A Metric for the Comparison of Surface Topographies of Standard Reference Material (SRM) Bullets and Casings

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Keywords: surface metrology, topography comparison, standard reference material, SRM, standard bullets, standard casings.

Abstract: Based on the maximum cross-correlation function, CCF_{max}, a new parameter called signature difference, D_s, is developed for verifying the similarity of the 2D and 3D ballistics signatures of the standard bullets and of the prototype standard casings. It is suggested that the parameter and algorithm developed for the standard bullets and casings project could be used for any 2D and 3D surface topography comparisons in surface metrology.

1. Introduction

The Standard Reference Material (SRM) 2460 standard bullets are developed at NIST for testing the calibration of the Integrated Ballistics Identification Systems (IBIS*) used in the National Integrated Ballistics Information Network (NIBIN) [1]. The SRM bullet is a physical standard, which is fabricated using a virtual standard. The virtual standard is a set of digitized bullet profile signatures traced from master bullets provided by the Bureau of Alcohol, Tobacco and Firearms (ATF) and the Federal Bureau of Investigation (FBI). By using the virtual standard to control the tool path of a numerically controlled diamond turning machine at NIST's Instrument Shop, 40 SRM 2460 standard bullets have been produced [1, 2]. The SRM 2461 standard casings project is currently in progress. 21 prototype standard casings have been produced and are under test [1]. In order to inspect the quality of the standard bullets and casings, a new parameter called signature difference, D_s, is developed based on the maximum cross-correlation function, CCF_{max} [3]. A comparison system was established at NIST based on a stylus instrument [4]. So far 240 bullet profile signatures on 40 SRM bullets are measured and shown high measurement reproducibility [1, 4]. It suggests that the comparison parameter and algorithm developed from the standard bullets and casings project could be used for any 2D profile and 3D topography comparisons in surface metrology.

2. 2D Profile Comparison Parameters

For the comparison of bullet profile signatures and verifying that the 2D profile signatures from comparable land engraved areas on different SRM bullets are essentially identical, we use parameters based on the auto- and cross-correlation functions (ACF and CCF) in signal processing. The autocorrelation function is defined as [5]:

$$\mathrm{ACF}(\tau) = \mathrm{ACV}(\tau)\big/Rq^2 \,, \tag{1}$$

where ACV(τ) represents the auto-covariance function:

$$\mathrm{ACV}(\tau) = \lim_{L\to\infty}\left(\frac{1}{L}\int_{-L/2}^{L/2} Z(x)\,Z(x+\tau)\,dx\right), \tag{1a}$$

$Z(x)$ is the measured profile, and τ is the shift distance. Rq is the root-mean-square roughness [6].

The cross-correlation function of two profiles A and B is defined as [5]:

$$\mathrm{CCF}(\mathrm{A,B},\tau) = \frac{\mathrm{CCV}(\mathrm{A,B},\tau)}{Rq(\mathrm{A})Rq(\mathrm{B})}, \tag{2}$$

where CCV(τ) represents the cross-covariance function:

$$\mathrm{CCV}(\mathrm{A,B},\tau) = \lim_{L\to\infty}\left(\frac{1}{L}\int_{-L/2}^{L/2} Z_A(x)Z_B(x+\tau)\,dx\right), \tag{2a}$$

and $Z_A(x)$ and $Z_B(x)$ are two signature profiles.

From the cross-correlation function we calculate a parameter called CCF_{max}, which is the maximum value of the cross correlation function when the two profiles are shifted. When two bullet profile signatures are compared with each other, one is taken as the reference signature A and the other is the compared signature B:

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[*] Certain commercial equipment, instruments, or materials are identified in this paper to specify adequately the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

- If the two profile signatures are exactly the same, A = B, their ACF achieves the maximum value (1.00) when the shift distance is zero.
- If two compared bullet profile signatures A and B have essentially the same pattern but small differences in the profile details, then A ≅ B. For example, when two bullets are fired from the same gun, their profile signatures may have strong correlation. When these two profile signatures are shifted, their CCF_{max} will have a maximum value but not as large as 1.00, because there are some differences between these two profile signatures.
- If two compared profile signatures A and B are not correlated, for example, when two bullets are fired from different guns, then A ≠ B. Their CCF curve will have only random variations without a significant correlation peak.

