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A comparison of quality control methods for scratch detection on polished metal surfaces

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ABSTRACT

Scratch detection and the location of the scratch on the surface is important in the quality control of multi-layered, functional and polished surfaces. Visual examination in good lighting conditions has been previously used to detect scratches, but interest to see finer scratches and their location should consider use of the optical microscope, and compare it with other imaging methods at the same magnification. Stainless steel was polished, scratched and then one specific location analyzed at the same magnification with all methods to determine the level of scratch detection. Atomic force microscopy, as the technique with a higher resolution, was used to determine the mean depth of every scratch as a reference. An image was then recorded with the different techniques and the number of visible scratches counted. Profilometry did not clearly identify scratches due to limitation of the 2 μm probe size. Light microscopy provided the fastest and most appropriate technique for quality control, detecting 70% of the scratches. Scanning electron microscopy only showed 35% of the scratches at the same magnification, but provided a good 2-D image of the scratch and the resulting metal pile-up.

1. Introduction

Quality control of polished surfaces is essential to maintain the longevity and performance in a range of engineering applications. Quality control presently relies on careful inspection in good lighting conditions by the naked eye, but there is a limit to the detection of defects seen by the naked eye [1], and so this initiates the inquiry of the best scratch detection method at a higher magnification. This study will use the highest magnification common to the selected imaging methods, to determine the best quality control method.

Scratches are best detected against a highly polished surface. A high surface finish can be attained by mechanical polishing [2], chemical polishing [3,4] or high temperature treatment (vapour [5], laser [6] and flame polishing [7]). Keeping scratch-free surfaces is important; for image quality on films in the film industry [8], for file storage in magnetic disk storage devices [9], and for maintaining low wear on CoCr hip prostheses [10]. Scratches are the most common form of surface degradation, but previous studies on scratches cannot be readily found, and despite extensive reports on scratch resistance, a Web of Science search – using search terms “surface imaging” and “scratch”, “imaging” and “scratch”, “microscope” and “scratch” – does not provide the requested information.

After knowing that a scratch is present, the size, location and orientation of the scratch can offer further useful information. This is important for understanding the damage to multilayered surfaces and thin films covering underlying sensors, but also for surfaces where the scratch orientation can influence the interaction with radiation, water flow, air flow or movement over other surfaces. Methods such as interferometry do not show scratches smaller than about 0.5 μm [11,12] and so will not be considered. This investigation will address non-contact methods (optical microscopy and scanning electron microscopy) and contact methods (profilometry and atomic force microscopy). Examination conditions that improve the level of detection, but distort the scratch size and location of one scratch relative to another scratch will not be used. This rules out placing the surface at an angle to the incident electron beam in scanning electron microscopy, that otherwise improves the quality of the image.

The best measurement method should assess large areas, be portable and fast. Larger areas are more easily assessed by light microscopy and profilometry. Other optical methods such as vertical scanning interferometry [13] and digital holography [14] are also available for detecting scratches on large surfaces, but will not be considered since it is

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Table 1
A comparison of scratch detection methods.

	Light microscopy	Electron micoscopy	Profilometry	Atomic force microscopy
Practical considerations				
Portability	✓	✓	✓	x
Speed	Fast	Slow	Slow	Slow
Evaluate large areas	✓	x	✓	x
Advantages/disadvantages				
Advantages	Works in air and liquids, Posible to differentiate chemical phases	High magnif., Large depth of field, Elemental analysis	3D image, Clear wave profile	3D image, High magnif., High resoution
Disadvantages	Lowest resolution, 2D image, Lowest magnif.	2D image, Difficult to locate scratch	Stylus wear, Scratches surface, Vertical features not accurate	< 20 μm high features, Small scan area, Stylus wear, Difficult to locate scratch

not as portable like optical microscopy and profilometry, Table 1. A fast assessment of the surface is only provided by optical microscopy. This then raises the question of how effective optical microscopy is for detecting scratches. What is the level of scratch detection by optical microscopy?

