



BASIC STUDIES CONCERNING CHEMICALLY ACCELERATED VIBRATORY SURFACE FINISHING (CAVSF)

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ABSTRACT

It is known that with the inexpensive chemically accelerated vibratory surface finishing (CAVSF) process it is possible to reduce the average surface roughness of helicopter gear teeth from the conventional 16 micro-inches (0.39 μm) down to approximately 2 micro-inches (0.05 μm). The friction and the surface stress at the mating surfaces are remarkably decreased. This results in an increase of the fatigue lifetime on the order of 300 to 400%, reduced downtime, reduced component weight in new designs, less noise, higher energy efficiency, and lower overall costs.

The CAVSF process was studied, and the effects of different factors such as the chemical reaction and erosion during the process were examined both separately and in combination with each other. The variation in the average material removal and the roughness during the process for different steels and alloys was investigated, as well as the change in chemistry of the solutions used during CAVSF. Relations were drawn from the lowest possible roughness values to the microstructure of different carbon steels. New treatment solutions for the CAVSF process and process parameter variation were studied.

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INTRODUCTION

Machining grind lines are a problem in critical working surfaces on gears, splines, journals, crankshafts, bearings, camshafts, and couplings. These grind lines can have an average roughness of around 12 micro-inches (0.30 μm) and will cause vibration, friction, torque, high operation temperature and noise and will impair lubricity. This leads to metal debris, plastic deformation, scuffing, wear, and several forms of fatigue, which limit the useful life of equipment.

Chemically accelerated vibratory surface finishing (CAVSF), also called isotropic surface finishing, (ISF) or super-finishing is an environmentally friendly, inexpensive process to reduce the stress raisers, damaged material, and asperities from the metal surface^{1,2,3}. The average surface roughness of case hardened steel surfaces on gear teeth decreases from around 12 micro-inches (0.30 μm) to around 2 micro-inches (0.05 μm) by using CAVSF. During the process, generally less than 200 micro-inches (5 μm) of material is removed. The geometry of the part is not impaired.

In this report, the “removed material” is measured in micro-inches and represents the average thickness of solid removed material across the whole geometrical surface area of the part. It is obvious, then, that the local removed material is higher on corners and edges and lower in cavities and recesses than this average. The weight loss and the specific density of the part are used for the calculation.

The average roughness R_a is measured with a profilometer that has a stylus with a 45 degree diamond cone. The tip of the cone has a radius of 1 micrometer or approximately 40 micro-inches. The measured values for the average roughness are mostly between 0.5 and 30 micro-inches. The diamond tip cannot measure the real average roughness which is about 4 times higher than the measured average roughness⁴. The measured maximum roughness is about 10 times higher than the measured average roughness.

It was found that the measured life improvement for super-finished gears was a factor of approximately five compared with conventional gears (average roughness: up to 16 micro-inches (0.41 μm) on the pitch line)⁵. A run-in time for super-finished surfaces is not required. Other benefits connected with the CAVSF process are reduced downtime, reduced component weight in new designs, less noise, less vibration, higher energy efficiency, and lower overall costs.

This report is part of the combined efforts of the University of North Dakota and Alion Science and Technology to validate, investigate, optimize, and possibly improve the existing CAVSF process from Houghton International Inc. for critical surfaces. The report shows the results from the University of North Dakota Engineered Surfaces Center concerning the investigation of the CAVSF process. Material removal and roughness changes during the process on different surfaces were measured, and process parameters were varied.

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Two different vibratory bowls (**Figures 1 - 3**) were available for testing the CAVSF process. The first has an inner diameter of 45.5 inches (1.16 m), and the second has an inner diameter of 11 inches (0.28 m).



Figure 1: Big vibratory bowl with 45.5 inches (1.16 m) inner diameter and a dosing station in the background for continuous flow of chemicals through the bowl.



Figure 2: Big vibratory bowl filled with large ceramic media.

During the process, a continuous flow of chemical solutions runs through the big vibratory bowl, which is filled with ceramic media, test pieces, and additional steel parts. The vibratory motors run at 1800 rpm. The media, the test parts and 12.5 square feet (1.16 square meter) of filler strip steel move in a toroidal helix around the bowl. Acid gets sprayed into the bowl with a flow rate of 1.5 gal/hour for the first two hours, followed by a 15 minute water rinse cycle of 15 gal/hour. Finally, 10 gal/hour burnishing liquid runs through the vibratory bowl. The parts are taken out, rinsed in tap water and then demineralized water, and dried with paper towels.

The small bowl (**Figure 3**) runs discontinuously and is filled with 4 kilograms of big ceramic media, test pieces, and a defined amount of treatment solution (hold-up). The acid treatment time is mostly two hours like in the big bowl. It was found useful to run these quick tests with small amounts of different treatment solutions in the small bowl before testing the process in the big vibratory bowl.

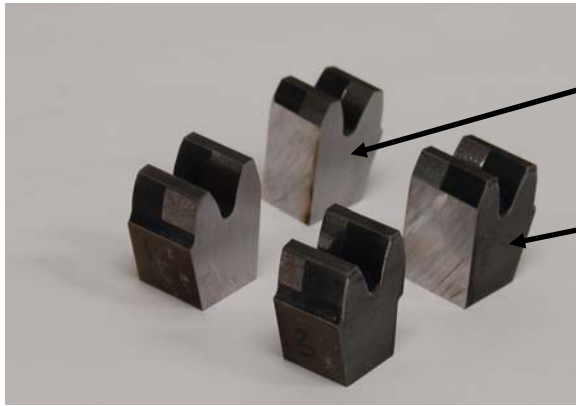


Figure 3: Small vibratory bowl with 11 inches (0.28 m) inner diameter filled with 4 kg of large ceramic media.

Comparing erosion, corrosion, and the combined effect

A case-hardened, ground gear made of Pyrowear 53™ was cut into pieces. The test pieces shown in **Figure 4** were used to determine the material removal and roughness changes in the CAVSF process. Microsurface 5132™, a pyrophosphoric acid based treatment solution for alloys, was used in the 45.5 inch (1.16 m) diameter vibratory bowl. During the acid treatment, single test pieces were taken out of the bowl, the weight loss was established, and the average removed material thickness was calculated (**Figure 5**). The removal rate at the beginning was around 150 micro-inches per hour (3.8 μm/hr) and then changed to a stable value of around 110 micro-inches per hour (2.8 μm/hr). Also after the acid treatment was run for 6 hours, the removal rate did not change.

During the acid treatment, the sample gets coated with a black layer consisting of phosphorous containing iron salt together with iron oxide/hydroxide. The rubbing ceramic media exposes fresh metal at the peaks of the asperities. Further reaction occurs mostly in these exposed areas. The asperities slowly get smaller, and the coating in the valleys of the rough surface slows down the reaction in these areas. The reaction here is strongly controlled by diffusion. **Figure 5** shows a curve labeled “Etching with Microsurface 5132™ in the beaker without ceramic media”. Here the acid etching was done without the action of the ceramic media in a beaker. Before the part was weighed, the coating was brushed away with non-abrasive toothpaste. It is obvious that the thicker the crust the slower the reaction with the alloy.



Side with exposed non-hardened substrate.

Side with case hardened layer.

Figure 4: Pyrowear 53™ test samples cut out of a full gear.

The results of two more tests are documented in **Figure 5**. In one test, the CAVSF process was completed with water instead of acid. In the other, only the abrasive action of the dry ceramic media was investigated. The corrosion in water gives a very slow reaction and a low material removal. The material removed during treatment with dry media is 5 to 10 times lower than the material removed with water. About 2% of the metal removed in the CAVSF process is taken away by only the abrasive action of the ceramic media. It is fair to say that the ceramic media only attacks the crust built by the acid.

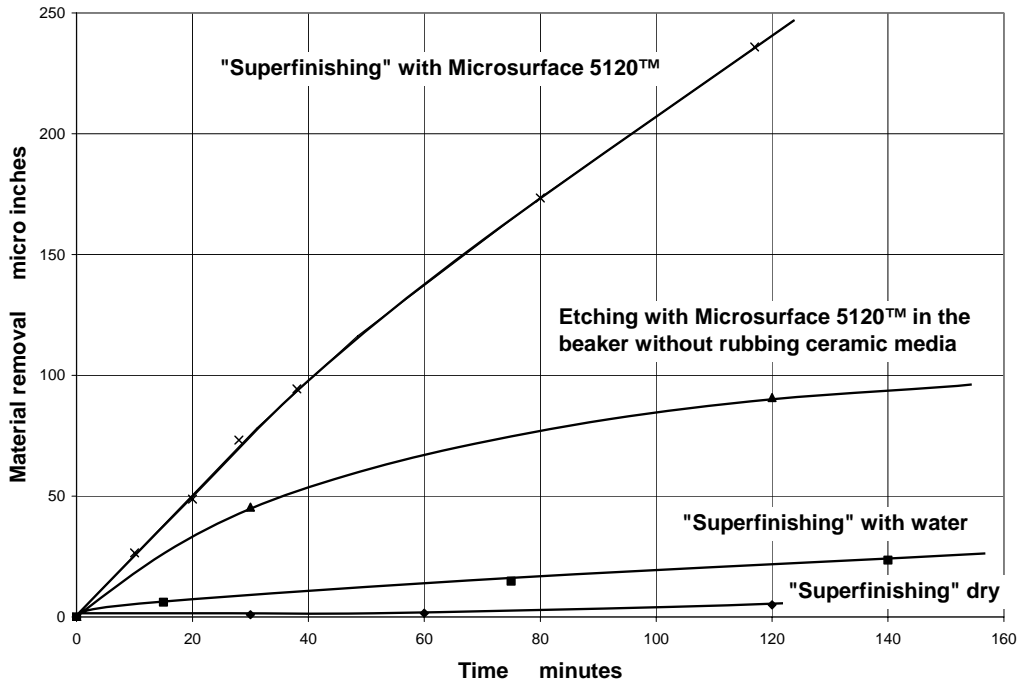


Figure 5: Material removal on Pyrowear 53™ during different processes versus time.

