*KSTLE International Journal, Vol. 6, No. 1, June 2005, pp. 21-27*

# Improvement and Verification of the Wear Volume Calculation

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**Abstract: A technique for a wear volume calculation is improved and verified in this research. The wear profile data measured by a surface roughness tester is used. The present technique uses a data flattening, the FFT and the windowing procedure, which is used for a general signal processing. The measured value of an average roughness of an unworn surface is used for the baseline of the integration for the volume calculation. The improvements from the previous technique are the procedures of the data flattening and the determination of a baseline. It is found that the flattening procedure efficiently manipulates the raw data when the levels of it are not horizontal, which enables us to calculate the volume reasonably well and readily. By comparing it with the weight loss method by using artificial dents, the present method reveals more volume by aroung 3~10%. It is attributed to the protruded region of the specimen and the inaccuracy and data averaging during the weght loss measurement. From a thorough investigation, it is concluded that the present technique can provide an accurate wear volume.**

**Keywords:** Wear volume, weight loss, wear depth profile, integration

## Introduction

Wear is a material removal on the surface caused by a relative motion of contacting bodies. To quantify the wear damage or to predict the life reduction due to wear, a modeling is necessary. Therefore, a focus has been placed on a wear modeling. More than 300 models were developed during 1957 ~1992 [1]. A general type of wear model is to correlate the influencing parameters of a wear and the resultant amount of wear. In general, there are numerous influencing parameters that affect the wear. For instance, a hundred parameters and constants were found to be used even in a sliding wear only [1]. Mechanical, material and environmental parameters were referred to. On the contrary, much simpler parameters such as a wear volume, depth, area or a weight loss have been used for the wear amount. It is very important to accurately evaluate the wear amount not only to determine the wear severity but also to develop a reliable wear model. Among the above parameters, the wear depth, area and weight loss can be measured by using a surface roughness tester, a measuring microscope and a weighing machine, respectively. However, the wear volume cannot be directly measured, it needs to be calculated from either the weight loss or the geometry of the volumetric shape. For generating the volumetric shape, a surface roughness tester is usually used. As the technology has been enhanced recently, a laser scanner is being used as an alternative.

Wear volume has been widely used as a degree of wear severity. Wear model often uses the wear volume as a parameter of the wear amount since it is regarded as an output of the energy dissipation that is interpreted as a wear. For instance, the well-known Archard wear model [2] and the workrate model [3], which deal with the wear volume, are often used for the wear model of nuclear components such as a fuel rod, a control rod and a steam generator tube, which are the typical components suffering from a fretting. Therefore, an accurate determination of the wear volume is important in the wear analysis. If the weight loss due to a wear is measured, a wear volume can be obtained by dividing the weight loss by the material density. However, a difficulty arises in this. In general, a weight loss due to a wear is very small compared with the overall weight of the specimen. It is often in the order of $10^{-4}$~$10^{-6}$ g. Therefore, the precision of a weighing machine should be enough to detect such a tiny weight difference. It is also extremely necessary to prepare and handle the specimen with great care to guarantee the reliability of the weight data. If the specimen is corroded during the wear test, an additional care should be given to discriminate the weight difference caused by a wearing and a corrosion.

Alternatively, the wear volume can be obtained from the profiles of the worn region. A surface roughness tester or a laser scanner can generate a three dimensional (volumetric) shape of the worn region, which is composed of the two dimensional profile data. Then, the wear volume can be calculated by a mathematical integration of the three dimensional shape. Since it is difficult to evaluate the wear volume from a tiny weight loss as aforementioned, the calculation method must be a strong candidate. Another advantage of the calculation with the wear profiles is that it is much less sensitive in the case of a specimen corrosion. This calculation technique has been developed and presented previously [4]. An algorithm of a signal processing technique for the volume calculation was introduced in that paper. The influence of the simplified volumetric shape as a hemisphere [5] or a semi-ellipsoid [6,7]