Scratching could create pile-ups at the side of the scratch and so assist in the detection of scratches by modifying the intensity of the signal in light and electron microscopy. Scratches from a symmetrical 1 μm wide diamond probe have aided the detection of scratches due to the light reflection from pile-ups, when viewed by the naked eye under good lighting conditions [15]. There is a high likeliness of the pile-up since symmetrical hard asperities only need to be tilted by 5° to create pile-up [14], and the source of scratches such as grains of sand will always be non-symmetrical, thus increasing the likelihood of metal pile-up. Consequently, metal pile-up could be used to identify scratches in images from light microscopy and electron microscopy.

Polished surfaces are being investigated to determine the effect of scratches on the movement of polished metal over cold surfaces. For this reason, a fast surface evaluation method is required for evaluating small polished metal blocks in laboratory tests and larger objects in field experiments. Since a fast assessment of each surface is required, then optical microscopy is the obvious choice, and so a comparison to other imaging techniques is required.

The objective of the investigation is to determine the ability of optical microscopy to locate scratches, in comparison to other methods used at the same magnification. Higher magnification methods such as atomic force microscopy and scanning electron microscopy will be used to collect additional information on the depth of the groove and the presence of pile-ups. These features will be mentioned during the discussion on the limits of light microscopy.

2. Methods

2.1. Preparation of metallic surfaces

A sectioned austenitic stainless steel block (62% Fe, 16% Ni, 14% Cr, 4.5% Mo, 1.4% Co, 1.25% Mn, 0.8% Cu) was hot mounted in a MecaTech 334 hot press (Presi, Brié-et-Angonnes, France) to form a 30 mm diameter disc. The mounted steel sample was then ground on a Reflex Max 120 surface rotating at 250 rpm under a load of 40 N for 120 s, and then on a Reflex Max 220 surface with the same conditions. Polishing was conducted with 9 μm, 3 μm and 1 μm diamond suspensions (together with a Reflex Lub lubricant) on Reflex MedB, Reflex Ram and Reflex NT surfaces, under loads of 40 N, 35 N and 30 N, for 5 min, 4 min and 2 min, respectively. Reference scratches were introduced, indentations made to frame the area of investigation and then the surface was cleaned with ethanol before applying the different scratch detection methods.

2.2. Visual examination

Three areas of investigation were marked on the polished surface with indentations from a Vickers indenter. Indentation marks spaced 100 μm from each other helped to maintain sample orientation as well as the same field of view for the different imaging methods. Images were taken with a light microscope, a scanning electron microscope, an atomic force microscope and a profilometer.

A Nikon LV150 Eclipse light microscope (Tokyo, Japan) collected an image in darkfield imaging conditions of the surface through a 100× objective lens (0.9 NA) to capture the scattered light from the scratches. The contrast and brightness of the image was then adjusted on the computer screen.

A Hitachi S-4800 scanning electron microscope (Tokyo, Japan) with a field emission electron source was operated at 15 kV and 1 nA to view the surface. An image at the highest resolution of 5120 × 3840 pixels was obtained at the same magnification as the optical microscope image. The sample surface was kept at 90° to the electron beam to prevent distortion of the image and maintain the same distance between scratches in the x and y directions.

A Smena NT-MDT atomic force microscope (NT-MDT Spectrum Instruments, Moscow, Russia) with a 10 nm sized probe scanned the surface along 1024 lines to obtain a 60 μm × 60 μm view. To optimize the resolution, a smaller total vertical movement was chosen by not including the indent within the imaging area. Since AFM is the most sensitive in detecting scratches, the total number of scratches, the position and depth of each scratch was determined from the AFM image as a reference to see how effective other methods would reveal the scratches.

A Talysurf Intra 50 (Taylor Hobson, UK) profilometer scanned the surface with a 112/2009 stylus (4 μm tip diameter). Calibration was conducted with a 112/2062-D-4148-04 ball (25 μm diameter). The precision of the profilometer verified with a Taylor Hobson Reference 112/1534 (R_a = 6 μm and R_{Sm} = 0.133 mm) and a surface roughness standard comparator Flexbar Composite Pocket set No 16008 gave a 10% error in the recorded values. Data on the probe position was recorded for a total of 800 points by 800 points with an area outlined by a 1.8 × 1.8 mm rame at a speed of 0.5 mm/s. A 12 nm vertical resolution and a 1 μm horizontal resolution were recorded from measurements on the calibration ball.