Although the CCF_{max} can be used for profile signature comparison, it is not a unique parameter. Based on the definition of the cross-correlation function [5], if two compared profile signatures have the same shape but different amplitude scales, their CCF_{max} is still 100 %. This is not designable. We have developed a unique parameter we now call the signature difference, D_s, which is highly correlated with the CCF_{max} but which directly quantifies bullet profile signature difference [3]. The parameter D_s is calculated in the following way:

- At the shift τ_0 where the CCF_{max} between profile signatures B and A occurs, construct a new profile $Z_{B-A}(X)$, which is equal to the difference of the offset profile $Z_B(X - \tau_0)$ and the reference profile $Z_A(X)$:

$$Z_{B-A}(X) = Z_B(X - \tau_0) - Z_A(X). \qquad (3)$$

- Calculate the roughness value $Rq(B - A)$ for the new profile $Z_{B-A}(X)$.
- Calculate the signature difference D_s between signatures B and A defined as

$$D_s = Rq^2(B - A) / Rq^2(A), \qquad (4)$$

Date: 24/09/2003 11:40:20
Bullet No. 1
Land No. 1
Signature A: C:\bullet\CNC Profile-rev\Atf2r.dat
Signature B: C:\Work\Data\Bullets - Casings\RM 8240 01-20 Data\RM 8240 0
CCF (ACF) : 99.55 %
Shift distance: +0.03375 (mm)
RqA: .467 (um)
RqB: .460 (um)
Rq(B-A): .0447 (um)
Signature difference Ds: .92 %

Fig. 1. User screen for a bullet profile signature comparison of S/N SRM 2460- 001 standard bullet (Signature B, shown as the second profile from the top) and the virtual standard (Signature A, shown on the top). The maximum of the cross-correlation function CCF_{max} = 99.55 %, the signature difference D_s = 0.92 %. The units of the top and bottom vertical scales are µm. The units of the lateral scales are mm.

where $Rq^2(\mathrm{A})$ is the mean square roughness of the reference signature Z_A (X), used here as a nominalization factor. From Eqs. 3 and 4, it can be seen that when two compared profile signatures are exactly the same, $Z_{\mathrm{B}-\mathrm{A}}$ (X) = 0, then Rq^2 (B – A) =0, and $D_s = 0$.

A bullet signature measurement program was developed to calculate the above parameters. A screen output of the measurement program is shown in Fig. 1. These modified profiles result after curvature removal, resampling, and bandpass filtering (2.5 µm to 250 µm) of the measured profile signatures [4]. The top one is the virtual bullet signature standard, or "Signature A", which is one of the modified profile signatures from the master bullets provided by the ATF and the FBI. The second one shows the measured bullet profile signature, or "Signature B", which in this case is a profile signature from a bullet land impression of the SRM 2460-001 bullet. The maximum of the cross correlation CCF_{max} is equal to 99.55 %. At this position, a new profile signature (B – A) (see the bottom profile in Fig. 1) is constructed, which is equal to the difference between the two compared signature profiles. Then the signature difference D_s is calculated from Eq. 4 to be 0.92 %. Considering CCF_{max} = 100 % and $D_s = 0$ mean that the two compared profiles are exactly the same (point by point), this result shows a high agreement between the profile signature on the SRM bullet and the virtual standard.

So far 240 bullet profile signatures on 40 SRM bullets have been measured by this system. The measured signatures are compared with the virtual bullet signature standard. All the CCF_{max} values are higher than 95 % and most are higher than 99 %. These results demonstrate high repeatability and reproducibility for both the manufacturing process and the measurement system for the SRM bullets.