Material removal and roughness changes during CAVSF with continuous flow of chemicals in a 45.5 inch (1.16 m) diameter vibratory bowl

In this chapter, a closer look is taken at the material removal and the roughness changes during the whole CAVSF process in the 45.5 inch (1.16 m) vibrating bowl with a continuous flow of chemicals. Twenty strip steel pieces (2 x 1 x 0.17 inches, 0.05 x 0.03 x 0.0043 meters) were ground to an average roughness of around 19 micro-inches (0.48 μm). After the parts were weighed, they were put into the vibratory bowl using Microsurface 5132™ as the acid. After the water rinse, Cerfa-Kleen 5502™ was used as burnishing liquid. During the process, parts were taken out to monitor the removed material and the roughness changes. A second test was performed with polished strip steel samples (R_a around 0.86 micro-inches (0.022 μm)). The results are shown in **Figures 6 and 7**.

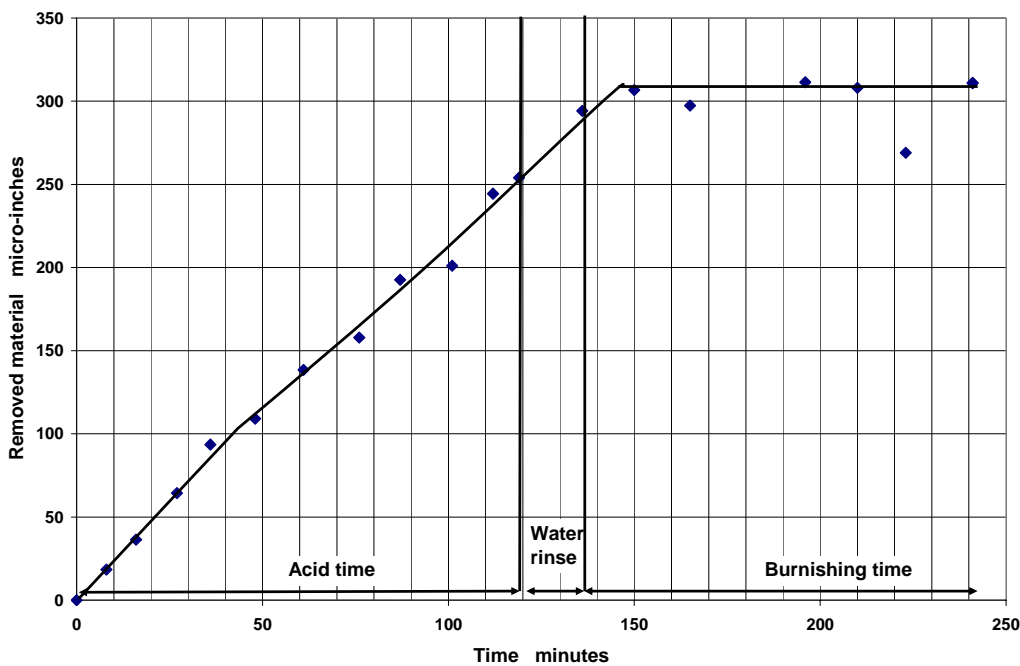


Figure 6: Material removal on strip steel during the CAVSF process in the 45.5 inches (1.16 m) vibratory bowl.

After 45 minutes of the acid treatment, the end-roughness is reached, and the slope of the removed material versus process time curve changes; the removal rate slows down slightly.

During the 15 minute water rinse, the material removal continues, and the roughness decreases from 5 to 6 micro-inches (0.13 to 0.15 μm) to the final level of 3.5 to 4 micro-inches (0.089 to 0.10 μm). Burnishing removes the dark crust from the surface and gives a brighter optical appearance as shown in **Figure 8**.

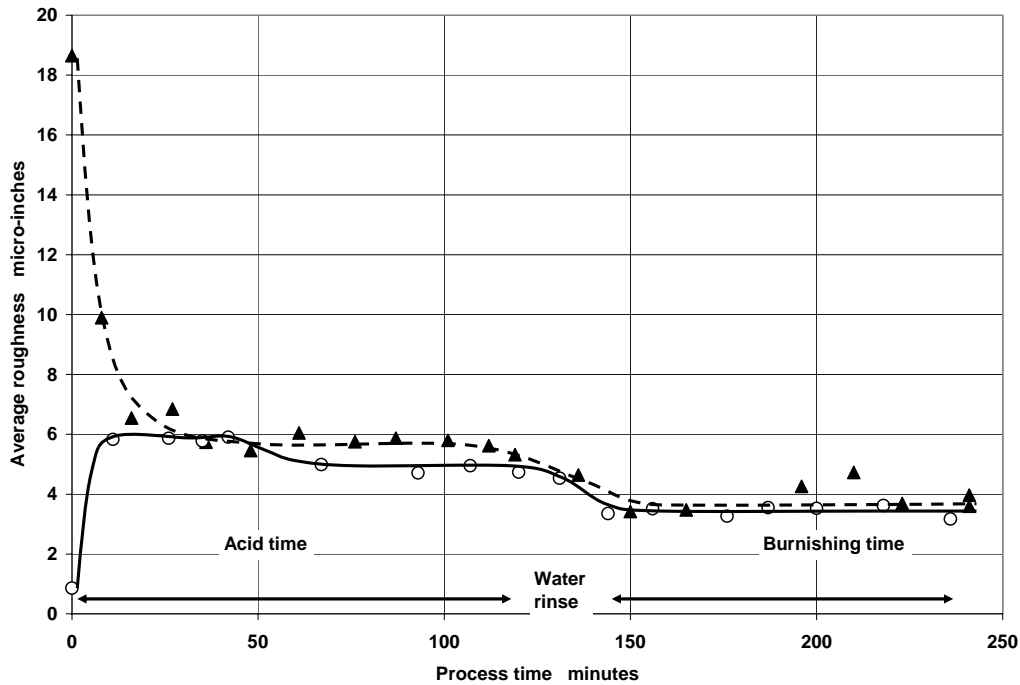


Figure 7: Average roughness of strip steel pieces versus CAVSF time

If polished samples ($R_a =$ around 0.86 micro-inches (0.022 μm)) are used initially, the acid destroys the smooth surface and reveals the microstructure of the surface. At the end, the chemically accelerated vibratory surface finishing is more or less a chemical attack of the metal surface controlled by the rubbing action of the media. It is important to understand the thermodynamics and kinetics of the etching.

The local etching rate depends on the energy level of the metal atoms involved and the activation energy of the reaction. This driving force causes a substrate specific end-roughness if a certain CAVSF process is used. The following situations can lead to thermodynamic differences in the local etching rate:

- In a metal some components are unevenly distributed - for example carbon in steels and inclusions in certain alloys.
- The crystal sizes in the metal might be different.
- The grain boundaries are different than the grain itself.
- Failures in the crystal structure; tension in the lattice.
- The kind of crystal structure (martensite, ferrite, retained austenite, pearlite, bainite, cementite, ...) in the metal causes different energy levels. For example, the free energy of martensite is 1.7 kJ per mol higher than that of ferrite⁶.
- The grains are randomly oriented, and different lattice planes get exposed during cutting (111 or 100 or 110 or ...), which creates atoms surrounded by 6 atoms or only 4 atoms or
- Atoms in tips and edges of crystals.

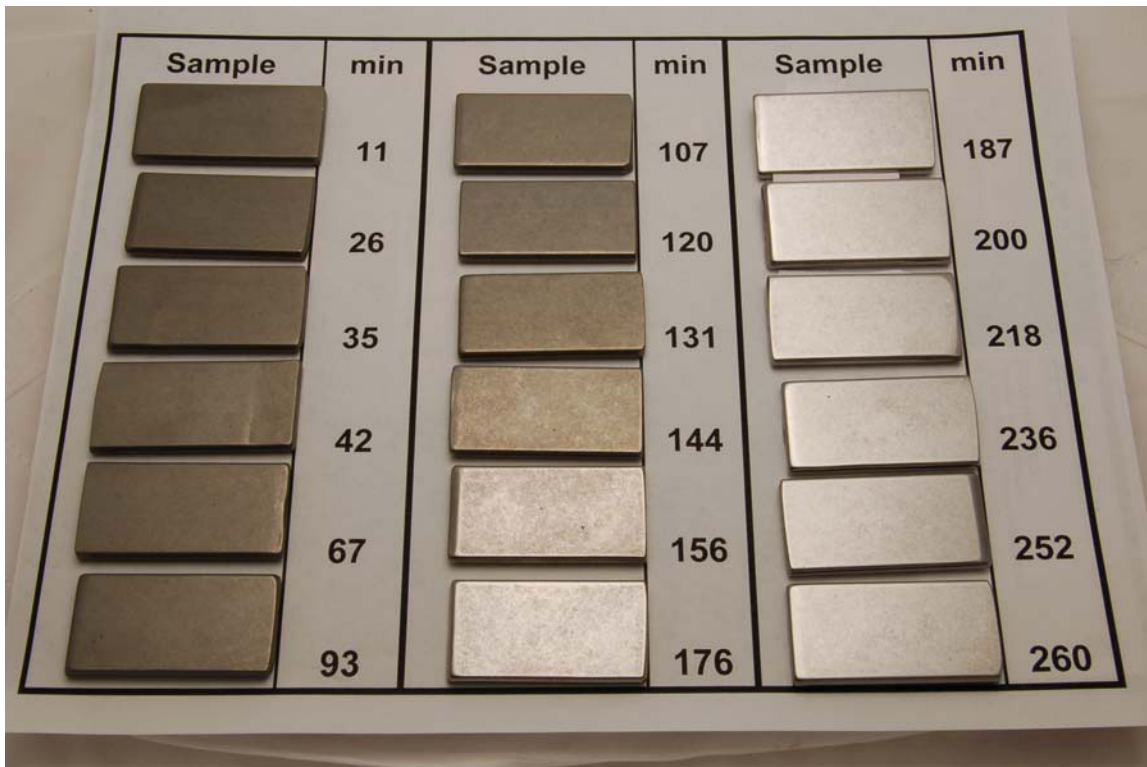


Figure 8: Visual appearance of strip steel test pieces during the CAVSF process.