The total number of scratches detected by each method, was expressed as a percentage of the total number of scratches, obtained from the AFM image. Scratch profiles from the AFM traces were used to

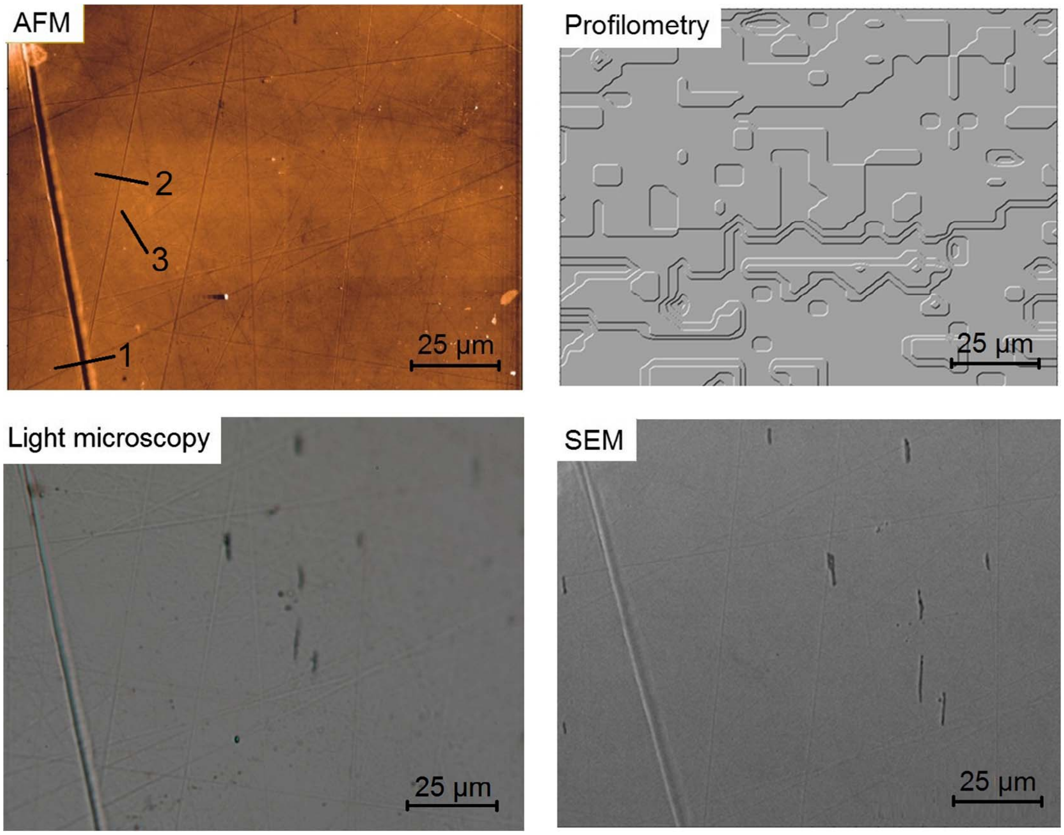

Fig. 1. A comparison of contact methods (AFM and profilometry) and non-contact methods (dark-field light microscopy and SEM) for imaging minor scratches on polished metal. The large scratch, labeled as 1, is made for reference. The three labels reference the scratch profiles shown in Fig. 2.

determine the depth of scratches detected by each imaging method.

2.3. Data analysis

Scanning Probe Image Processor (SPIP) software was used to ensure that the data obtained from the AFM and the profilometer is processed in the same manner. This removed the error associated with data processing from software provided by each equipment supplier. The image was placed on a level background by removing the slope using the *Global Leveling* function and was made flat by removing the curviness with the *Form Removal* function.

The total number of scratches was determined by AFM. The number of identifiable scratches were counted on the computer screen in images from the light microscope, SEM, AFM and profilometer. A comparison was then made to determine the number of scratches detected by the contact and non-contact imaging methods.

For quantitative analysis, the scratch profile from the 3D image was extracted along the length of the scratch with the *Cross Section Profile* function in the SPIP software. For more statistically reliable data on the scratch depth, the *Average Profile* function mathematically averaged the scratch depth and determined the average scratch shape.