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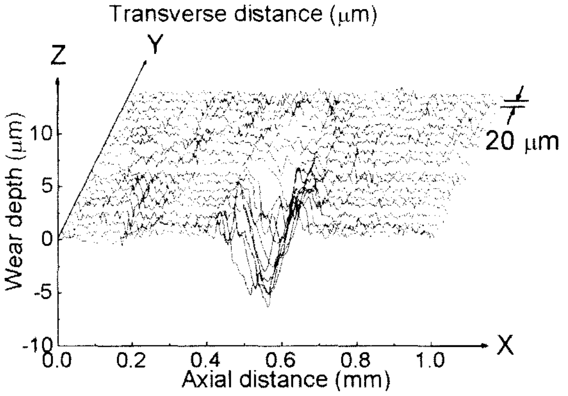


**Fig. 1. Typical surface profile of the worn surface measured by a surface roughness tester.**

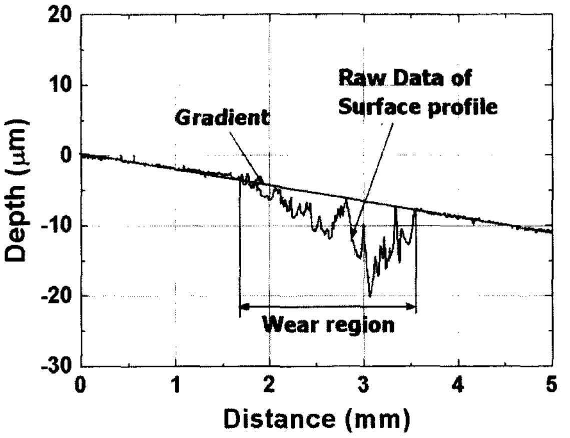


**Fig. 2. Typical measured result during one stylus pass. The misalignment between the locus of the stylus tip and the specimen axis causes a slant profile, for example.**

has also been investigated. As a result, it has been found that this simplification caused a considerable error. From this, the importance of defining a precise shape of a wear volume has been addressed [7].

In this paper, the previously developed method is improved. As for the improvement, a flattening of the raw data obtained form the surface roughness tester is added. The method to set an integration baseline is also improved. The previous algorithm is refined and a completely new program is created. Moreover, an independent test for measuring the weight loss is carried out to compare it with the volume data. In this test, a generic deficiency of the weight loss method is also discussed. The validity of the present technique is verified from these investigations.

## Improved Procedure of Wear Volume Caculation

### Measurement of the wear depth profiles

Wear depth profiles are measured using a surface roughness tester. It detects a height difference of a surface during a stylus of the tester as it touches and passes over it. Two dimensional data (i.e., the depth vs. moving distance of a stylus) is obtained from each pass. As the stylus pass is repeated by moving it in a transverse direction by a predetermined increment per a pass, three dimensional data of the wear region is obtained. Resultantly, a volumetric shape of a wear can be generated as shown in Fig. 1. The accuracy of the volumetric shape is affected by the resolution of the tester, the sharpness of the stylus tip and the increment size in the transverse direction. A commercial tester generally provides a resolution of 0.1 μm in the depth direction, 0.5 or 1 μm in the moving direction depending on the measuring length while the depth of a detectable wear is in the order of 1 μm. Therefore, the tester itself can provide sufficiently precise data for the volumetric shape. However, the increment size is determined by a user. So it influences the volumetric shape as well as the magnitude of a volume. The increment is set at 20 μm in most of our experiments.

### Data flattening

During the measurement, the profile data of an unworn region is also included when a stylus passes over the worn area on the specimen surface. The levels of the two horizontal lines before and after the worn area (unworn area) may not be coincident if the specimen surface is not parallel to the locus of the stylus tip during it passing over the specimen. If a worn area is located on a tubular surface, a discrepancy of the level occurs when the direction of the stylus pass is not coincident with that of the tube axis. These circumstances generally occur during the measurement. An example is shown in Fig. 2. If it happens, it is difficult to determine a baseline of an integration for calculating the wear volume, which will be explained later. Therefore, it is necessary to adjust the raw data to have a coincident level by applying a proper manipulation to the data such as a tilting.