0-120 minutes = acid treatment
 120-135 minutes = water rinse
 135-260 minutes = burnishing

Differences in the local etching rate are also caused by the kinetics of the etching. In the case of superfinishing, it is mostly diffusion controlled. The crust at the surface varies in thickness. The diffusion of the chemicals reacting with the metal surface and the diffusion of reaction products away from the surface changes if the crust is thicker, as it is in roughness valleys. The chemical composition of the solution at the surface will be very different from in the acid bulk. The pH at the surface will be much higher and probably change the chemical reaction to the build up of more product containing oxides and hydroxides instead of salt.

Here are three examples underlining the two lists above:

- A long hex-bar was super-finished in the 45.5 inch (1.16 m) bowl to prove that CAVSF is isotropic. Because of the geometry of both the bowl and the bar, it was assumed that the part would travel lengthwise and a pattern could be discovered by lengthwise and widthwise roughness measurements. It was found that the roughness measured lengthwise was always lower than the roughness measured widthwise. It was shown under the microscope that the etching revealed a pattern of the stretched grains, which was the result of drawing during the manufacturing process. After the stretched grains are removed, the roughness after CAVSF was found to be equal in both directions. This is important for the CAVSF of drawn material at the surface.
- AISI 9310, a common steel for gear manufacturers, was super-finished to an end-roughness of 2 to 3 micro-inches (0.051 to 0.076 μm). For another batch of AISI 9310, the end-roughness was found to be 5 to 7 micro-inches (0.13 to 0.18 μm). Both batches were prepared with the same specified procedure. The microstructure under the

microscope revealed that differences in the amount of retained austenite in the case hardened layer were responsible for the differences in end-roughness.

- The Pyrowear 53™ samples, shown in **Figure 4**, were super-finished. It was found that the case hardened layer always showed a smoother finish ($R_a = 3$ micro-inches ($0.076 \mu\text{m}$)) than the side with the exposed substrate ($R_a = 7$ micro-inches ($0.18 \mu\text{m}$)). **Figure 9** shows the edge of the substrate side where both layers are visible. The case hardened layer can be found at the edge $400 \mu\text{m}$ into the substrate. The microstructure of the surface revealed by CAVSF is finer in the area with the case hardened layer than in the substrate.

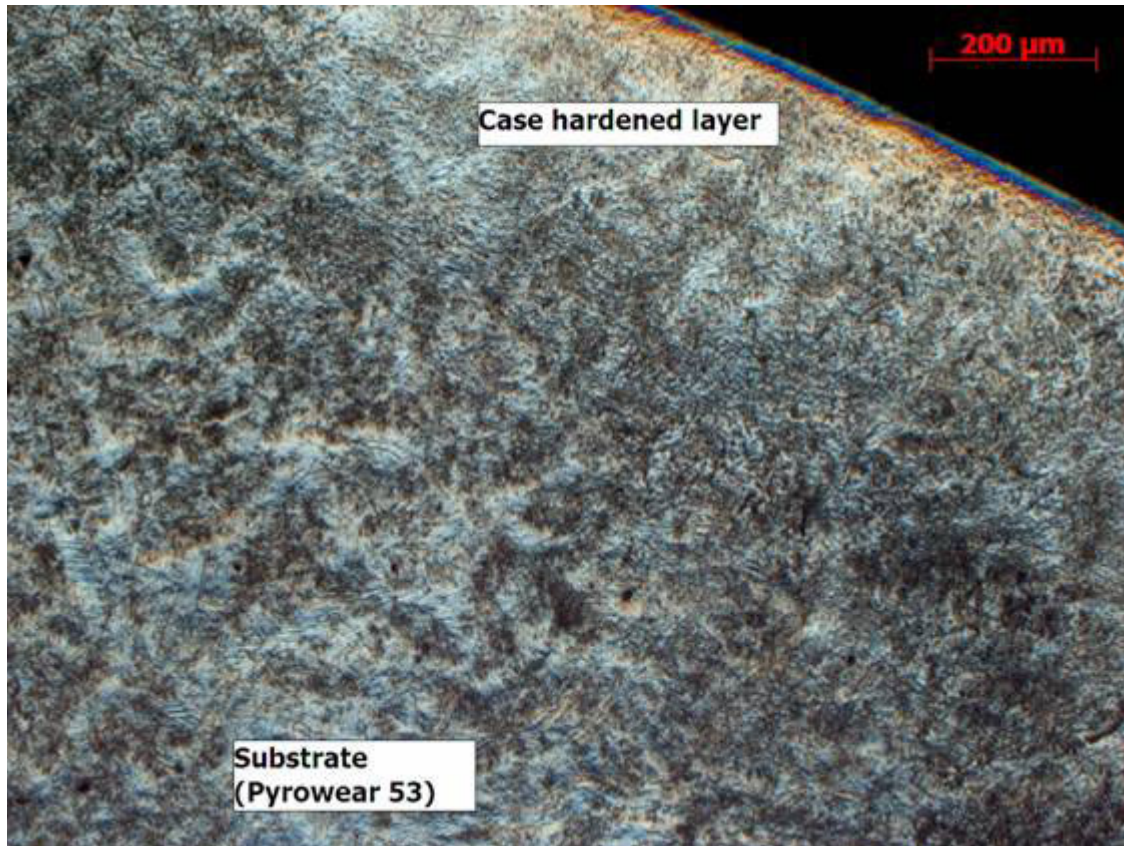


Figure 9: Cut Pyrowear 53™ sample with super-finished surface. The case hardened layer is smoother ($R_a = 3$ micro-inches ($0.076 \mu\text{m}$)) than the substrate ($R_a = 7$ micro-inches ($0.18 \mu\text{m}$)). CAVSF reveals the microstructure of the surface through etching.

The end-roughness of different carbon steels with different heat treatments

In this chapter, the end-roughness of different carbon steels with different heat treatments is investigated. **Figure 10** shows the test samples. After the first heat treatment, the test samples were cooled down at different speeds. The samples were cooled using several methods: quenching with water, cooling between wet paper towels or thick metal plates, letting the samples air cool, shutting off the oven, and finally conducting a proper annealing procedure⁷. Sometimes after water quenching, a second heat treatment at 300 or 350°C was

used to bring the hardness of the coupons slightly below the hardness of the water quenched samples.

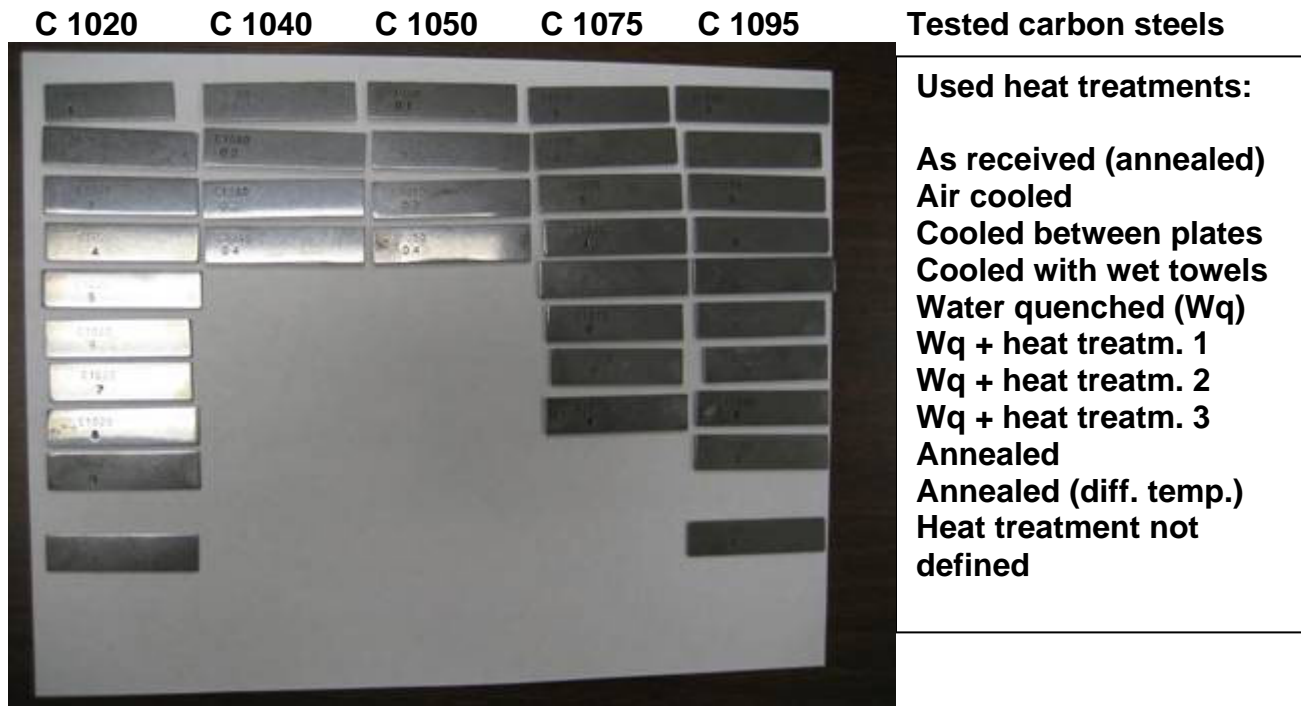


Figure 10: Carbon steel test samples with different carbon contents and different heat treatments to create different hardnesses and a variety of grains (ferrite, cementite, pearlite, bainite, martensite, retained austenite ...)

