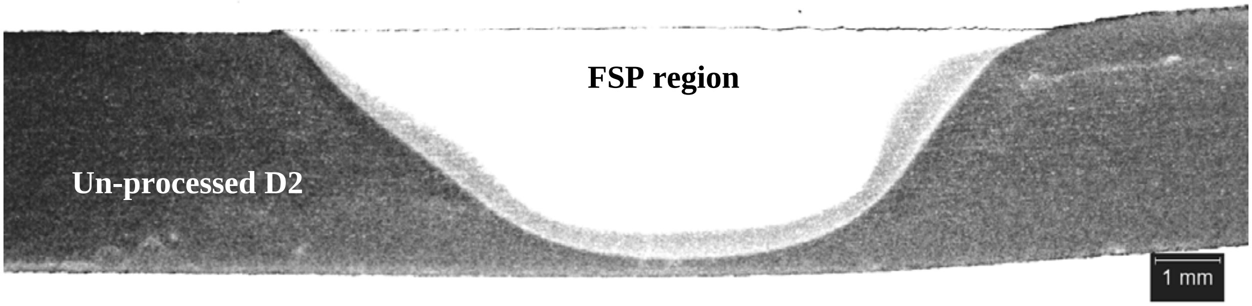


Figure 6: Photomacrograph of FSP D2 steel etched with 10% Nitric acid in methanol.

Microhardness Results

Figure 7 shows typical microhardness results for the FSP zone in the D2 blades. As can be seen, there is no reduced hardness associated with the HAZ. The hardness in the stir zone is uniformly high, with some scatter that is mostly due to the presence of carbides in the microstructure. The peak hardness in the stir zone is over 1000 HV, and the minimum hardness is the stir zone is over 900 HV. These hardnesses are typical of cemented carbide, and significantly higher than those usually seen in D2.

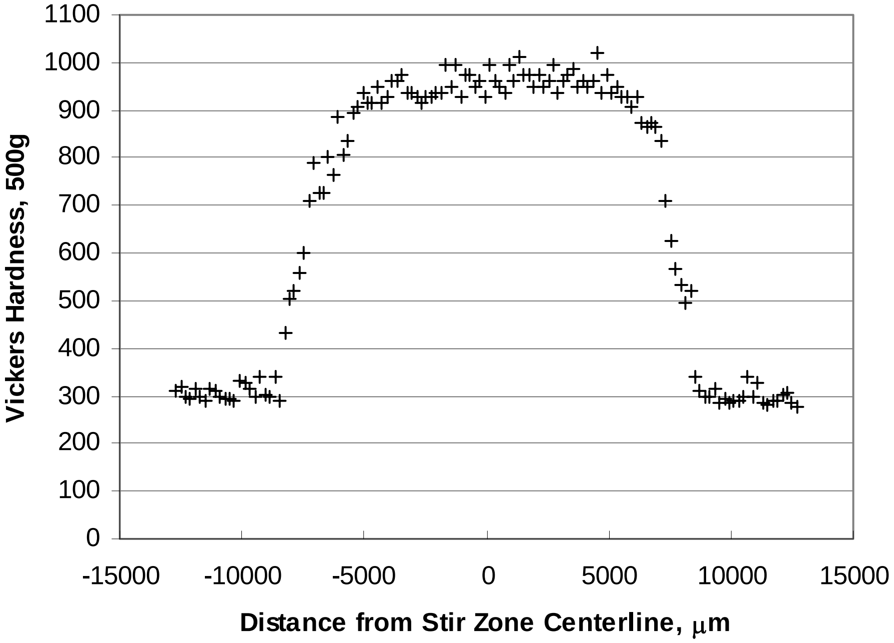


Figure 7: Measured microhardness data near the FSP zone.

Sharpness Testing

The primary functional test for the sharpness of an outdoor knife is the ability to shave with the knife. A series of D2 blades was tested in this sequence, coupled with a shaving test. Following each REST test, the blade was tested to see if it would shave the arm hair of the operator. The

REST value and the shaving ability of the blade were recorded and used to determine the REST value that constituted the loss of shaving sharpness. Over this testing, the average minimum REST value that led to a loss of shaving was 3.07 N. Accordingly, 3 N was chosen as the limit for shaving sharpness.

Figure 8 shows the performance of four different blade steels in the ERT test using manila rope. All blades had identical edge geometry. As can be seen, the FSP D2 blade (called Friction Forged^{TM} in the legend) cuts 50% more rope on the first stroke than S30V, and 80% more than S90V and traditionally processed D2. This higher initial sharpness lasts throughout the entire testing cycle. One way of determining blade durability is to measure the total amount of rope cut before the blade reaches a minimum sharpness level. If we use the 0.25 inches/stroke sharpness value for comparision, we see that the FSP blade falls permanently below 0.25 at 200 inches of rope cut. In contrast, the S30V reaches this sharpness at 40 inches, S90V reaches this sharpness at 15 inches, and D2 reaches this sharpness at 5 inches. By this measure, FSP D2 is five times as durable as S30V and 40 times as durable as traditionally processed D2.