For the purpose of the above levelling, a numerical procedure, called a "flattening", is carried out in the present research. Firstly, the data at the beginning and the end of the stylus pass is checked and the distance between them is evaluated. A linearity of the data except for that of the worn area is simulataneously checked. In reality, an approximate linearity is usually found. If it reveals a better linearity, an easier manipulation can be expected. Then, an average depth of the data of the unworn area is evaluated to obtain a datum for the adjustment. In this period, it is necessary to use a sufficient distance for evaluating the average depth. A slope of the data in the unworn area is obtained as a result. This slope is tilted appropriately to achieve the same horizontal level. Fig. 3 shows the result of a data flattening.

It is necessary to include the number of data, as many as possible, to calculate the slope more accurately. On the other hand, the computing time is extended depending on the number of data. So it is required to determine a minimum number of data that can generate the slope to within an acceptable accuracy. It is also checked in this research. Fig. 4 provides the result of an investigation when the number of data is increased by 100 to 500 with a step of 100. It is coincident with the distance of 0.1 to 0.5 mm with a step of 0.1 mm along the unworn area. It is shown that the surface profile of the unworn area rotates counterclockwise infinitesimally as the

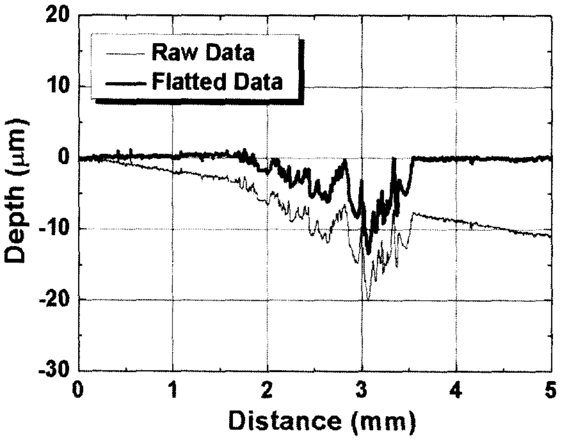


**Fig. 3. Result of the data manipulation by the flattening algorithm. A slant profile of an original data is tilted to have a coincident level.**

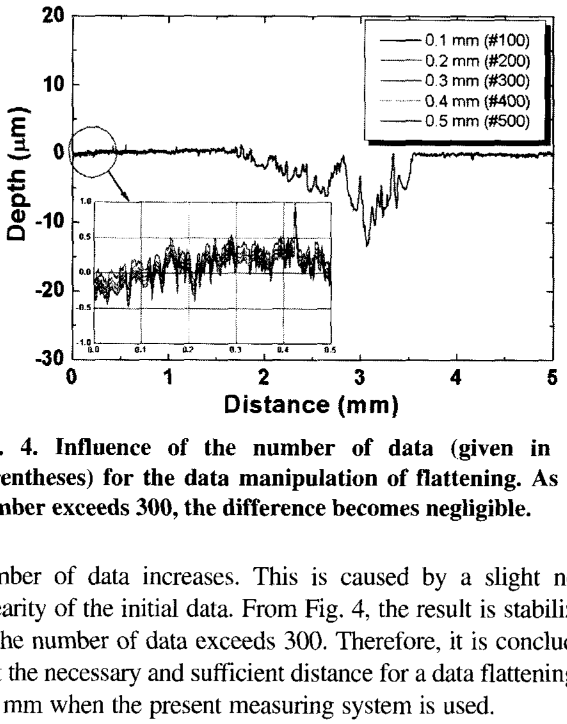


**Fig. 4. Influence of the number of data (given in the parentheses) for the data manipulation of flattening. As the number exceeds 300, the difference becomes negligible.**

number of data increases. This is caused by a slight non-linearity of the initial data. From Fig. 4, the result is stabilized as the number of data exceeds 300. Therefore, it is concluded that the necessary and sufficient distance for a data flattening is 0.3 mm when the present measuring system is used.