The average end-roughness after the usual CAVSF (with Microsurface 5132™ as the acid and Cerfa-Kleen 5502™ as the burnishing liquid) is charted versus the hardness of the steel in **Figure 11**. Every curve in this chart represents an average curve from values of several test runs. With annealed ferritic C-steel - hardnesses around 100 HV – the CAVSF process produces an average end-roughness of around 5.3 micro-inches (0.13 μm). These relatively high roughness values are probably caused by these samples containing soft ferrite with some hard cementite crystals having slightly lower free activation energy. If the carbon content is higher – around 0.8 weight% - and the hardness around 200 HV, the end-roughness of the annealed material is about 4 micro-inches (0.10 μm). The constituents are globular cementite and ferrite. If the hardness of the carbon steel is between 400 and 700 HV, the average end-roughness is between 2 and 3 micro-inches (0.051 to 0.076 μm). Here the microstructure is very fine pearlite, or bainite. It seems like a fine microstructure supports a low end-roughness in the CAVSF process. Carbon steel with a carbon content around 0.8 weight% has an increased average end-roughness if the hardness is higher than 700 HV. The constituents in these cases are tetragonal plate martensite and carbide.

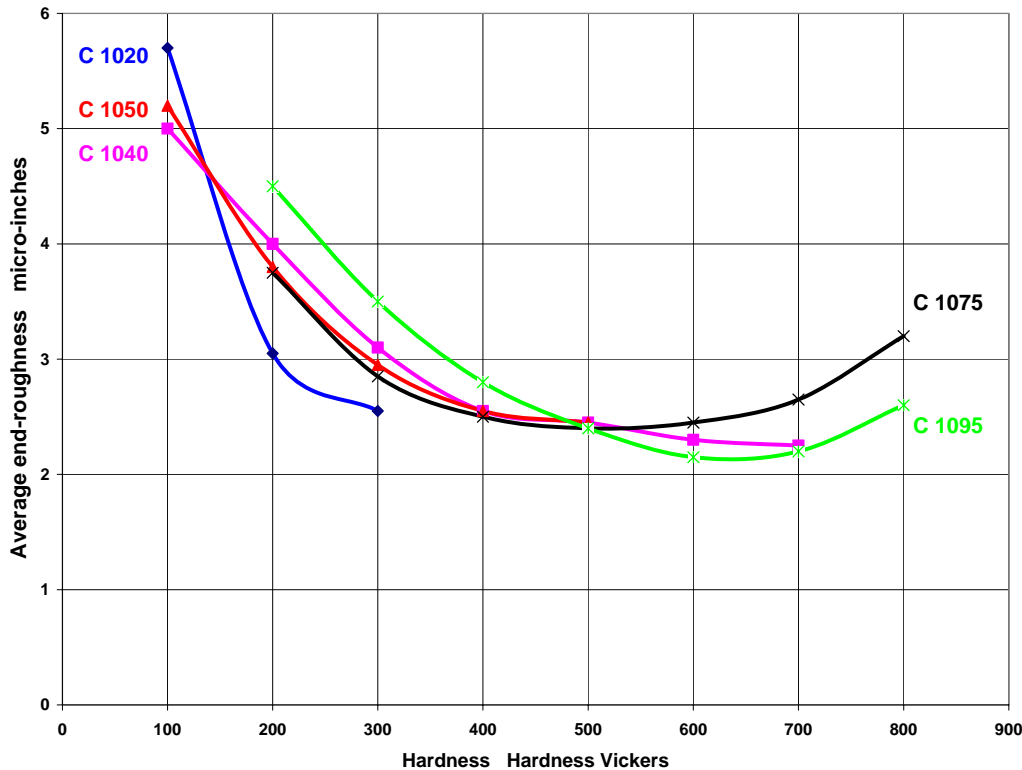


Figure 11: Average end-roughness versus hardness for C-steels with different carbon contents and heat treatments.

Material removal and roughness changes during CAVSF in an 11 inch (0.28 m) diameter vibratory bowl without continuous flow of chemicals.

To investigate the chemistry and other process parameters involved in the CAVSF, a smaller 11 inch (0.28 m) diameter vibratory bowl was used as shown in **Figure 3**. In this chapter the material removal and the roughness changes during CAVSF in the 11 inch (0.28 m) bowl, which runs without a flow of chemical solutions, and in the 45.5 inch (1.16 m) bowl are compared. The usual strip steel pieces with 0.18 weight% carbon were used for the tests. The 11 inch (0.28 m) bowl was loaded with 3975 g large ceramic media, four strip steel samples, and 40 mL acid, which is 1 weight% of the ceramic media. This value of 1 weight% was found at the top of the moving ceramic media bulk in the 45.5 inch (1.16 m) bowl. Inside the bulk where the media moves up, the acid concentration is much higher because the liquid has the tendency to flow down. Every 30 minutes, a strip steel test piece was taken out of the small bowl, and the weight loss and roughness change determined.

An average end-roughness of 5 to 6 micro-inches (0.13 to 0.15 μm) was found in the 45.5 inch (1.16 m) bowl with large ceramic media after a 2 hour treatment with Microsurface 5132™ and Microsurface 5401™ (**Figure 7**). The active acid in Microsurface 5132™ is pyrophosphoric acid and in Microsurface 5401™ it is oxalic acid. With these acids, tests were performed in the 11 inch (0.28 m) bowl. The results are documented in **Figures 12 and 13**.

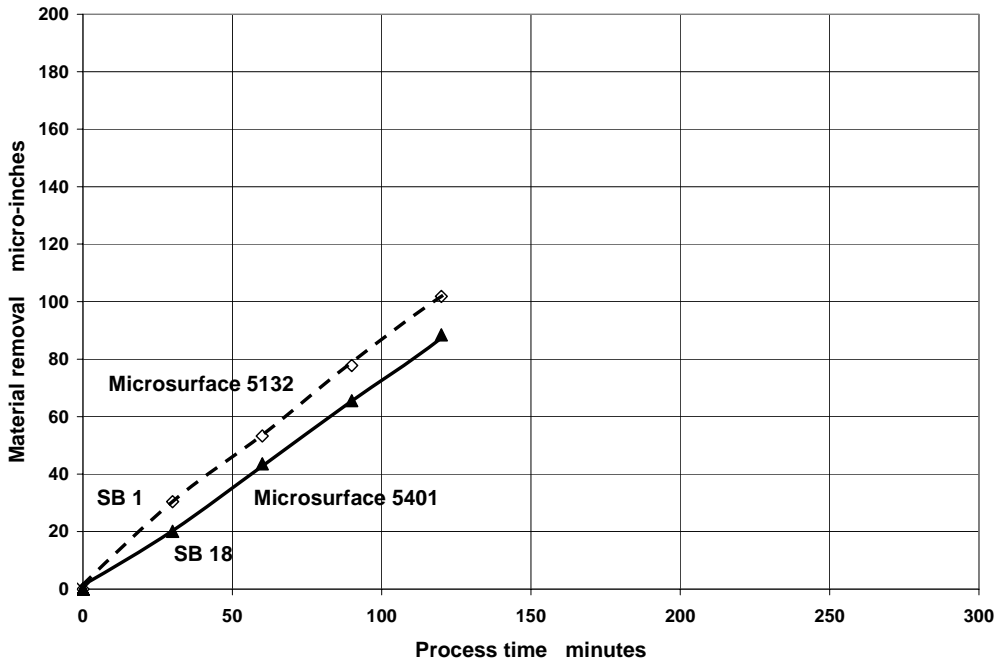


Figure 12: Material removal versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 1 weight% acid content.

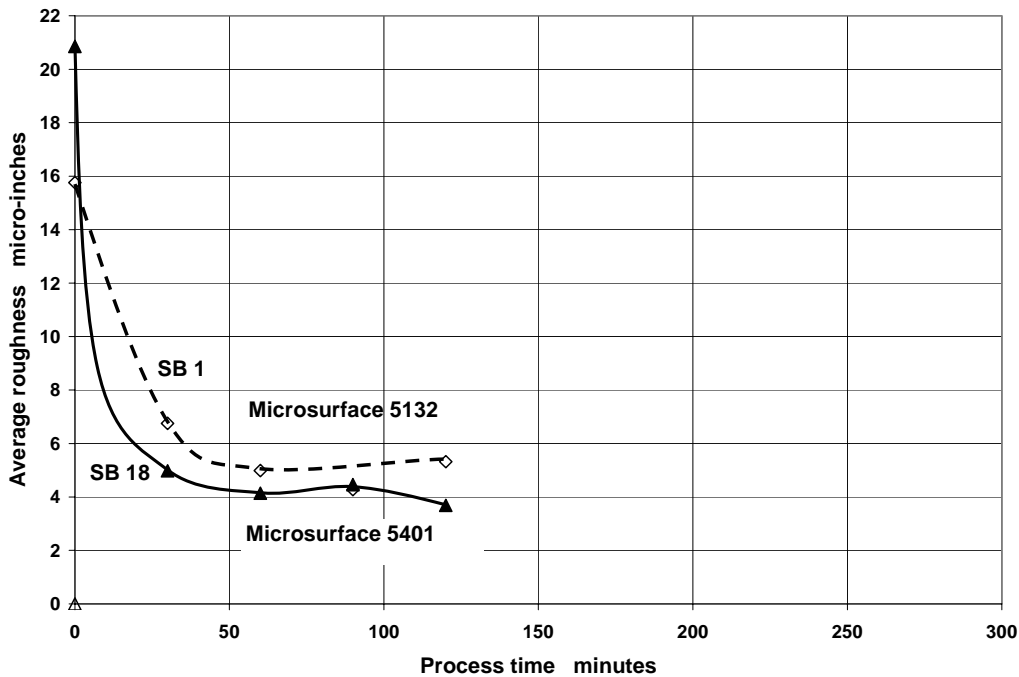


Figure 13: Average roughness versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 1 weight% acid content.

