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THE EFFECT OF COMPONENT THICKNESS ON THE FLATTENING OF SURFACE ASPERITIES

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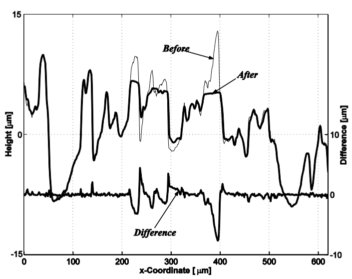
Graphical abstract



Abstract

An experimental investigation of a deformable flat rough surface being in contact with a hard smooth ball indenter was presented to evaluate the effect of thickness on the flattening of surface asperities. A novel method to determine the asperities flattening was deployed. The method uses a matching and stitching technique for analyzing the 3D measurement surface data. Two different materials of flat surfaces, aluminium and brass, were used. Results were presented for very thin and thick specimens, showing that there is no effect of thickness on the deformation degree of the surface asperities. Comparisons were made with the published models for predicting the deformation degree of the contacting surface and the results obtained confirm very well the model.

Keywords: Contact mechanics, indentation, thickness, deformation, asperity

Abstrak

Sebuah penyelidikan eksperimental dari permukaan kasar datar yang bisa terdeformasi di kontakkan dengan sebuah indentor bola yang halus dan keras, disajikan untuk mengevaluasi efek ketebalan terhadap deformasi plastis asperiti permukaan. Sebuah metode baru untuk menentukan besarnya deformasi plastis asperiti diberdayakan. Metode ini menggunakan teknik pencocokan dan pengabungan untuk menganalisis data pengukuran permukaan 3D. Dua bahan permukaan datar yang berbeda, aluminium dan kuningan, digunakan dalam studi ini. Hasil penelitian disajikan dengan spesimen yang sangat tipis dan specimen yang sangat tebal, yang menunjukkan bahwa tidak ada pengaruh ketebalan terhadap tingkat deformasi plastis asperiti permukaan. Perbandingan dilakukan terhadap model yang telah terpublikasi untuk memprediksi tingkat deformasi plastis permukaan yang berkontak. Hasil-hasil menunjukkan bahwa model yang digunakan terkonfirmasi dengan baik.

Kata kunci: mekanika kontak, indentasi, ketebalan, deformasi, asperiti

1.0 INTRODUCTION

When two engineering surfaces are placed in contact, contact occurs at discrete spots due to the roughness of the surfaces. Summation of the contact area of the spots constitutes the real contact area. Analysis of the real area of contact between two contacting solids is an important issue in understanding the tribological properties of systems such as friction, wear, lubrication, adhesion and leakage. Therefore, tribologists are concerned with what happens when two asperities are being in contact due to static indentation, rolling or sliding. Many variables contribute to the development of the real contact area, such as the surface topography or asperity geometry and the mechanical properties of the asperities. Many attempts have been conducted to study the real contact area which is indicated by the flattening of the asperities.