### Generation of the three dimensional volumetric shape

When the two dimesional data of the worn region is obtained along the transverse direction, it can be stacked with the same distance of the stylus pass (20 $\mu$m usually). To compose a complete three dimensional volumetric shape from the stacked two dimensional data sets, it is necessary to connect each data set. If the increment in the transverse direction is small enough, the data sets can be connected linearly. However, the linear connection intrinsically contains an error since the actual contour of a wear should be random. A connection with a curve more than a second order can reduce the error. For this, a spline function of a cubic power is used in the present method. After this connection procedure, the volumetric shape of a wear is composed of continuous curves from which a volume calculation procedure can be applied.

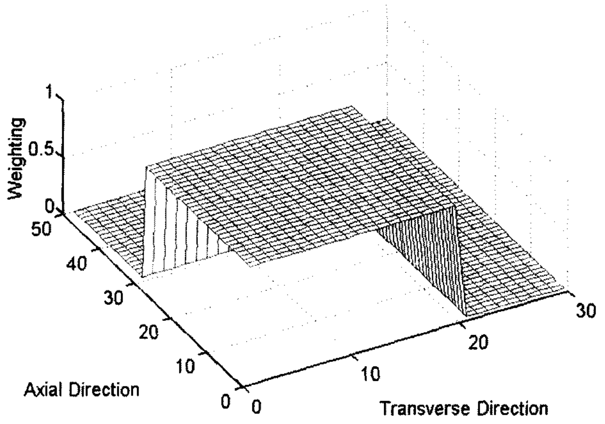


**Fig. 5. Low pass filter shape in frequency domain (cutoff frequency: 20th and 30th components in transverse and axial direction, respectively) [4].**

### Extraction of the worn region data

Before proceeding to the volume calculation procedure, it is very important to extract the profile data of the worn area from the all data acquired during the stylus pass since it also includes the data of the unworn region besides that of the worn one explained previously. This importance also arises due to the intrinsic roughness of the unworn area. The roughness makes it hard to determine the baseline of an integration for the volume calcularion. By a precise investigation, it is found that the roughness of the unworn surface is relatively larger than that of the worn area. In this regard, it is possible to regard a roughness variation along the measuring distance as a vibration amplitude with respect to the time. So to speak, the roughness variation and the distance of the stylus pass can be regarded as a vibration signal amplitude and the time, respectively. Then, it is possible to apply a conventional signal processing technique to the obtained profile data including the intrinsic roughness. Since it has been found that the roughnesses of the unworn and the worn area are different, the frequencies must be different if the velocity of the roughness variation is assumed as a frequency. It enables us to apply the Fourier transform method for use a filtering technique to extract the worn region from the unworn region.

In the present procedure, the two-dimensional Fast Fourier Transform (so called FFT) algorithm is used. The directions of the stylus pass and its perpendicular (transverse) direction are set as an $x$- and $y$-direction, respectively. After the FFT is applied, the data of a higher frequency is removed since it is the frequency component of the unworn area. In short, a low-pass filtering is applied in this process as illustrated in Fig. 5. In this step, the cut-off frequency for the low-pass filtering is set as a user-defined value so that it can be varied at a user's request by considering the roughness data of the unworn area. A process of the inverse FFT is carried out for the low-pass filtered data after the FFT. As a result, smoothed data of the unworn area is obtained, which enables us to extract the actual worn region easily.

A further step to extract the actual worn region is to use the "windowing technique". A fluctuation of the data of the