3. Results and discussion

3.1. Detection of minor scratches on a polished surface

Only three imaging methods detected scratches at a magnification of 1000×, when the image was taken at the highest resolution. Both non-contact methods (light microscopy and scanning electron microscopy) and atomic force microscopy displayed scratches.

The 2 μm probe on the profilometer limited the measurement capability and so did not clearly show the small scratches, Fig. 1. A smaller 0.2 μm radius probe has been used for greater sensitivity in other studies [16], but the large step size of the measuring method further limits the ability to detect scratches.

Image resolution and contrast are required for the best detection ability. Atomic force microscopy has the highest resolution and showed the most scratches. The SEM image had poor contrast and did not show small scratches when imaged at the same 1000× magnification as the optical microscope. The large vertical reference scratch, at the left side of the image, was easily seen in the SEM due to the larger depth of the scratch and the pileup on both sides of the scratch. Higher magnification is required to detect scratches with the SEM, but the need to refocus, and the difficulty of finding scratches on the surface is not suitable for quality control in a timely manner, even in a more affordable benchtop scanning electron microscope.

The smallest visible scratch size, imaged at a magnification of 1000x was detected with the AFM; further analysis provided the depth of each scratch. From a total of 24 scratches, 7 scratches (3 nm and deeper) were easily detected by all three microscopy methods (AFM, SEM and light microscopy), 13 scratches (1 nm to 3 nm deep) were visible, but four scratches at a depth of 1 nm could not be seen. The ease of viewing is appreciated by matching the scratches in Fig. 1 with the depth profiles in Fig. 2. The light microscope detected 70% of the scratches recorded by the AFM, but the SEM only showed 35% of the scratches seen by the AFM.

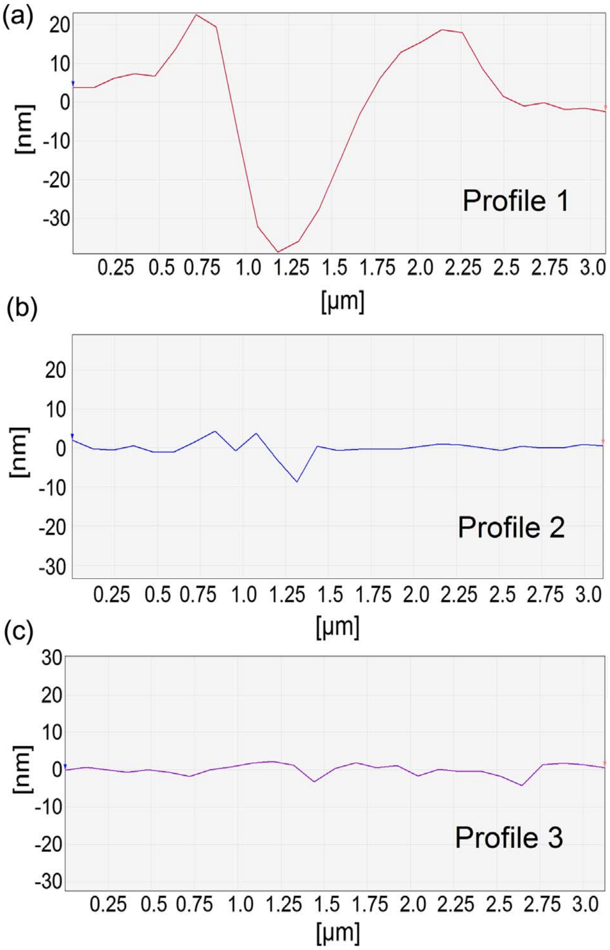

Fig. 2. The profile of three scratches as marked on the AFM image in Fig. 1.

Compared to previous studies, the optical microscope showed 500 times smaller scratches than the naked eye, as referenced to the study of scratches made by a nanoindentor and viewed by the naked eye [1]. This makes the optical microscope a powerful tool to inspect larger objects, quickly examine the surface, and detect 10 nm deep scratches on the polished steel surface. It would seem logical that a 1000× magnification will show 1000× smaller objects but this relies on tilting the surface to provide the best angle of light reflection for seeing the scratch. It is not possible to readily tilt polished steel objects on the light microscope at higher magnifications.