In 1948, Moore [1] demonstrated the remarkable persistence of surface asperities for the line contact situation. Moore pressed a highly polished hard steel roller against a face-turned copper plate. The copper had been previously work hardened so that it is not capable of much additional work hardening and therefore, an additional hardness of the asperities due to turning is not expected. It was shown that even for very high loads the ridges in the copper remained clearly visible in the indentation profile. The work of Moore has been extended by many other researchers. Williamson and Hunt [2], for instance, indenting a flat by a hard ball. They concluded that asperity persistence does not depend on the particular material and the ratio of the real contact area to the nominal contact area depends on the hardness of the material. The dependence of A_r/A_n on load was studied by Pullen and Williamson [3] using a rough aluminium surface compressed by a hard flat punch. The persistence behaviour of the asperities was analyzed theoretically by Childs [4] and Wanheim [5] using the slip line field method and Chivers *et al*. [6] and Wilson and Sheu [7] using an upper-bound theorem. Most of the experiments used a model asperity where a surface roughness is modeled as a uniform array of wedge-shaped ridges. Close agreement between the theoretical and experimental results were reported. Sutcliffe [8] investigated the surface asperity deformation under bulk plastic flow using slip line field for different directions of the roughness. The model of Wilson and Sheu [7] was also modified to longitudinal roughness. It was concluded that the degree of the flattening of the asperities increases as the bulk plastic strain increases. Finite element analysis was employed by Makinouchi *et al*. [9], Ike and Makinouchi [10] and Korzekwa *et al*. [11] to study the asperity deformation mechanism under plastically bulk deformation. A surface ridge model was also used in this finite element analysis. Sutcliffe [12] introduced a model surface with two wavelength components for studying surface flattening undergoing bulk deformation. Lee-Prudhoe *et al*. [13] showed the asperity persistence by plotting the profile for before and after indentation of line contact. Sub surface stresses were also calculated numerically, however, there is no clear explanation under which conditions the surface starts to deform plastically on asperity level or in the bulk [14]. Jamari and Schipper [15, 16] have also presented the asperity persistence under bulk deformation for a three-dimensional surface. A criterion to determine under which contact conditions the surface deforms plastically in the asperities or in the bulk was also proposed.

All the aforementioned studies are devoted to heavily loaded contacts and the effect of the thickness of the specimens is not involved. Milner and Rowe [17] performed an experiment where a 'penny-shaped' rough surface specimen is compressed between smooth anvils, for which bulk plastic flow implies that every element of the specimen deforms plastically. It was reported that depending on the relative hardness the asperities either were flattened or 'pressed into' the smooth surface. Based on the work of Moore [1] and Milner and Rowe [17], Greenwood and Rowe [18] performed an experiment to study the effect of the thickness on the flattening of surface asperities under bulk plastic flow. In their experiment, a rough flat surface of a cylinder (R_a = 1 μm) was pressed against hard smooth steel (R_a = 0.03 μm) anvils. Profiles of the deformed surface after 10% compression of tall and 'penny-shaped' cylinders were compared which imply different specimen thickness. In both cases, there is a bulk dented area around the center of the contact. However, the degree of asperity deformation is different. Analysis of Schroeder *et al*. [19], explains such phenomena. The maximum contact pressure occurs at the center of the contact, therefore, the deformation of the bulk surface is higher around the contact center. If there is no sticking in the contact interface and the coefficient of friction is not zero, the required mean contact pressure decreases as the thickness of the blank increases, see Figure 1.

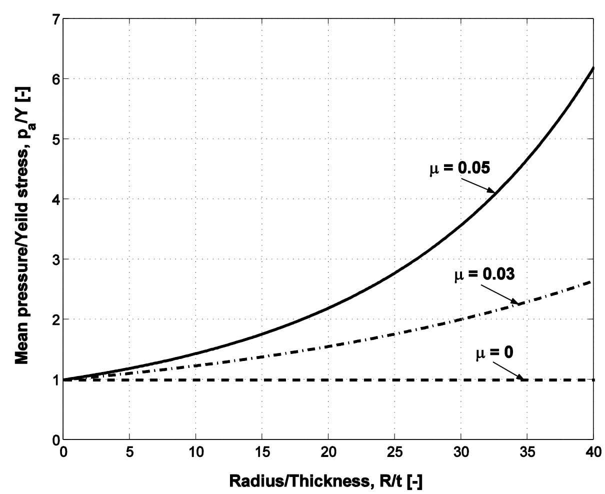


Figure 1 Non-dimensional mean pressure as a function of non-dimensional thickness of compression a blank specimen

This behaviour becomes more pronounced as the coefficient of friction increases. Up to a certain value of the coefficient of friction the assumption of pure sliding is invalid as the sticking mechanism start to occur. Greenwood and Rowe [18] explained that the degree of flattening of the asperities for a thin 'penny-shaped' cylinder is because of the plastic deformation extends to the surface while for the thick or tall cylinder the plastic deformation still occurs in the bulk (below the surface), therefore, the asperities persist. Kimura and Childs [20] studied theoretically and experimentally the effect of thickness on the asperity deformation under bulk plastic straining conditions based on the velocity field and approximate energy minimization method. The asperities were modeled by an array of ridges. It was found that the ratio of the real contact area to the nominal contact area, which implies the degree of asperity flattening, is sensitive to the thickness, t, of the specimen when $t/\lambda < 15$ with λ is the wavelength of the surface ridges.