The material removed is only 40% of the value removed from the big 45.5 inch (1.16 m) bowl. It will be shown later that this is probably caused by the smaller amount of acid in the small bowl. Despite the remarkably lower material removal rate in the small bowl and the very

different methods of adding acid to each vibratory bowl, the drop of the roughness is similar in both cases. In this test series, Microsurface 5401™, the acid based on oxalic acid, seems more powerful and delivers a 1 micro-inch lower average end-roughness than Microsurface 5132™. It was decided to run tests in the small bowl to study the influence of process parameters on the performance of the process. The chemistry of the acid, concentration, temperature, and hold-up (amount of treatment solution in the bowl) was changed.

Investigating process variables of the acid time

Tests were run to simulate the performance of the proprietary solution Microsurface 5401™ with 0.7 molar oxalic acid. Approximately 0.1 mol Fe II per liter was found in the effluent of the 45.5 inch (1.16 m) bowl during acid treatment. An additional test was performed with 0.7 molar oxalic acid and 0.1 molar Fe II (sulfate based) to study the effect of the iron concentration in the process. The results are shown in **Figures 14** and **15**.

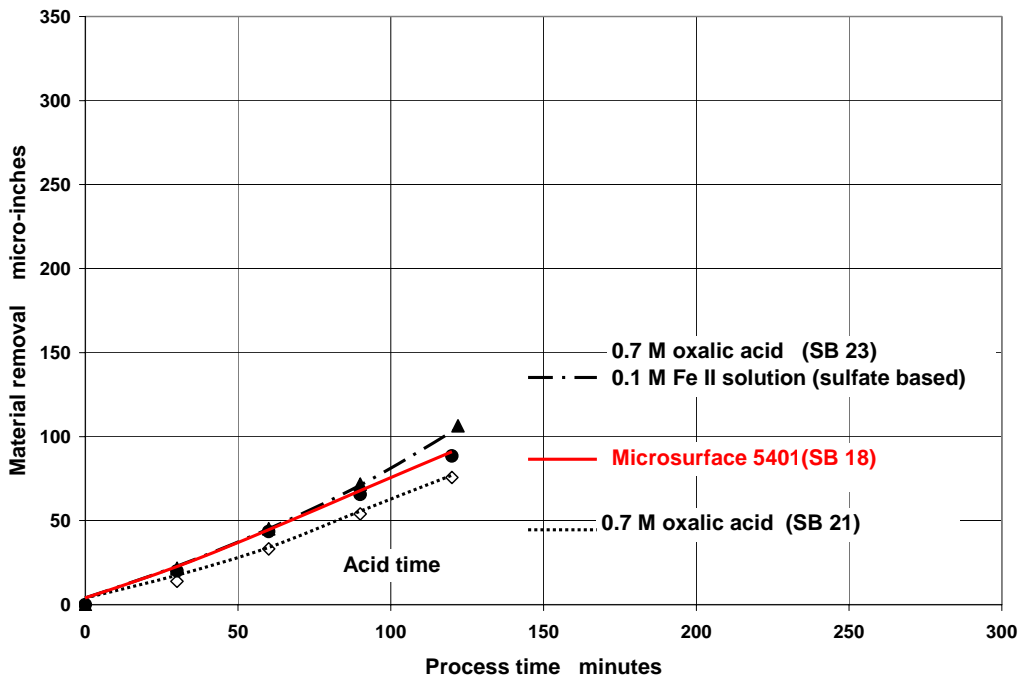


Figure 14: Material removal versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 40 mL (1 weight%) acid content.

The performance of Microsurface 5401™ can be simulated with 0.7 M oxalic acid. An addition of 0.1 mol Fe II (sulfate based) per liter increases the removal rate but does not affect the drop in roughness versus acid time. The end-roughness in all cases is around 4.5 micro-inches (0.11 μm) which is approximately 1 micro-inch (0.03 μm) better than the result with Microsurface 5132™.

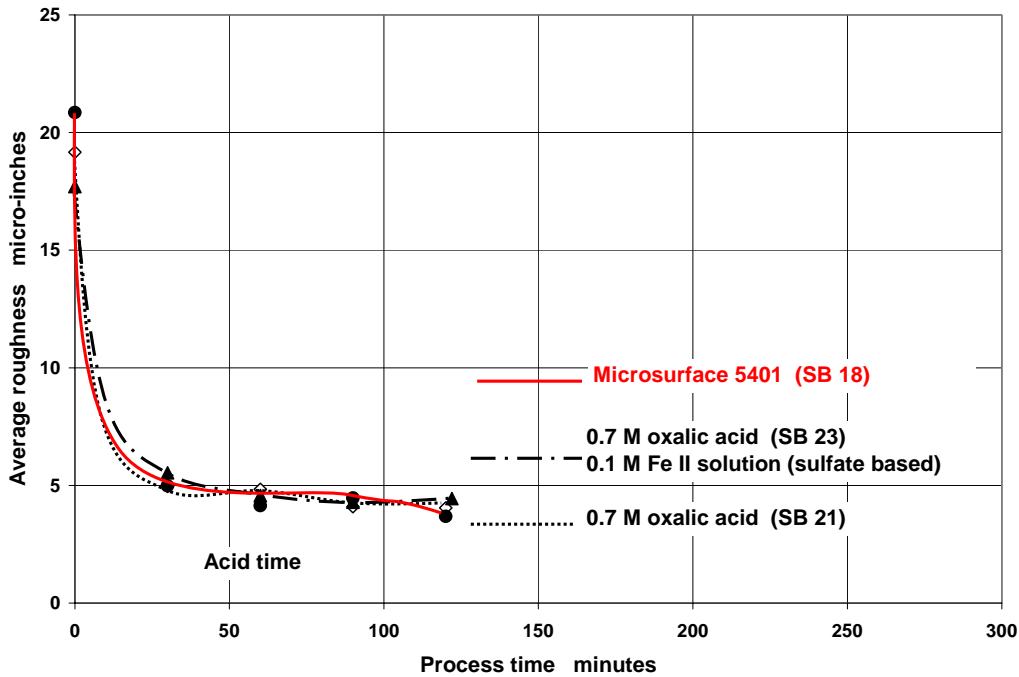


Figure 15: Average roughness versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 40 mL (1 weight%) acid content.

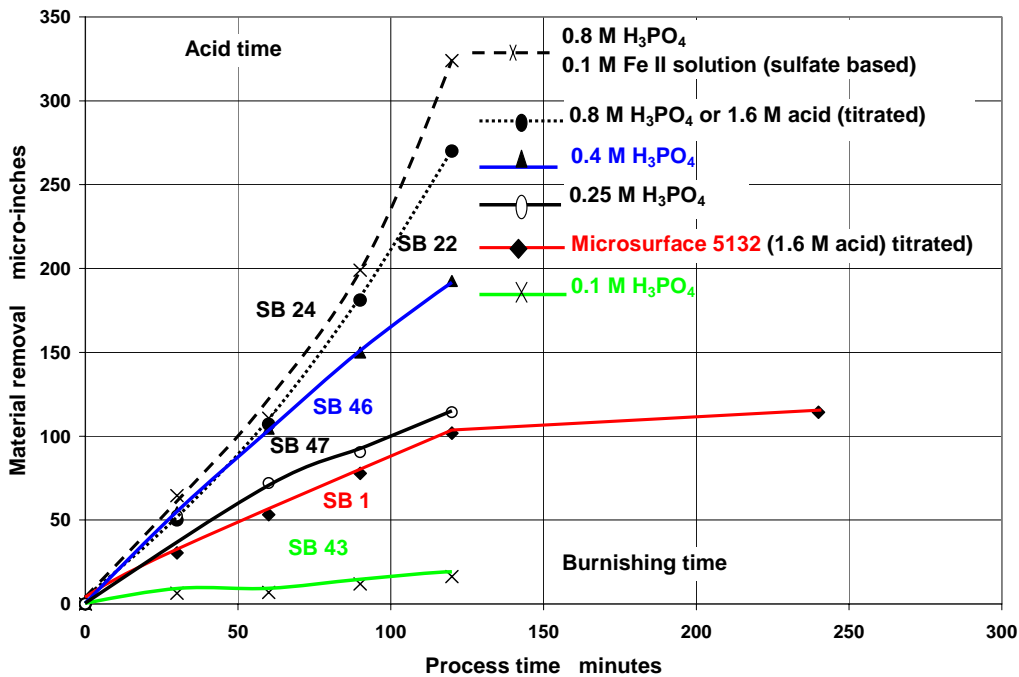


Figure 16: Material removal versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 40 mL (1 weight%) acid content.

Phosphoric acid with different concentrations was used in this test series to simulate the performance of the pyrophosphoric acid based Microsurface 5132™. **Figures 16 and 17** show

the results. It was not possible to get the roughness down to the desired level in two hours acid time.