The measurement results also show that there is a strong linear correlation between CCF_{max} and D_s [4]. Therefore, in practice, either parameter can be used for representing the 2D profile signature differences.

3. 3D Topography Comparison Parameters

A 3D topographic comparison system for the SRM casings was developed to calculate the 3D versions of the above parameters. The areal cross-correlation function, ACCF, is given by [6]

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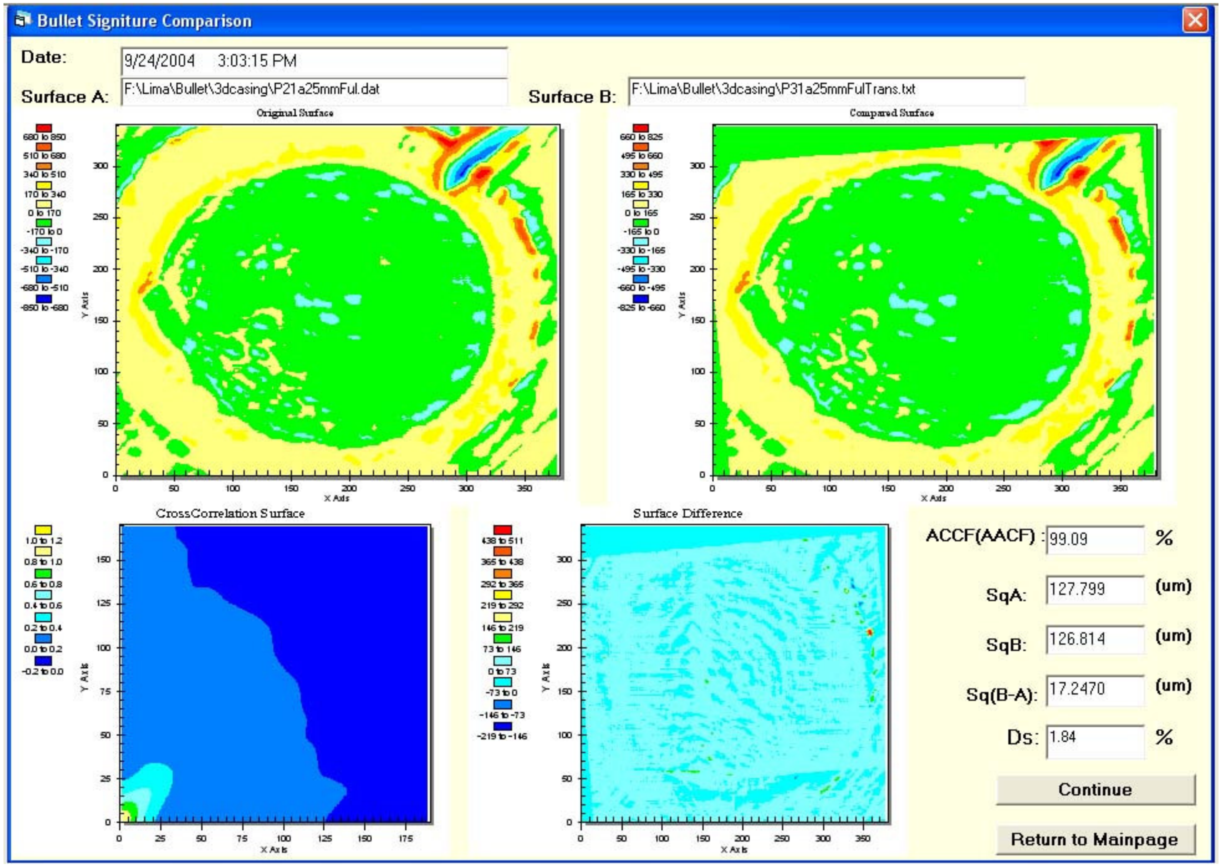