The main purpose of the present work is to further explore the effect of thickness on the flattening of the asperities under no-bulk deformation instead of bulk deformation as most frequently is studied. The flattening of asperities without bulk deformation is very important in, for instance, running-in process [21]. The presence of bulk deformation leads to the run-out or damage component. A novel measurement method is also introduced to observe the flattening of the three-dimensional surface asperities. The results are compared to the theoretical prediction of Jamari and Schipper [15] in predicting the degree of surface asperities flattening.

2.0 EXPERIMENTAL PROCEDURE

2.1 Specimens

In the present study, a deformable rough surface is compressed by a hard smooth ball indenter to study the thickness effect on the flattening of surface asperities. Hardened steel spheres (H = 7.5 GPa, E = 210 GPa and v = 0.3) with a diameter of 10 mm and a r.m.s. roughness R_q of about 0.01 μm were used as a hard smooth spherical indenter. The deformable flat specimens used were made from aluminium (H = 0.24 GPa, E = 75.2 GPa and v = 0.34) and brass (H = 1.2 GPa, E = 105 GPa and v = 0.34). For the aluminium two flat samples were used with a thickness of 0.3 mm and 10 mm and a r.m.s. roughness value of 2.2 μm and 4.8 μm, respectively. For the brass flat samples a thickness of 0.05 mm (R_q = 0.63 μm) and 8 mm (R_q = 0.68 μm) were used. The thin samples (less than 1 mm) were obtained from commercial supplier.

2.2 Matching and Stitching

Studying the characteristic of the changes in micro-geometry at the same position is more desirable, especially when studying the process of change. To measure the change of the surface topography (flattening of the surface asperity or bulk deformation) accurately, a new method, which is called matching and stitching method, was deployed. The method was introduced by de Rooij and Schipper [22] in 1998. It is not possible to get an accurate or detailed image of a complete cross section of the contact area in most practical situations. To determine an accurate image of the cross section a high lateral resolution is needed. However, due to the limitation of the hardware or measurement device only small areas can be measured. This problem is solved by matching and stitching a number of small but detailed images together from sequence measurements.

The matching process of two images can be defined as aligning or repositioning the overlapping part of two successive images. One of the approaches which can be followed to obtain the "best fit" between the matching images is by identifying certain distinctive features such as sharp edges or corners, contours, et cetera. However, such an approach is generally difficult to apply in roughness surface images, due to its stochastic properties. The template method was used by de Rooij and Schipper [22] and obtained very good results for matching the roughness images. The method extracts a certain neighborhood (template) from one image and determines the position which gives the best fit to other images. Instead of using small templates, the complete region is used by Sloetjes *et al.* [23]. The stitching process itself in fact is the matching process of several images in order to get a detailed and wide image of a complete section across the contact area. Several measurements are taken in the stitching process and each one having a certain overlap area with the previous one. For every stitching of the subsequence two images the mutual translations and rotations can be determined based on the overlapping area (matching process). Once all the images are matched, one large image is created as a complete of the stitching process. Figure 2 shows schematically the matching and stitching procedure used in the present experiments.