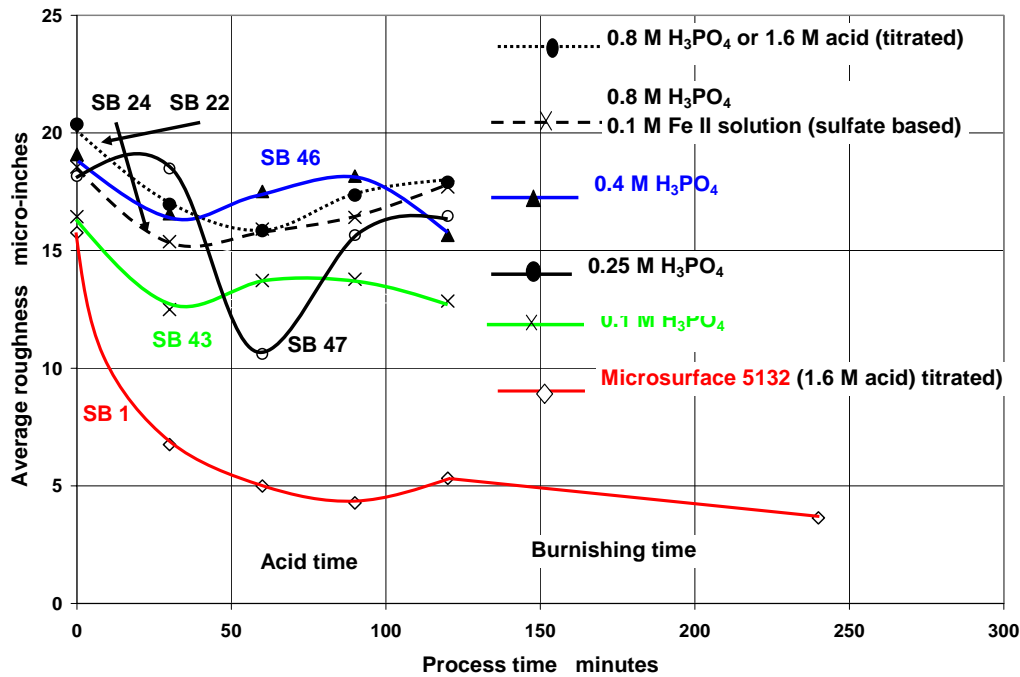


Figure 17: Average roughness versus acid time with various acid treatments in the small 11 inch (0.28 m) diameter vibratory bowl with 4 test pieces and 1 weight% acid content.

The main objective of the following series of tests was to find out how the hold-up (amount of treatment solution in the bowl) affects the process. 0.2 M sodium bisulfate (NaHSO₄), iron II (Fe II) (sulfate based) and iron III (Fe III) (sulfate based) were the acids used. The hold-up varied from 15mL to 90mL. The results are shown in **Figures 18 and 19**.

With an increase in the hold-up, the material removal rate increases and the roughness end points seem to stay consistent around 5 micro-inches (0.13 μm). The time to reach the average end-roughness is longer if the hold-up is increased. The lower the hold-up, the faster the end-roughness is reached until 20 mL hold-up. The 15 mL hold-up shows no improved roughness change but a lower removal rate. In this case it is important to have a relatively low hold-up for a fast roughness drop. The next test series will show that the total amount of chemicals in the acid is the determining factor for the performance with low hold-ups (no liquid puddle at the bottom of the bowl). Liquid hold-ups higher than 60 mL or 1.5 weight% of the large ceramic media mass lead to a puddle at the bottom of the bowl.

It is believed that the 90mL hold-up would have reached the same end point as the others if the test had been run longer.

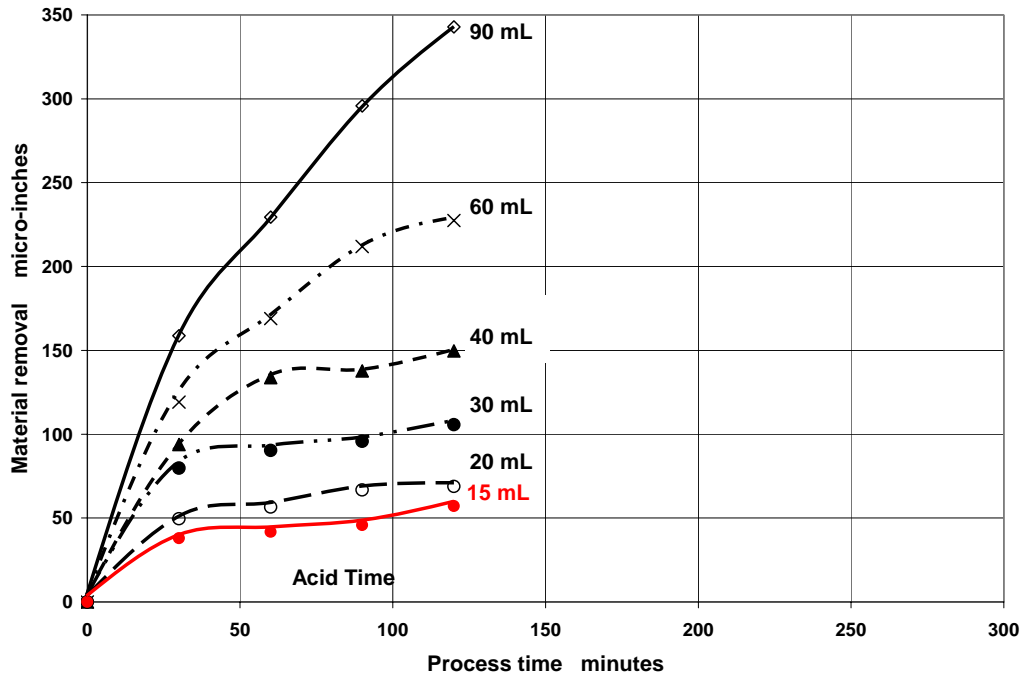


Figure 18: Material removal of strip steel during CAVSF versus time and various hold-ups consisting of 0.2 M NaHSO₄ and 0.2 M Fe II (sulfate based) and 0.2 M Fe III (sulfate based).

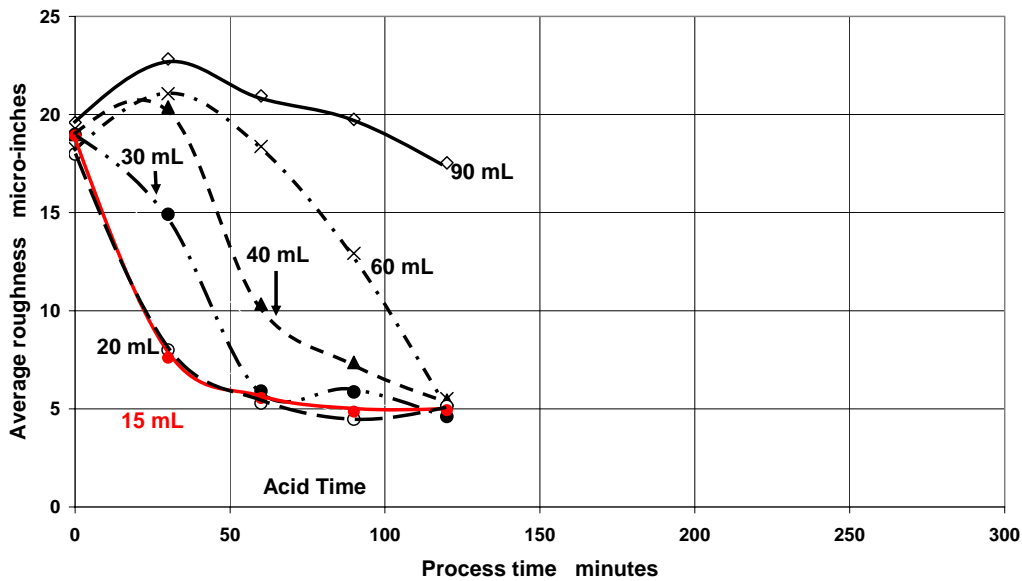


Figure 19: Average roughness change of strip steel during CAVSF versus time and various hold-ups consisting of 0.2 M NaHSO₄ and 0.2 M Fe II (sulfate based) and 0.2 M Fe III (sulfate based).

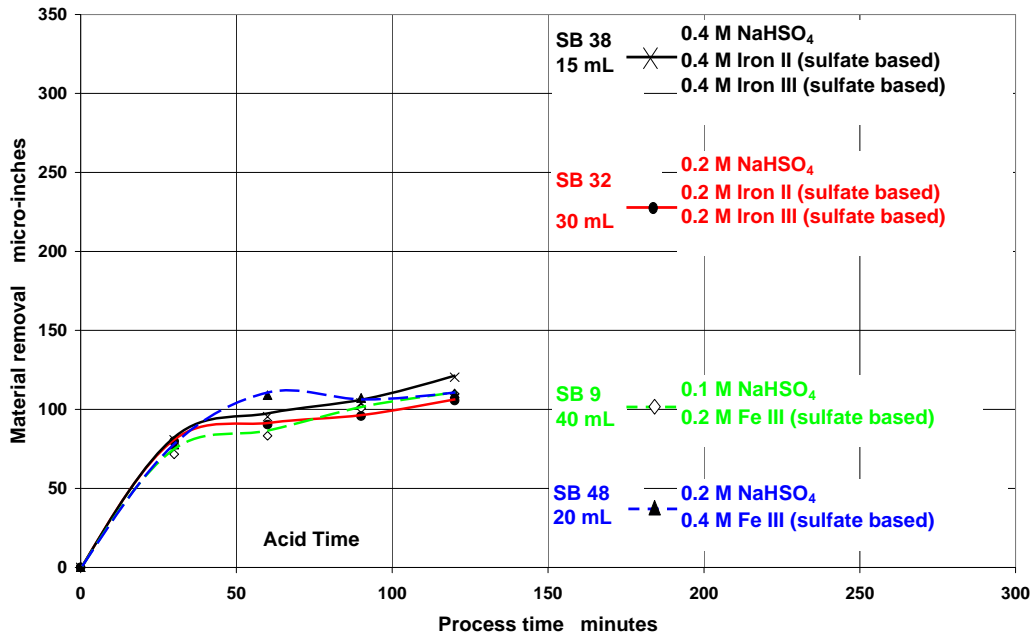


Figure 20: Material removal of strip steel during CAVSF versus acid treatment time using different hold-ups but the same amount of diluted chemicals. This was shown in two pairs of the same test.