Date: 9/24/2004 3:03:15 PM

Surface A: F:\Lima\Bullet\3dcasing\P21a25mmFul.dat

Surface B: F:\Lima\Bullet\3dcasing\P31a25mmFulTrans.txt

ACCF(AACF) : 99.09 %

SqA: 127.799 (um)

SqB: 126.814 (um)

Sq(B-A): 17.2470 (um)

Ds: 1.84 %

Fig. 2. Firing pin signatures of two prototype standard casings P21 (top, left) and P31 (top, right) are compared. The ACCF is shown at bottom left; $ACCF_{max}$ = 99.09 %. The topography difference is shown at bottom middle; D_s = 1.84 %.

$$\mathrm{ACCF}(\mathrm{A},\mathrm{B},\tau_x,\tau_{\mathrm{y}},\theta)=\frac{\mathrm{ACCV}(\mathrm{A},\mathrm{B},\tau_x,\tau_y,\theta)}{Sq(\mathrm{A})Sq(\mathrm{B})} \tag{5}$$

where ACCV represents the areal cross-covariance function:

$$\mathrm{ACCV}(\mathrm{A},\mathrm{B},\tau_x,\tau_y)=\lim_{L_x,L_y\to\infty}\left(\frac{1}{L_xL_y}\int_{-L_y/2}^{L_y/2}\int_{-L_x/2}^{L_x/2}Z_{\mathrm{A}}(x,y)Z_{\mathrm{B}}(x+\tau_x,y+\tau_y)dxdy\right) \tag{5a}$$

Sq represents the areal root-mean-square roughness [6].

By analogy with Eqs. 3 and 4, the 3D version of the signature difference D_s can be calculated by:

$$D_s\,(3\mathrm{D}) = Sq^2\,(\mathrm{B} - \mathrm{A})\,/\,Sq^2\,(\mathrm{A}). \tag{6}$$

Fig. 2 shows a firing pin signature comparison between two prototype standard casings P21 and P31, which are electroformed replicas from the same master casing provided by the ATF and which ideally should be identical. The firing pin signatures were traced by a stylus instrument using a 2 µm radius diamond stylus. The resulting 3D surface topographies from the two prototype standard casings are shown on the top of Fig. 2. These two surface topographies are shifted along the X- and Y-directions and rotated around the Z-axis (registration) by the measurement program until the maximum correlation position is found. This registration is accomplished via an affine and rigid (rotation and translation) image registration method, as described by Bergen, *et al* [7]. The multi-scale registration scheme is described further by Heeger [8] and implemented by Heeger as a suite of MATLAB™ functions [9] that were integrated into our 3D-topography comparison software codes.

Once registered, the $ACCF_{max}$ is calculated to be 99.09 % (see bottom left in Fig. 2). Meanwhile, a topography difference $Z_{\mathrm{B}\,-\,\mathrm{A}}$ (X, Y) is calculated at this position and shown in the bottom middle in Fig. 2. The signature difference between the two 3D-topographies is calculated from Eq. 6 to be $D_s = 1.84$ % (see Fig. 2).

4. Summary

The NIST proposed metric for bullet and casing signature comparisons have several features:

- They are easy to understand and use, and are traceable to the length standard.
- The same metric can be used for quantifying signature differences for both 2D profiles and 3D topographies.
- Although the metric is developed for NIST's SRM standard bullets and casings project, it could be used for any 2D profile and 3D topography comparisons in surface metrology.
- Because surface information of all 2D or 3D data points is used for comparison, the parameters have high sensitivity, and can yield high repeatability and reproducibility.
- For the collection of all 2D profile and 3D topography comparisons, the minimum signature difference is $D_s = 0$, which occurs when, and only when, these two profiles or topographies are exactly the same. That means, when any two compared 2D profiles or 3D topographies have a signature difference of $D_s = 0$, these two profiles or topographies must be exactly the same (point by point).

5. References

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