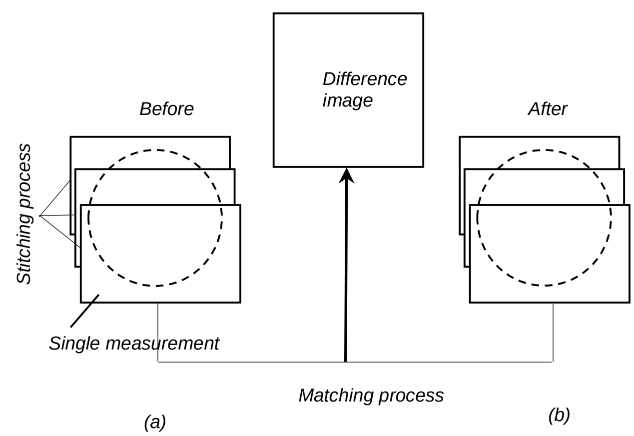


Figure 2 Matching and stitching procedure, schematically: (a) before and experiment and (b) after an experiment

As can be seen, in that schematically representation, the predicted contact area, shown by the dashed line, from the static compression of the sphere is wider than one single measurement of the optical profiler, therefore, the matching and stitching procedure is applied. This process is carried out for before and after an experiment. Due to some movement, the measurements position is shifted in the translation or rotation movement. To get the difference image between before and after loading or indentation the two large images are matched.

2.3 Experimental Details

A setup as shown in Figure 3 was used to perform the experiments. The maximum load which could be applied to this setup was about 30 N. The spherical and the flat specimens were cleaned with acetone and dried in air prior to any test.

In this experimental setup system an optical interference microscope was used to measure the three-dimensional surface roughness. An X-Y table which is controlled by stepper motors was employed to positioning the flat specimen from the loading position (position **A**) to the surface measuring position (position **A'**) and the other way around. Procedure of the measurement is described as follows. First, the flat surface was measured under the optical interference microscope (position **A'**). In this step the number of the stitching images which should be taken depends on the predicted contact area and the chosen magnification of the interferometer. Next, after finishing the surface measurement in position **A'** the flat surface was moved to the loading position **A**. In this loading position the statically mounted sphere specimen was moved down by the loading screw and subsequently loaded by the dead weight load system. In order to reduce the effect of friction the contact region was lubricated. The load was applied to the sphere specimen for 30 seconds and then unloaded. Before measuring the after loading contact area with the optical interference microscope, again the flat was cleaned and dried as was described earlier. After taking all the surface topography images data the matching and stitching calculation was performed separately by a personal computer.

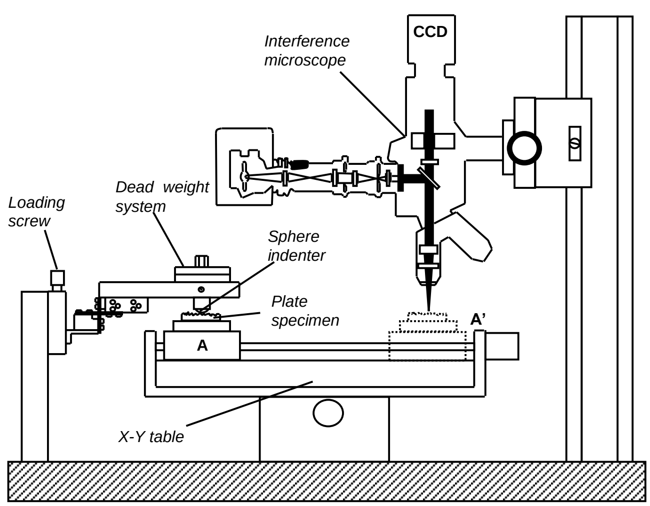


Figure 3 Experimental setup

3.0 RESULTS AND DISCUSSION

3.1 Experiments with Aluminium Specimens

Figure 4 shows the experimental results of the 0.3 mm thickness aluminium flat specimen. The initial surface (before indentation) was plotted in Figure 4(a) and the surface after indentation of 4 N load is plotted in Figure 4(b). As can be seen from these figures, the difference between Figures 4(a) and 4(b) is difficult to see by the naked eye. However, by the matching and stitching method such difference is clearly presented in Figure 4(c).