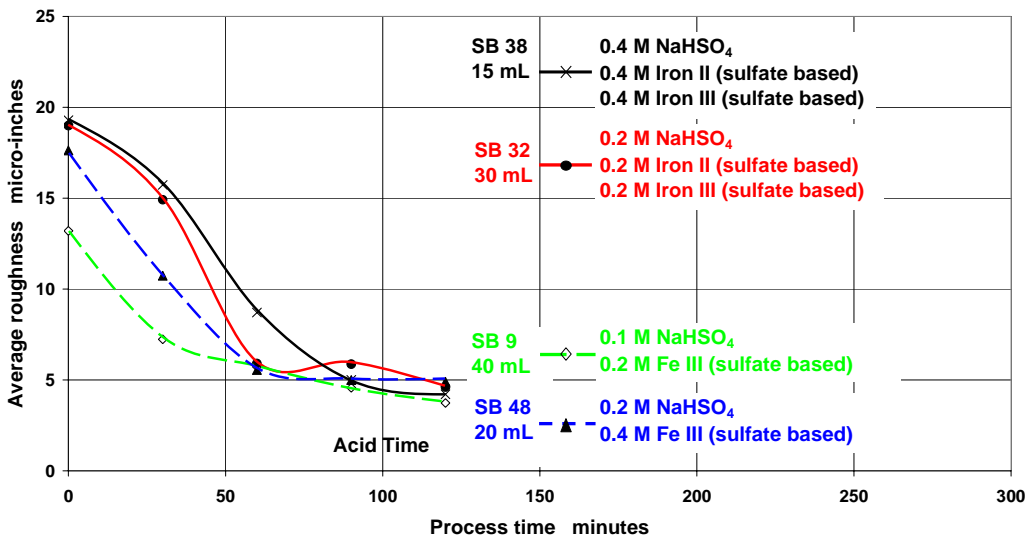


Figure 21: Average roughness changes of strip steel during CAVSF versus acid treatment time with different hold-ups but the same amount of diluted chemicals. This was shown in two pairs of the same test.

In the two test series documented in **Figures 20** and **21**, the amount of chemical reactants (acid and iron salt) was kept constant. The concentration changed according to the hold-up. **Figure 20** shows that the material removal in all cases is similar. The average roughness (**Figure 21**) reaches values just below 5 micro-inches. The 20 mL hold-up with 0.2 M sodium bisulfate and 0.4 M Fe III (sulfate based) reached the end-roughness quickly and without

unevenness in the curve. The question is, how different Fe III to Fe II ratios affect the CAVSF process. This was the theme of the next test series.

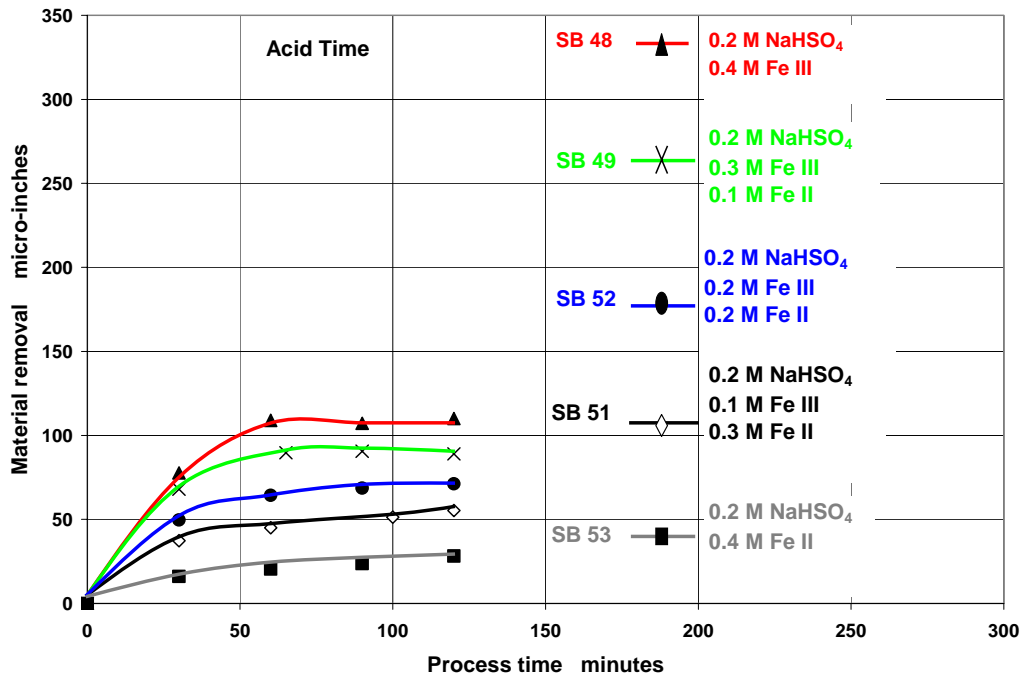


Figure 22: Material removal of strip steel during CAVSF versus time with 20 mL hold-up of 0.2 M NaHSO₄ with 0.4 M FE in various ratios of sulfate based Fe III to Fe II

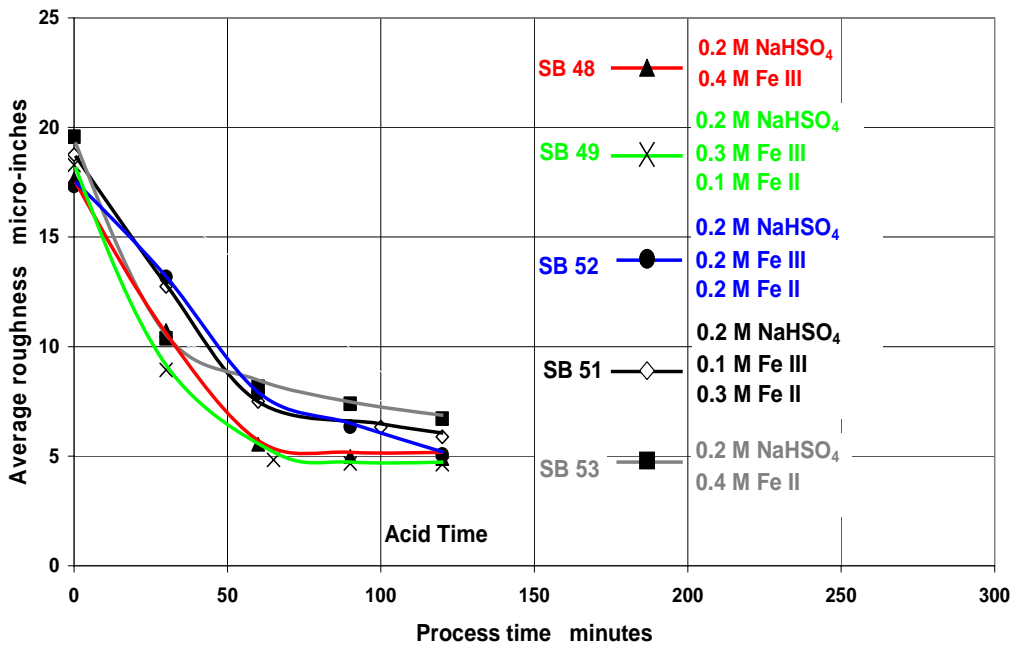


Figure 23: Average roughness changes of strip steel during CAVSF versus time with 20 mL hold-up of 0.2 M NaHSO₄ with 0.4 M Fe in various ratios of sulfate based Fe III to Fe II

A 0.2 M NaHSO_4 solution with 0.4 mol iron (sulfate based) per liter were used for the trials. The Fe III to Fe II ratio at the beginning of the CAVSF process was varied from infinity to 3 to 1 to 0.33 to 0. During the process Fe III changes into Fe II by oxidizing metallic iron into iron II. The results are shown in **Figures 22 and 23**.

A higher Fe III to Fe II ratio makes a higher material removal rate (**Figure 22**) at the beginning of the treatment. The Fe III disappears fast, and after that the material removal rate is very low and close to 0. The roughness changes were best when some Fe II was present right at the beginning. It seems that the presence of acid suppresses the increase in roughness seen in tests with pure Fe III sulfate solutions between 0.5 hour and 1 hour process time (**Figure 23**).

The following tests were conducted to see how the different concentrations of Fe III can affect the super-finishing process. In these tests 40 mL of 0.4 M, 0.2 M, and 0.1 M Fe III solutions (sulfate based) were used. The results are shown in **Figures 24 and 25**.

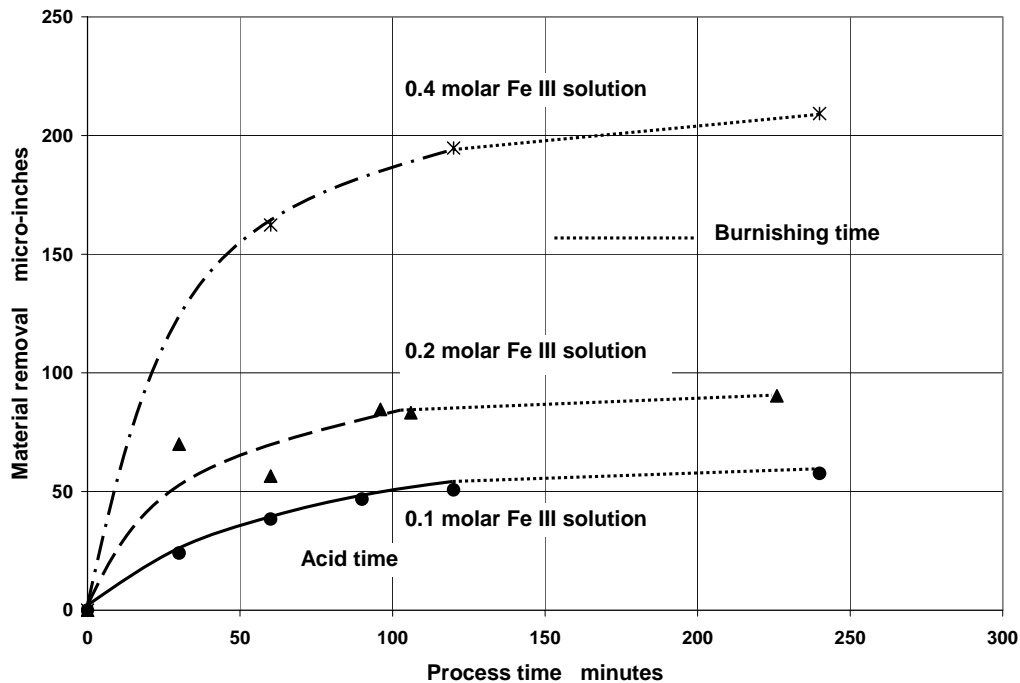


Figure 24: Material removal versus process time with various Fe III concentrations and 40 mL hold-up

0.4 M Fe III has a great removal rate, but the roughness is not satisfying. 0.1 M Fe III does not have a good removal rate, and the roughness was still fairly high. 0.2 M Fe III seemed to work the best; it has a good removal rate and decreases the roughness to just below 6 micro inches ($0.15 \mu\text{m}$). In all tests the roughness decreased in the first 30 minutes of the test and then increased to a maximum of 13 micro-inches ($0.33 \mu\text{m}$) average roughness after 1 hour before decreasing again to the end-roughness. It is assumed that the correct ratio of Fe II to Fe III decreases the roughness quickly and a certain Fe II to Fe III ratio produces an “extreme” rough surface by building up a certain crust.