Figure 8: Rope cut (ERT sharpness) per stroke as a function of total rope cut for various blade materials.

Figure 9 shows total inches of rope cut as a function of REST value. As mentioned previously, a REST value of 3 is the mean value of the loss of shaving sharpness. D2 loses its shaving sharpness at less than 5 inches of rope cut. S30V loses shaving sharpness at 100 inches of rope cut. S90V loses shaving sharpness at 140 inches of rope cut. FSP D2 retains shaving sharpness at over 250 inches of rope cut. The FSP blade has significant advantages in edge retention by this measure as well.

Conclusions

FSP has been successfully used to increase the durability of knife blade edges. The grain size in the processed zone was greatly reduced from the base metal, with a typical grain size of 500 nm.

The FSP zone also had higher concentrations of chromium and carbon in the martensite, as indicated by the stainless nature of the stir zone. The additional Cr and C lead to high hardness in the stir zone. The hardness in the FSP zone exceeded 900 HV. This high hardness allows the formation of an exceptionally sharp edge. It also results in an extremely durable knife edge, with the edge up to 40 times as durable as traditionally processed D2.

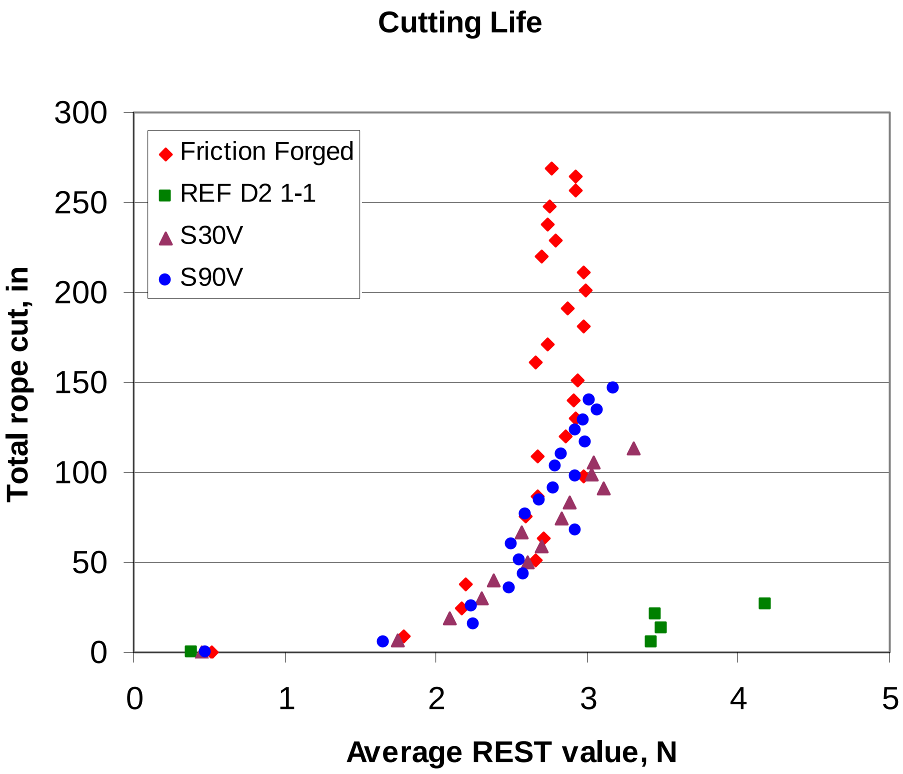


Figure 9: Total rope cut as a function of average REST value for various blade steels.

References

1. The Welding Institute; TWI; W.M. Thomas, E.D. Nicholas, J.C. Needham, M.G. Murch, P. Temple-Smith, C.J. Dawes, PCT World Patent Application WO 93/10935. Field: 27 Nov. 1992 (UK 9125978.8, 6 Dec. 1991). Publ: 10 June 1993.
2. Z. Y. Ma, R. S. Mishra and M. W. Mahoney, Superplastic deformation behavior of friction stir processed 7075Al alloy, *Acta Materialia*, **50** (2002) 4419.
3. M.W. Mahoney, R.S. Mishra, T.W. Nelson, (2002) “Friction Stir Processing Creates Aluminum Alloy Superplasticity,” *Industrial Heating*, February, pp. 31-33.
4. The Effect of Friction Stir Processing on 5083-H321/5356 Al Arc Welds: Microstructural and Mechanical Analysis" by Christian Fuller and Murray Mahoney
5. J.Q. Su, T.W. Nelson, and C.J. Sterling, (2003) “A New Route to Bulk Nanocrystalline Materials”, *Journal of Materials Research*, 18(8), pp 1757-1760.
6. Murray W. Mahoney, “Friction Stir Welding and Processing: A Sprinter’s Start, A Marathoner’s Finish”, *Proceedings of the 7th international Conference on Trends in Welding Research*, pp 233-240. April 2005.
7. Cutlery and Allied Trades Research Association, http://www.catra.org/products/testing/knives/knives_aet.htm, visited October 2006.
8. Cutlery and Allied Trades Research Association, http://www.catra.org/products/testing/knives/sharpness_tester.htm, visited October 2006.