This full text version, available on TeesRep, is the post print (final version prior to publication) of:


For details regarding the final published version please click on the following link:
http://compeng.hud.ac.uk/icac11/ProgrammeICACv6.pdf
When citing this source, please use the final published version as above.

Copyright © 2011 IEEE. This material is posted here with permission of the IEEE. Such permission of the IEEE does not in any way imply IEEE endorsement of any of Teesside University's products or services. Internal or personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution must be obtained from the IEEE by writing to pubs-permissions@ieee.org.

By choosing to view this document, you agree to all provisions of the copyright laws protecting it.

This document was downloaded from http://tees.openrepository.com/tees/handle/10149/143809
Please do not use this version for citation purposes.

All items in TeesRep are protected by copyright, with all rights reserved, unless otherwise indicated.
Finite Element Investigation of Nano-indentation of coated Stainless Steel

Qiang Xu, Chulin Jiang, Dezheng Liu, Yongxin Pang, Simon Hodgson
School of Science and Engineering
Teeside University
Middlesborough, Tees Valley, TS1 3BA
q.xu@tees.ac.uk

Abstract—An finite element analysis was used to investigate the nano-indentation testing process in different kinds of coating on 316 Stainless Steel, in order to determine the properties of coating material and to and investigate the influence of different of the material coating materials on 316 Stainless Steel. The finite element analysis was based elastic-plasticity properties of material. The results were three main points: 1) the simulation force-depth relationship was agreed with the experimental force-depth relationship for 316 stainless steel; 2) the range of Modulus of Elasticity for specific coating was determined as between 5GPa to 60GPa; 3) the influence of the thickness of coating material on the force indentation depth relationship was investigated. The project offers suggestions to further design of coating process research.

Keywords: coating material and property, nano-indentation, finite element analysis

I. INTRODUCTION

The nano-indentation is an experiment for testing properties for coating and film and finite element method has been used in such research, for example [1]. Part of the objectives of the current project [2, 3] was specified as:

1) Testing for plate with only 316 Stainless Steel was simulated with FE, comparing with the result of experiment in nano-indentation in order to validate the correctness and accuracy of the FE analysis;

2) Determination the Modulus of Elasticity for specific ceramics coated 316 stainless steel, comparing with the result of experiment in nano-indentation;

3) Investigation the influence coating thickness on the force-indentation depth.

This paper reported the research work in order achieving the above objectives including the background information, the FE model developed and a series of case study.

II. BACKGROUND INFORMATION

Stainless Steel: The property of stainless steel at room temperature is shown in Table 1 and Figure 1.

Table 1 Basic Property of Stainless Steel [4]

<table>
<thead>
<tr>
<th>Modulus of Elasticity</th>
<th>Poisson Ratio</th>
<th>Yield Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>193GPa</td>
<td>0.263</td>
<td>300MPa</td>
</tr>
</tbody>
</table>

Figure 1: Relationship between stress and strain [5]

Indenter: The indenter was diamond. The geometry of the indenter was shown in Figure 1: Geometry of Indenter; the properties of the diamond was shown by Table 2: Synthetic diamonds values.

Table 2. Synthetic Diamonds Property

<table>
<thead>
<tr>
<th>Young’s Modules</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1220 GPa</td>
<td>0.2</td>
</tr>
</tbody>
</table>

It is understood that the ceramic material is of brittle fracture nature and it is idealized as rigid plasticity for simplification and due to the limit of the I-DEAS software [6]. The base material stainless steel is modeled as elastic-plasticity accurately. It is also assumed no friction between the coating and indenter tip.
The FE analyses were organized as:

1) **Validating FE Model**

Experimental nano-indentation test data of 316 stainless steel obtained from an industrial funded research project at Teesside University was used for validating the FE model developed.

2) **Determination of the value of Modulus of Elasticity for the coating material**

A series of trial and error FE analysis were conducted with varying Young’s modules of coating material. The FE obtained displacement and force relationship were used to determine the range of the Modulus of Elasticity through comparison with experimental data.