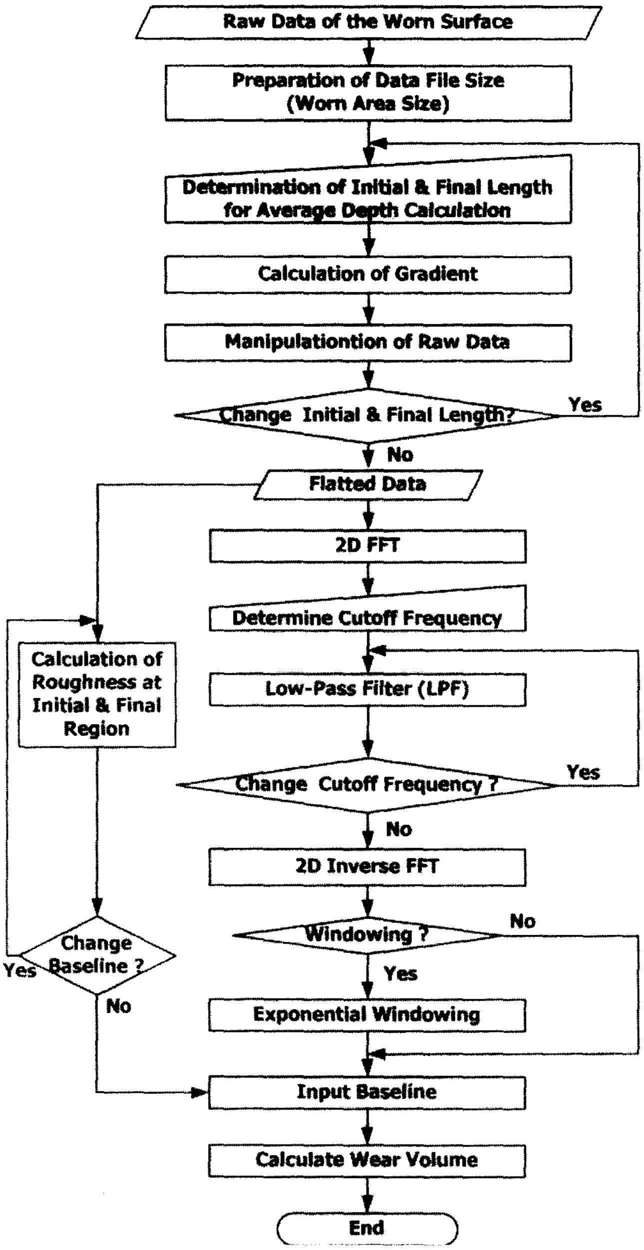


**Fig. 6. Flowchart of the present algorithm for wear volume calculation.**

unworn area cannot be removed completely after the above-mentiond filtering technique is applied. The windowing technique can decrease the fluctuation further so that the baseline of an integration for the volume calculation can be set more easily. This is carried out by using the following function for the smoothed data after a low-pass filtering.

$$Z(x,y) = w(x,y)\cdot(1-e^{-|w(x,y)|/K}) \qquad (1)$$

where, $w(x,y)$ is the smoothed data and $Z(x,y)$ is the final data for the volume calculation. $K$ is a parameter that alters $w(x,y)$. If $K = w(x,y)$, $Z(x,y)$ is about 63.2% of $w(x,y)$. When an average roughness ($R_a$) of the unworn surface is used for $K$, it is found that a fluctuation less than $R_a$ is considerably decreased. In the present processing, $K$ is also set as a user-defined value so that a user can define the best value incorporating the measuring conditions to obtain an accurate volume.

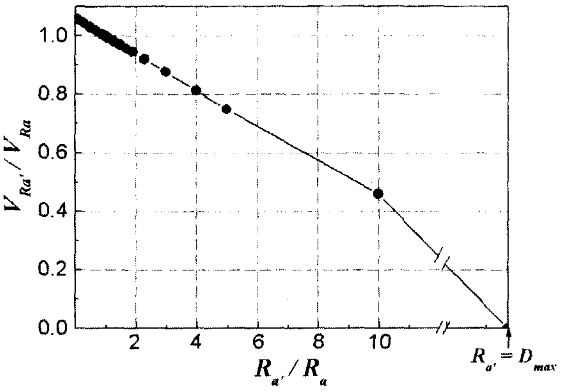
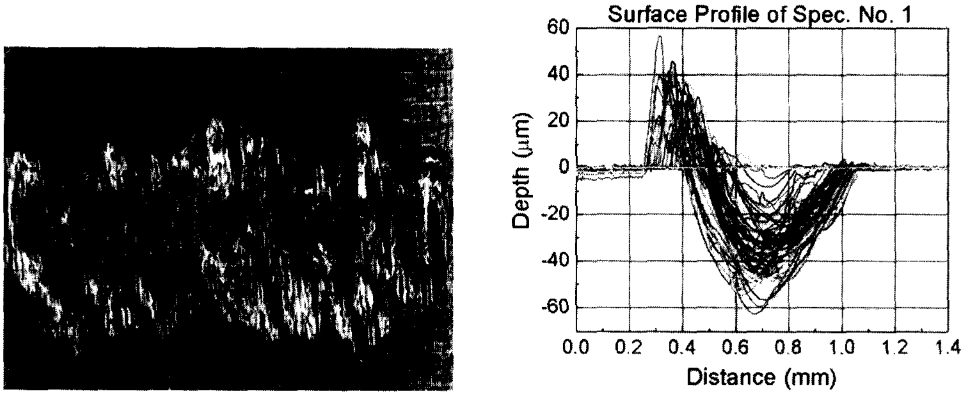