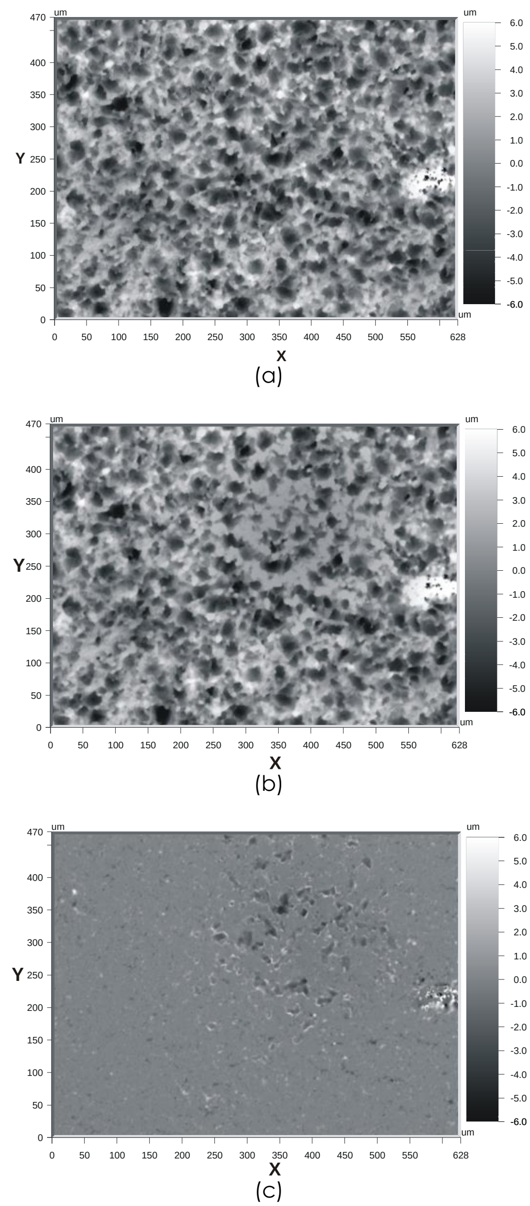


Figure 4 Matching and stitching results of an aluminium surface, t = 0.3 mm, load = 4 N, α = 3.36 and C_m = 0.56: (a) before, (b) after and (c) difference

Asperity flattening without bulk deformation is observed from this difference image. A more detailed picture of the flattening of the asperities is presented in Figure 5 where the x-profile at y = 325 mm of Figures 4(a), 4(b) and 4(c) are plotted together. The difference profile in Figure 5 lies nominally along the x-axis at y = 0 with some higher magnitude in some locations meaning that the deformation takes place on the asperity level without bulk deformation.

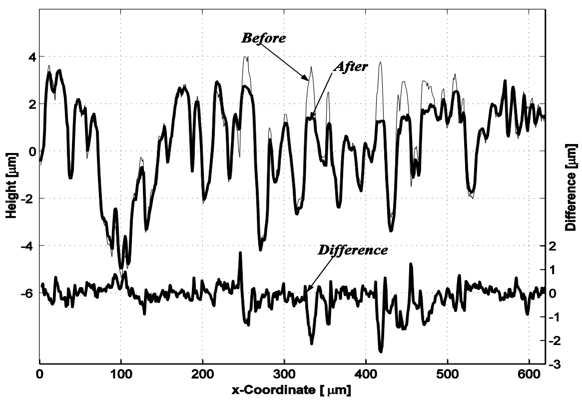


Figure 5 Profile of the matching and stitching results of aluminium surface at y = 325 µm, t = 0.3 mm, load = 4 N, α = 3.36 and C_m = 0.56

Result of the experiment on 10 mm thick aluminium flat specimen with the same 4 N load is presented in Figure 6. Similar results were found in this case, therefore, the plot is presented on the surface profiles only. The same as for 0.3 mm thick aluminium specimen, the asperity flattening without bulk deformation is also observed for 10 mm thickness. Based on the results of these experiments the effect of thickness is not confirmed on the flattening of surface asperities. Both experiments show no-bulk deformation.