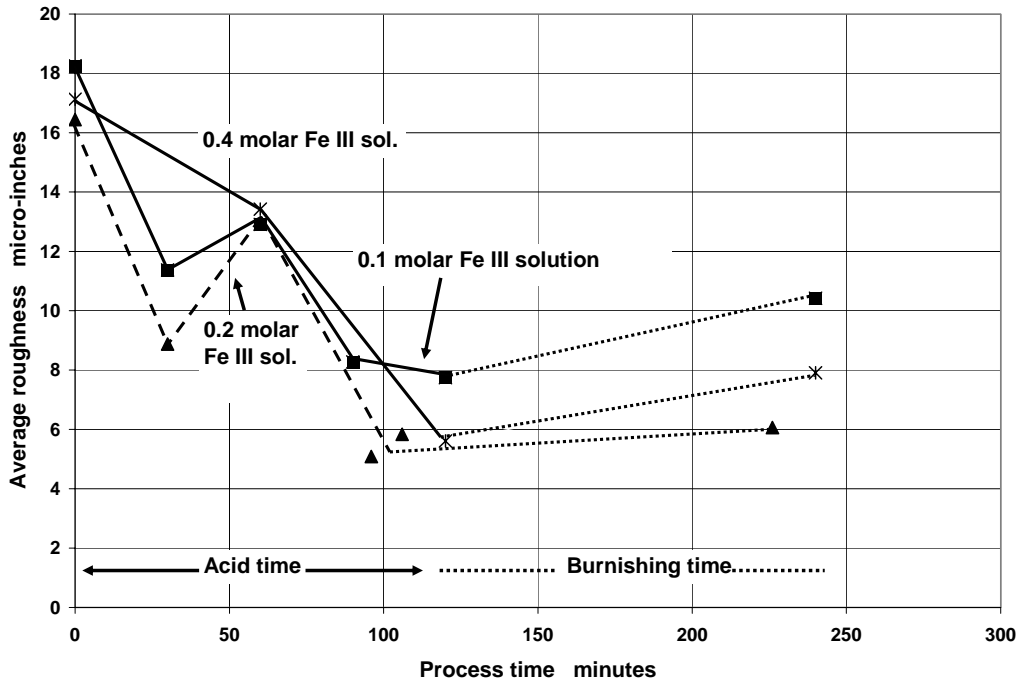


Figure 25: Average roughness change versus process time with various Fe III concentrations and 40 mL hold-up

The goal of this test series is to analyze the effect that temperature has on the process. In this series 0.1 M NaHSO_4 with 0.2 M Fe II (sulfate based) and 0.2 M Fe III (sulfate based) were used. Three identical tests were run at 35°F, 50°F, and 70°F.

The results are shown in **Figures 26** and **27**. The material removal rates of all three tests were almost identical. The average roughness and maximum roughness ended at about the same point but took different paths to get there. The temperature dependence of the process seems negligible in the given temperature range from 35° to 70°F.

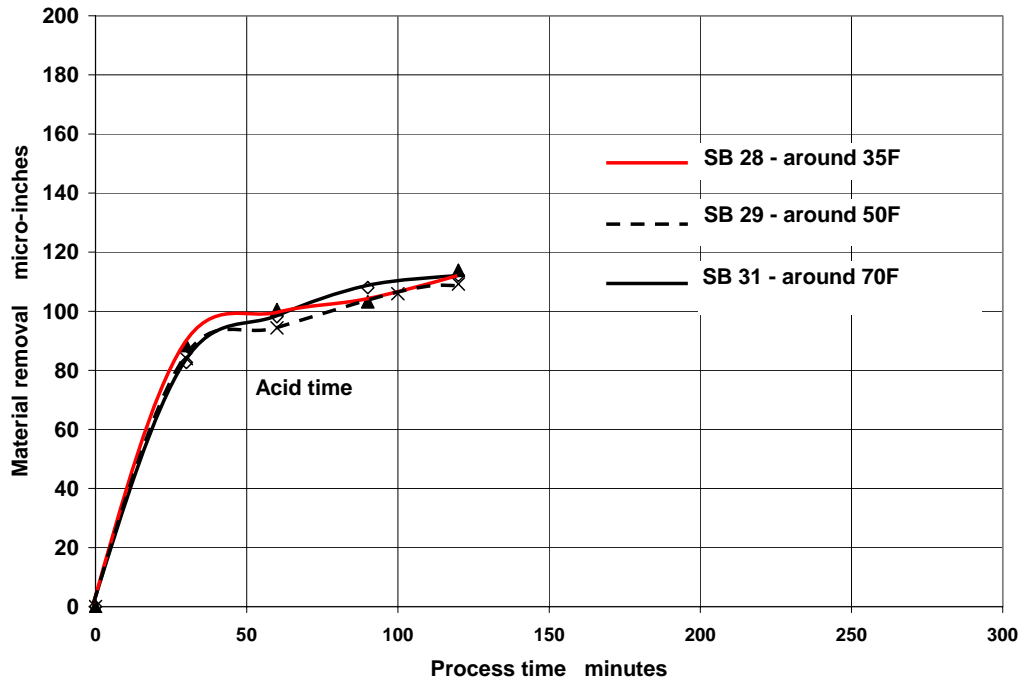


Figure 26: Material removal of strip steel during CAVSF versus time with 40 mL 0.1 M NaHSO₄ and 0.2 M Fe II and 0.2 M Fe III (sulfate based) solution at different temperatures.

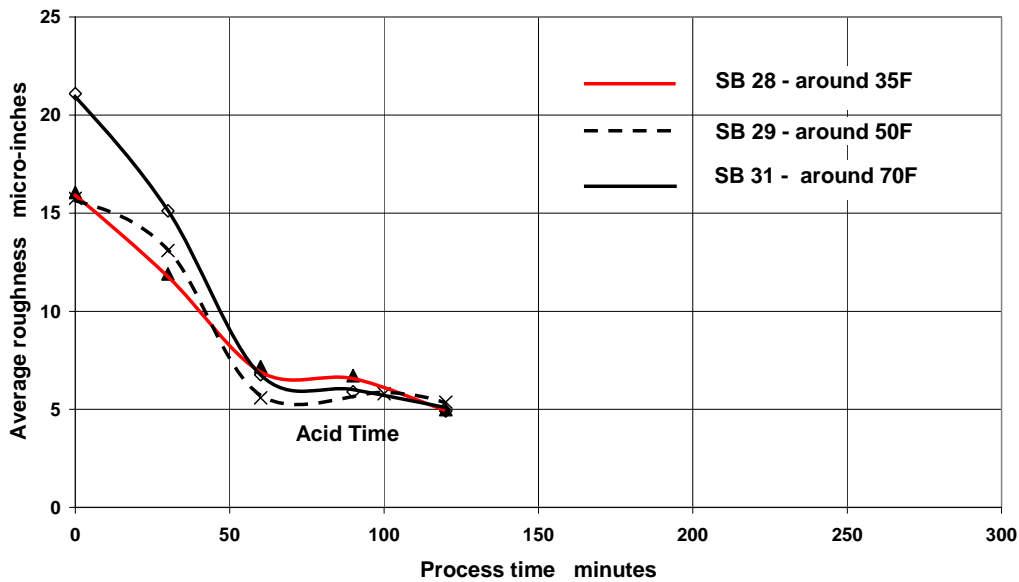


Figure 27: Average roughness change of strip steel during CAVSF versus time with 40 mL 0.1M NaHSO₄ and 0.2 M Fe II and 0.2 M Fe III (sulfate based) solution at different temperatures.

SUMMARY

The combined effect of corrosion (etching) and erosion in the Chemically Accelerated Vibratory Surface Finishing (CAVSF) process with continuous flow of chemicals produces a constant material removal rate of around 120 micro-inches (3 μm) per hour. The chemical attack of the surface reveals the microstructure of the substrate at the surface. During super-finishing the average roughness reaches a characteristic end-roughness, which is determined by the process and the materials and the micro structure of the surface. Low end-roughnesses with carbon steels (C 1020 till C 1095) are produced if a very fine microstructure like bainite or a low carbon lath martensite is present. Relatively high end-roughnesses are reached if annealed carbon steel is super-finished. Water quenched carbon steels with 0.75 to 0.95 weight% carbon consist of plate martensite and carbide gives slightly increased end-roughnesses.

Tests in a small vibratory bowl with 11 inch inner diameter and without a constant flow of chemicals through the bowl was used to study the influence of process parameter on the material removal and the changes in average roughness in the CAVSF process. It was found that:

- The hold-up of the acid has a significant influence on the time in which the end-roughness is reached. An acid hold-up of 0.5 weight% of the mass of the media produces the desired end-roughness much faster than the usual acid hold-up of around 1.5 weight% of the mass of the media.
- The CAVSF process showed no visible temperature dependency in the range of 35 to 70°F.
- Adding some Fe III sulfate to the acid has a beneficial effect on the process time.

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