3.2. *Characterization of scratches*

The polished steel abraded by the 3000 grade sandpaper contained similar sized scratches on the surface, and showed that optical microscopy is the most appropriate quality control method. The black line arising from the pile-up next to the scratch showed the location of the scratch; brighter areas in the AFM image arose from the difference in height associated with the scratch, and the bright line in the SEM arose from a greater electron emission, Fig. 3. So, pile-up next to the groove provided easier scratch detection, Fig. 4. Absence of the pile-up makes it difficult to identification scratches.

After detecting the scratch, complementary information can be obtained from the pile-up with SEM and AFM. Preferred plastic deformation from an unsymmetrical sand grain led to a higher pile-up on one side of the scratch, Fig. 3. Previous studies have also shown that the pile-up in front of a scratch may be up to three times higher than the pile-up on the sides of the scratch [9]. These pile-ups in front of the scratch will not be easily seen, since the elevated peak will be more difficult to detect than the line of pile-ups on the surface.

Atomic force microscopy together with scanning electron microscopy can provide a more complete interpretation of the scratch and the associated pile-up. The AFM probe shows shallower depths of narrow scratches and peak rounding [17–19]. This occurs from “stylus flanking” where the edge of the stylus cone makes contact with the highest point [20]. Selection criteria for the tip radius have been proposed to improve the reproduction of the surface topography [21]. Scanning electron microscopy is recommended for complementary information on the pile-up, providing a good 2-D map of the surface, as well as retrieving elemental information. The true geometry of the pile-up and the groove provides an insight into the process of scratching, the groove depth, and the pile-up, Fig. 4.

Metal pushed out from the groove can offer information about the applied load and damage to the surface. At low loads, only a groove is formed, at intermediate loads a pile-up on the side of the groove will appear, but at higher loads the plastically deformed metal pushed out of the groove will chip and occasionally be released [22]. The absence of pile-up on the side of the scratch makes it more difficult to identify scratches. A pressure of 16 kPa on the 3000 grade sandpaper was sufficient to cause chipping and loose debris on the abraded surface.

Lower yield point metals will scratch more easily and are likely to have deeper scratches, making it easier to identify scratches. The ease of scratch detection on plastics has been reported to depend on the size of the scratch, the roughness of the scratch and the gloss of the background [23]. This study was focused on an austenitic stainless steel. Further work could determine the ease of scratch detection from different types of particles and loading conditions. Additional work may look at how the polished surfaces hardness influences the ease of scratching.

This investigation addressed alterations to the surface, but it should be noted that scratch formation could also change the subsurface. Plastic deformation from scratching will change the number and arrangement of subsurface dislocations [24], that will change the yield strength or hardness.

This study has shown that polished surfaces can be quickly assessed for scratches by light microscopy, firstly in the darkfield imaging mode to identify the fine scratches on the polished steel, and then in the brightfield imaging mode to show larger scratches. More detailed characterization with AFM provides scratch depth, but further analysis with the SEM will show metal pileup or chipping. Such an approach can be used both for assessing a polished surface and for determining the performance of smooth surfaces in different environments.

4. Conclusions

A comparison of different imaging methods showed that light microscopy is best suited for quality control. Light microscopy identified 70% of the scratches imaged by the atomic force microscope on the same scratched area. The ability to detect scratches as shallow as 3 nm in the light microscope is attributed to the pile-up next to the scratches. When samples are small, the scratch depth and adjoining pile-up may be obtained by atomic force microscopy, and a more detailed 2-D view seen by scanning electron microscopy.