3) **Influence of coating thickness**

A series of FE analysis with varying thickness of coating was conducted in order to obtain the quantitative results of its influence on the force-indentation depth.

### III. RESULTS

#### 3.1 Validating FE Model

The main aim was to validate the method of finite element techniques for the investigation of the nano-indentation test through the comparison of the predicted and the experimental force-depth relationship of 316 Stainless Steel. The FE model developed is illustrated in Figure 3.

The solution of model was illustrated as Fig. 3: the Model of Nano-indentation for 316 Stainless Steel. From this Figure, it was known that the maximum stress was at the top and it is contact stress, which was brought by the indenter.

Through the comparison of the FE prediction and experimental measurement shown in Figure 4, it is clearly that the FE prediction agrees very well with experimental data which confirms that the correctness and the accuracy of the FE model developed.

#### 3.2 Determination of the Modulus of Elasticity for specific coated 316 stainless steel

<table>
<thead>
<tr>
<th>Depth (nm)</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td></td>
</tr>
<tr>
<td>450</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td></td>
</tr>
<tr>
<td>750</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3 The FE Model and stress distribution

Table 3: The FE prediction of force and displacement during indenting pure stainless steel

Figure 4 Comparison of FE predicted and experimental measured force-indentation depth relationship

Figure 5 The FE Model and Contact of Top surface
Table 4 Trial values for the lower and upper limit of E

<table>
<thead>
<tr>
<th>Lower Limit E</th>
<th>4.5GPa</th>
<th>5GPa</th>
<th>5.5GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limit</td>
<td>55GPa</td>
<td>60GPa</td>
<td>62GPa</td>
</tr>
</tbody>
</table>

Figure 6 The load vs indentation depth with Modulus of Elasticity of 5 GPa and 60 GPa

The FE model developed for this investigation and the top contact area are shown in Fig. 5. Fig. 6 shows the indentation depths for a given load assuming the coating material with E of 5 GPa and 60 GPa, which corresponded to the upper and lower limit of experimental observation. Fig. 7 shows the force indentation depth relationship during the whole indentation process, which clearly demonstrated a very good agreement between the FE prediction and experimental observation.

3.3 Influence of coating thickness

Three coating thickness were chosen, namely, 4, 5, and 6 and the two values of E (5 GPa and 60 GPa) were used in the FE analysis. The typical FE Model is shown in Fig. 8 and the results are shown in Fig 9.

It is interesting to note from Fig. 9 that the thickness seems no significant influence on the force-indentation depth. This is supported by the fact observed from the Fig. 10, Fig. 11, Fig. 13 that the deformation under the tip of indenter is very localized within the coating, further increase of its thickness would not affect the relationship.

Figure 8 Typical FE Model

Figure 9 The effect of thickness on the force-displacement relationship: , , and for 4, 5, and 6 respectively

Figure 10a Effective Strain Distribution for Coating with 4μm Thickness and 5GPa Modulus of Elasticity
Figure 10b Effective Stress Distribution for Coating with 4μm Thickness and 5GPa Modulus of Elasticity

Figure 11a Effective Strain Distribution for Coating with 5μm Thickness and 5GPa Modulus of Elasticity

Figure 11b Effective Stress Distribution for Coating with 5μm Thickness and 5GPa Modulus of Elasticity

Figure 12a Effective Strain Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity

Figure 12b Effective Stress Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity

Figure 13a Effective Strain Distribution for Coating with 6μm Thickness and 5GPa Modulus of Elasticity
IV. CONCLUSION

The overall conclusions are:

1) The FE analysis based on contact and elastic-plasticity model is reasonably accurate to depict the force-indentation depth;
2) The use of such FE model has been successfully used to determine the lower and upper limit of $E$ for coating material;
3) It was revealed that when the coating thickness is in the order of 4 to 6 μm, the thickness of coating has not significant influence on the force-indentation relationship. It is suggested that there is a lower bound for coating thickness which has practical significance in developing coated functional material.

V. REFERENCES

[6] I-DEAS