**Fig. 7. Variation of the calculated volume corresponding to the alteration of the baseline of an integration.**

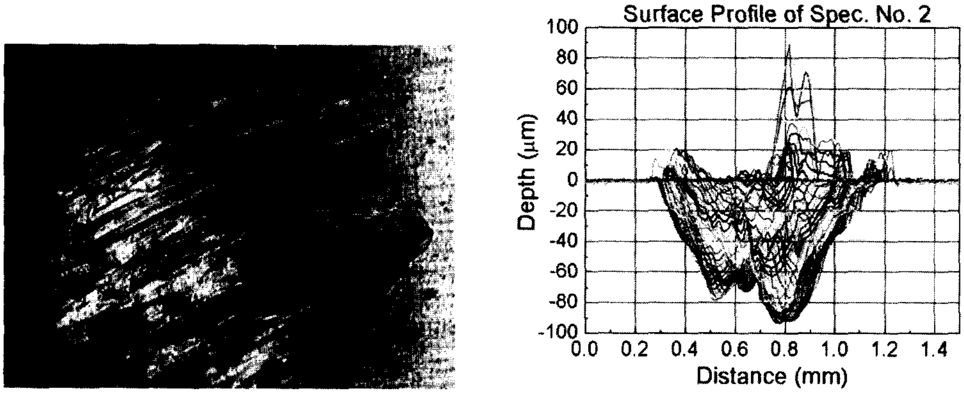
## Set a baseline of integration

A final step for the volume calculation is to determine a baseline of the integration for the flattened data, $Z(x,y)$. The calculated wear volume is the volumetric portion beneath the baseline, so it is the most influencing parameter in the calculation. It can be a line of zero-depth (i.e., $Z(x,y) = 0$) in theory. However, the line of the unworn region cannot be perfectly coincident with it in reality due to the properties of a specimen's surface such as an overall waviness. Therefore, a proper line needs to be determined for the baseline. In the present technique, a user can alter it. Average surface roughness value ($R_a$) of an unworn area may be a strong candidate for the baseline [4]. However, it is necessary to investigate the influence of the baseline value on the variation of a wear volume. In this regard, the range of the baseline is from a zero-depth to the maximum roughness of the unworn surface. Consequently, the flowchart for the volume calculation is provided in Fig. 6.