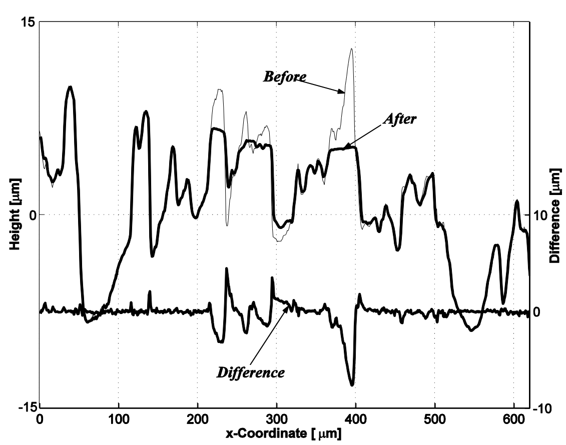


Figure 6 Profile of the matching and stitching results of aluminium surface at y = 302 µm, t = 10 mm, load = 4 N, α = 6.2 and C_m = 0.41

For a given r.m.s. roughness and the load for a certain geometrical contact condition values for the constants α and C_m can be determined according to Jamari and Schipper [14]. Following the work of [14] the contact properties of a 0.3 mm aluminium flat surface against a 10 mm diameter steel ball with 4 N load are 3.36 and 0.56 for α and C_m, respectively. The same contact condition was applied for the 10 mm thick aluminium specimen which results in 6.2 and 0.41 for α and C_m, respectively. Interestingly, when the criterion of Jamari and Schipper [14] is applied, by using the contact properties above, the degree of the asperity flattening can be predicted. In this criterion, the effect of thickness is not involved.

3.2 Experiments with Brass Specimens

To get more insightful results experiments were performed with another material i.e. brass flat surfaces.

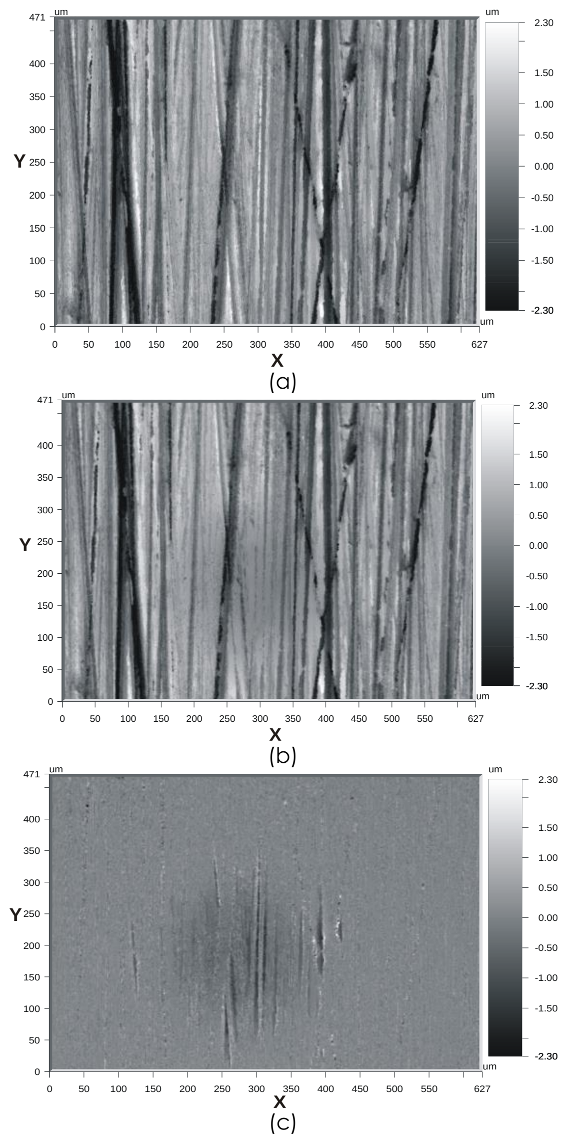


Figure 7 Matching and stitching results of an brass surface, t = 0.05 mm, load = 40 N, α = 0.26 and C_m = 0.8: (a) before, (b) after and (c) difference

