Optimization of the effect of indentation Load and dwell Time on Micro hardness values using Fuzzy logic predictive model

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Abstract. Nimonic 80A and Nimonic 90 belong to the family of nickel based super alloys and are widely used in high temperature applications. In this study, the effect of indentation load (10 to1000 gf) and dwell time (3 to 15 s) on the micro-hardness of Nimonic 80A and Nimonic 90 are investigated. A fuzzy logic predictive model is established to predict the micro hardness with respect to changes in the input parameters of indentation load and dwell time. The experimental results show a good degree of agreement with the fuzzy logic model, for both Nimonic 80A and Nimonic 90 with a minimum error percentage of 3.05 and 1.80 respectively.

1. Introduction

Micro indentation hardness testing is an important method, performed to study the mechanical property. Micro indentation hardness plays a significant role in wear control of metallic components, higher the micro hardness of material better is wear resistance and vice versa [1,10]. Various research studies have been conducted for determining the HV values of various materials [1-6]. The HV depends upon various material characteristics, which can be attributed to elastic recovery or the visco-elastic nature, the grain size effect, indentation cracks, surface texture, or diagonal measurement errors [7-9]. Micro hardness indentation method has been also used to determine the fracture toughness of various materials [1-13].

For calculating HV, indentation load from 1 to 3000 gf is used, depending upon the hardness of the materials [1-11]. For soft materials, metals, composites etc., smaller indentation load in the range of 1 to 300 gf is used and for hard materials, ceramics, super alloys indentation load in the range of 300 to 3000 gf is used with a dwell time of 5 to 15 s. It is evident from literature review that HV varies with indentation load and dwell time [1-11]. The Nimonic series of super alloys possess superior high temperature creep resistance, wear resistance, and oxidation resistance, high strength, high toughness at elevated temperature and low thermal diffusivity [12,13]. Hence for investigating, predicting and optimizing the results for Nimonic 80A and Nimonic 90, a computing tool like fuzzy logic model is used which plays a significant role in the prediction of results for input-output parameter relationship. Various researchers have used fuzzy logic modeling for the optimization of multiple responses to minimize the error in the approximation of data obtained from experiments [14-17]. The hardness of the materials Nimonic 80A and 21-4N was higher in comparison to the ductile iron GGG-40, under dry sliding conditions, at temperatures ranging from 50 oC to 500 oC [21]. Fuzzy based desirability function to optimize surface roughness and micro hardness has been performed [22].

In this research work, HV values of Nimonic 80A and Nimonic 90 are measured at different indentation load and dwell time (3 s, 5 s, 8 s etc). An approach in predicting the micro hardness with respect to indentation load and dwell time of Nimonic 80A and Nimonic 90, using fuzzy logic predictive model is implemented. The predicted results achieved via fuzzy logic model are compared to the experimental result. This paper applies the fuzzy logic to develop the rule model in order to predict the micro hardness performance of Nimonic 80A & 90 based on parameter and performance interaction.
2. Experimental

2.1. Materials
The details of Nimonic 80A and Nimonic 90 materials are reported elsewhere [18]. Standard polishing method was used to polish the samples before the indentation tests.

2.2. Characterization
Scanning Electron microscopy (SEM) and Energy Dispersive X-ray analysis (EDX) studies have already been reported [18].

2.3. Vickers Hardness HV test
In this research work, HV values of super alloys Nimonic 80A and Nimonic 90 were measured using a micro hardness tester (INNOVATEST FALCON 500XL). For calculating HV, indentation loads 10 to 1000 gf were applied and indentation was caused for dwell time of (3 s, 5 s, 8 s, 10 s, 12 s and 15 s). Each test was conducted minimum three times for repeatability. After indentation, the length of both diagonals of each indentation and depth of indentation was immediately measured by optical microscopy (LEICA CTR 6000) and surface Profilometer (Rtec) with a magnification of 50X.