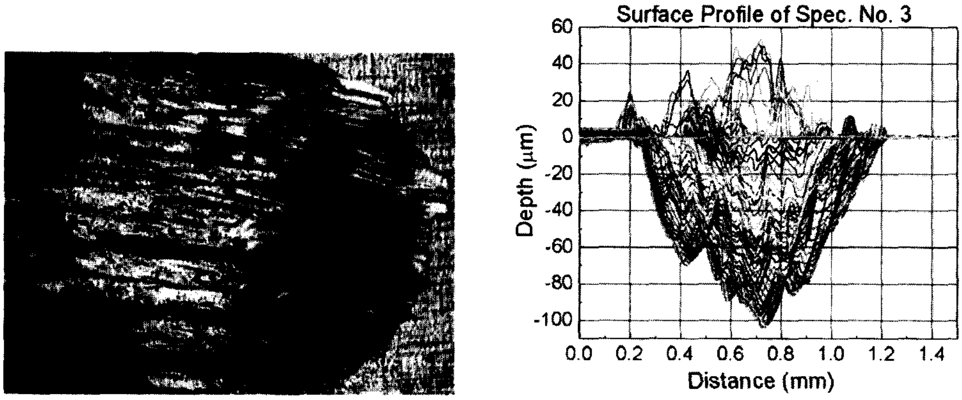
Fig. 7 shows a typical example of the wear volume variation as the baseline is altered. $R_a$ is an average roughness value of the unworn surface. $R_{a'}$ is an applied base line, which is tentatively altered from 0 to the maximum wear depth. $V_{Ra}$ and $V_{Ra'}$ are the wear volume calculated by using $R_a$ and $R_{a'}$ as the baseline, respectively. It is found that the wear volume linearly decreases as $R_{a'}$ increases at least up to $R_{a'}/R_a = 10$. When $R_{a'}/R_a = 10$, the wear colume is calculated to be 46% (almost a half) of that at $R_{a'}/R_a = 1$. It is interesting to observe that the wear volume increases by only 6% when the baseline is set as zero. From Fig. 7, the wear volume differs by less than ±5% when $0.3 < R_{a'}/R_a < 1.7$. It is somewhat different from what had been expected. The result implies that an inclusion of the intrinsic fluctuation of the unworn surface does not considerably affect the wear volume. In other words, the wear volume can be approximated without causing a considerable error as long as the baseline is set at smaller than the average roughness of the unworn surface. However, this result does not guarantee



(a) Specimen No. 1



(b) Specimen No. 2



(c) Specimen No. 3

**Fig. 8. Views and relevant profiles of the artificially dented specimens.**

that $R_a$ is a proper value of the wear volume calculation. Besides the above investigation of a volume behaviour corresponding to the baseline, it is necessary to check to see if there exists a best value for the baseline that gives the most accurate wear volume. This is presented in the next section.

## Verification

### Method

So far, an established procedure for the wear volume calculation has been introduced. The influence of the integration baseline on a variation of the wear volume was also investigated. Besides this, it is nessary to verify the present technique to use it for an actual wear analysis. This is carried out by comparing the calculated volume obtained from the present technique to that by considering the weigh loss and the density.

Three tubular specimens with artificial dents were prepared for the verification test. The diameter and the thickness of the specimens are 9.5 mm and 0.6 mm, respectively. The material of the specimen is Zircaloy-4 whose density is 6.6. The reason for using a specimen with an artificial dent rather than an actual wear scar is due to the specimen size. It needs to be very

**Table 1. Comparison of the wear volumes obtained from a weight loss and a calculation with $R_a$ ($\times 10^{-6}$ mm$^3$)**

| Specimen No. | 1 | 2 | 3 |
|---|---|---|---|
| From weight loss | 12424.24 | 21363.64 | 29545.45 |
| Calculated | 15790.96 | 24153.05 | 34525.53 |
| (when protrusion compensated) | (14315.15) | (23466.69) | (32474.99) |
| Difference | 27% | 13% | 17% |
| (when protrusion compensated) | (10.3%) | (2.9%) | (6.3%) |

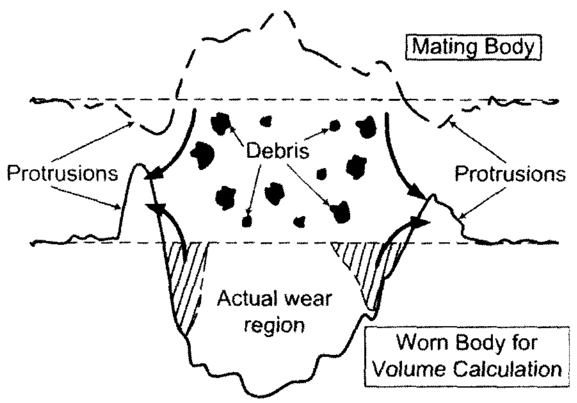


**Fig. 9. Schematic of the material transfer to form a protruded region.**

small such that the weight loss due to a wear can be distinguishable when compared with the total weight of a specimen. It is not possible to install such a small specimen into the presently used wear tester. A high precision weighing machine (resolution: 0.01 mg) measured the specimen weight before and after the dents were formed. Each weight was measured 7 times repeatedly. The obtained data was averaged after discarding the largest and the smallest values among them. The weight loss was finally evaluated from the averaged data.