In those specimens the relative difference of the thickness is increased. 0.05 mm and 8 mm thick brass flat surfaces were used. Results of the 0.05 mm thick brass specimen indented by a 10 mm diameter steel ball are shown in Figure 7 and Figure 8. Surface asperity flattening is depicted from these figures; however, there is also bulk deformation. If the analysis is taken carefully, the degree of asperity flattening is less than the degree of the bulk deformation. This phenomenon is also observed for the 8 mm brass flat surface, see Figure 9. Again, using the criterion of Jamari and Schipper [14] the 0.05 mm brass surface has 0.26 and 0.8 and the 8 mm brass surface has 0.22 and 0.83 for α and C_m, respectively. This bulk deformation is already predicted by the criterion regardless of the thickness effect.

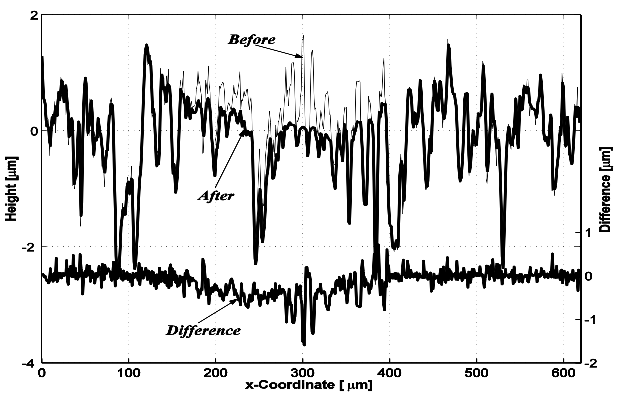


Figure 8 Profile of the matching and stitching results of brass surface at y = 180 µm, t = 0.05 mm, load = 40 N, α = 0.26 and C_m = 0.8

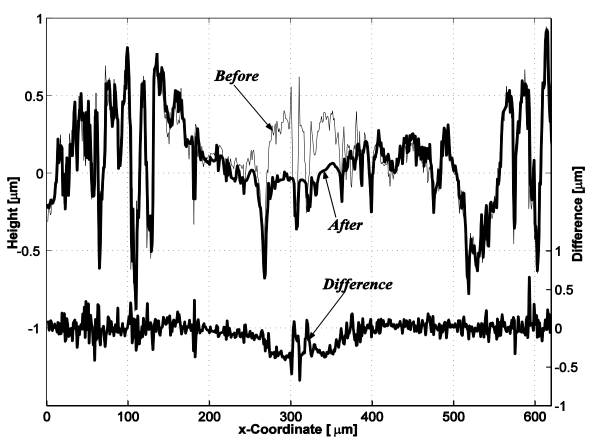


Figure 9 Profile of the matching and stitching results of brass surface at y = 191 µm, t = 8 mm, load = 40 N, α = 0.22 and C_m = 0.83

Based on these experimental results it can be concluded that there is no effect of thickness on the flattening of surface asperities or bulk deformation for a not very high load contact condition. For a very high load contact condition, such as deep-drawing processes (gross bulk plastic flow), the effect of thickness becomes significant as the effect of the friction in the contact interface is more pronounced, see Figure 1.

4.0 CONCLUSION

An experimental investigation was carried out to study the effect of specimen thickness on the flattening of surface asperities.

The main finding of the present experiments is that there is no effect of the thickness specimen on the flattening of the surface asperities or the bulk deformation. Instead of using the thickness criterion, as normally used, the criterion of Jamari and Schipper [14] is more useful for determining the state of deformation behaviour. Plastic deformation occurs on asperity level only when the value of C_m is less than 0.52.

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