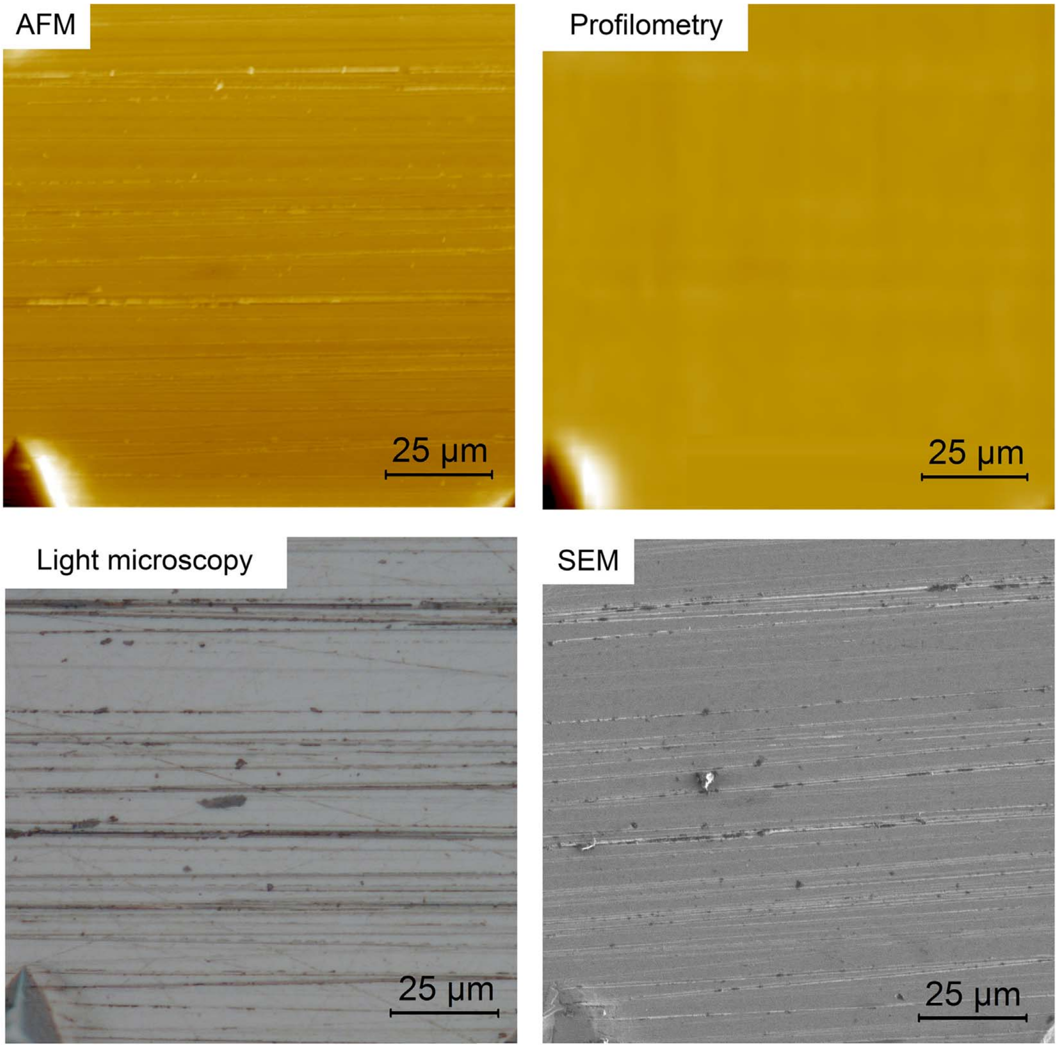

Fig. 3. A 3000 grade sandpaper scratched metal surface as seen by contact imaging methods (AFM and profilometry) and non-contact imaging methods (light microscopy and SEM).

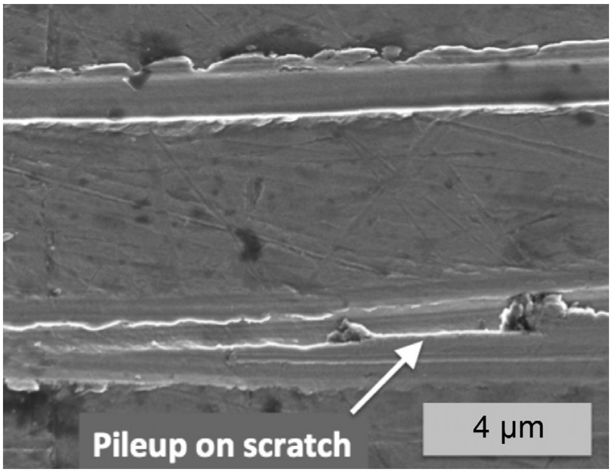

Fig. 4. Pile-up on the side of a scratch after abrasion with 3000 grade sandpaper. The bottom scratch shows only pile-up on the upper side of the scratch and a trapped abrading particle with a higher pile-up at the front.

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