## Results

Fig. 8 shows the views of the three artificial dents on the specimens. The profiles of each dent measured by a surface roughness tester are also provided. A protruding region appears in every specimen like a general worn specimen. In the case of the worn specimen, the protrusion is attributed to the accumulation of the wear debris produced from the contacting surfaces. A part of the debris produced from the mating surface is also transferred and pasted, which contributes to the protrusion. In the present case, it is made artificially as well.

The resultant weight losses are 0.082, 0.141 and 0.195 mg for each specimen (number 1, 2 and 3 in order). When these are divided by the material density (6.6), the wear volumes are 0.012, 0.021 and 0.030 mm$^3$, in the same order. On the other hand, the values of $R_a$ measured during the stylus pass are 0.43, 0.34 and 1.36 mm for specimen number 1, 2 and 3, in that order. The comparison between the wear volume obtained from the weight loss and that from the calculation with the base line of the measured $R_a$ is given in Table 1. It is found that the calculated volume is always revealed as larger than the one obtained from the weight loss. A large discrepancy (13~27%) appears. When we try to adjust the baseline in the calculation to create a similar volume to the one by the weight loss, 13, 14 and 6 times of $R_a$ are required for specimen number 1, 2 and 3 in the order. It does not make sense to take such a large value for the baseline. The protrusion region as well as the uncertainty of the weight loss are taken into consideration for the reasons of the present discrepancy.

Firstly, the volume of a protrusion is a portion of the metal removed from the surface. As a wearing process proceeds, most of the produced debris is dispersed out but some remains to form the protruded region. This results in a decrease of the weight loss value when it is compared with a real weight loss due to a material removal. A transfer of the removed material from the mating surface decreases the weight loss further. It is illustrated schematically in Fig. 9. Therefore, it makes sense if the calculated volume is larger than the volume by the weight loss. This is a generic deficiency of the wear volume evaluation by measuring the weight loss. Rather than this, an actually removed region of a contacting body is evaluated in the present calculation method. When the results of the weight loss method is compensated with considering the protruded region, it is found that the difference between the weight loss method and the calculation one decreases dramatically as shown in the prentheses of Table 1 (from 13~27% to 2.3~ 10.9%). The difference in the parentheses is regarded again as a contribution of the accumulation of the transferred debris from the mating surface.

Secondly, there seems to be an uncertainty in the weight measurement. During the measuring process, it was experienced that the digit of $10^{-3}$ mg in the readout of the weighing machine was varied at each measurement. Even, when the weight data was averaged. It implies that the volume difference due to the readout variation can be up to 10% approximately. It is soundly concluded that the observed discrepancy between the weight loss method and the calculation is reasonable if the above concerns are accommodated. Again, the result that the calculated volume was always larger than that by the weight loss also assures the validity of the present method.

## Conclusions

For an accurate wear analysis, a technique to calculate the wear volume is improved and verified in this research. The technique will be used not only for the determination of the wear severity but also for a wear modeling. From a thorough investigation of the present technique, the following can be summarized.

1) The improved technique adds the procedures of a data flattening and the application of a measured average roughness for a baseline of an integration to the previous one [4]. Following the algorithm of the improved technique, a completely new computer program is established.

2) The result from the present method provides a larger wear volume than that from the weight loss method. It is primarily attributed to the protrusion region, which usually occurs in an actual wear and cannot be evaluated by the weight loss method. An uncertainty of a weighing machine during the measurement of a very small weight loss is also associated with this discrepancy. Therefore, the present method can give a more accurate volume than the weighing method.

3) The present method as well as the algorithm is successfully verified from the thorough investigation with experiments. From this, a remarkable enhancement of wear analysis technique is achieved.

## Acknowledgment

This project has been carriedout under the Nuclear R&D Program by MoST, Korea.

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