3. Results and discussion

3.1. Study of Micro hardness
The HV values obtained after indentation are shown in Figure 1 and Figure 2. It is evident from Figure 1 that average HV values of Nimonic 80A vary from 6.411-4.285 GPa, 5.664-4.077 GPa, 5.686-4.265 GPa, 5.878-4.176 GPa, 6.222-4.312 GPa and 6.239-4.176 GPa at dwell time of 3 s, 5 s, 8 s, 10 s, 12 s and 15 s, respectively with indentation load (10 to 1000 gf). The average HV values of 5.366-4.271 GPa, 5.765-4.476 GPa, 6.005-4.499 GPa, 6.187-4.335 GPa, 6.028-4.292 GPa and 5.80-4.394 GPa at dwell time of 3 s, 5 s, 8 s, 10 s, 12 s and 15 s, respectively with indentation load (10 to 1000 gf) are obtained for Nimonic 90 as shown in Figure 2. It is clear from Figure 1 and Figure 2 that HV values decrease with the increase in indentation load. The HV values of Nimonic 80A vary from 4.855-5.386 GPa, 4.532-4.812 GPa and 4.077-4.312 GPa at specific indentation load 50 g, 200 g and 1000 gf with dwell time (3 to 15 s) is shown in Figure 3. The HV values of Nimonic 90 vary from 4.896-5.253 GPa, 4.699-4.939 GPa and 4.271-4.499 GPa at an indentation load 50 g, 200 g and 1000 gf with dwell time (3 to 15 s) is shown in Figure 4. It is clear from Figure 3 and Figure 4 that the values of HV do not exhibit a definite trend with the increase in dwell time. Multiple comparisons of HV values reveals that HV value at a particular dwell time differs from other dwell time for indentation load (10 to 1000 gf). It is also evident from Figure 3 and Figure 4 that the average HV values of Nimonic 80A and Nimonic 90 at a particular dwell time of 3 s differ from the average values of HV obtained at dwell times of 5 s, 8 s, 10 s etc. It is clear that values of HV are influenced by indentation load and dwell time to large extent.

![Figure 1.](image1.png) **Figure 1.** Average Vickers hardness values versus indentation load of Nimonic 80A at different dwell time.

![Figure 2.](image2.png) **Figure 2.** Average Vickers hardness values versus indentation load of Nimonic 90 at different dwell time.
Figure 3. Average Vickers hardness values of Nimonic 80A with respect to indentation time at different indentation load.

Figure 4. Average Vickers hardness values of Nimonic 90 with respect to indentation time at different indentation load.

The effect of indentation size effect (ISE) on HV is shown in Figure 5. It is evident from Figure 5 that with the increase in indentation load at specific dwell time, the indenter impression increases. At indentation load 1000 gf, plastic deformation of the material has been observed for Nimonic 80A and Nimonic 90 (blue circle). The effect of ISE on HV is also depicted in Figure 1, Figure 2 and Figure 5. The diagonal values of indentation size increase with the increase of indentation load which results in decrease of HV values. The effect of ISE on HV values of various materials is also reported in [10-11]. In these research studies it has been observed that there are two types of indentation size effect; normal ISE and reverse ISE. Normal indentation size effect revealed that decrease of micro hardness with the increase of indentation load and reverse indentation size effect exhibits that increase of micro hardness with increase of indentation load.

3D images of Vickers indentation were obtained using 3D surface profilometer to measure surface roughness (Ra) and depth of indentation (Rv) and to understand their influence on HV values for both Nimonic 80A and Nimonic 90. The Rv, Rm and HV values Nimonic 80A and Nimonic 90 is given in Table 1. 3D profilometer images of indentation are shown in Figures 6-11. It is clear from Figure 6 that the maximum value of Rv (0.228 µm) and Rm (0.734 µm) of Nimonic 80A is obtained at 8s with lowest value of HV (4.855 GPa) under applied load of 50 g. Therefore, lower the values of Rv and Rm, higher is the value of HV and vice-versa. Similar, results of Rv and Rm and HV values are obtained at higher indentation load of 1000 gf for Nimonic 80A as shown in Figure 7. Also, the maximum value of Rv (0.230 µm) and Rm (0.740 µm) is obtained at 10s with lowest value of HV (4.070 GPa) under applied load of 1000 gf (as given in Table 1). Figure 8 shows Rv and Rm at dwell time of 10 s for Nimonic 80A at indentation load of 50 g, 200 g and 1000 gf. It is clear from Figure 8 and Table 2 that Rv and Rm increase with increase in indentation load with the decrease in the HV values. The maximum value of Rv (0.230 µm) and Rm (0.740 µm) are obtained under applied load of 1000 gf with lowest value of HV (4.070 GPa) at dwell time of 10 s as shown in Table 2.

Figure 5. Optical image of indent impression at different load and dwell time.

(a)

(b)
Figure 6. 3D Profilometer images of Nimonic 80A for indentation load of 50 g at different dwell time (a) 3 s, (b) 8 s, and (c) 15 s.

Figure 7. 3D Profilometer images of Nimonic 80A for indentation load of 1000 gf at different dwell time (a) 3 s, (b) 10 s, and (c) 15 s.

Figure 8. 3D Profilometer images of Nimonic 80A for dwell time of 10 s at different indentation load (a)50 g, (b) 200 g, and (c) 1000 gf.
Figure 9. 3D Profilometer images of Nimonic 90 for indentation load of 50 g at different dwell time (a) 3 s, (b) 10 s, and (c) 15 s.

Figure 10. 3D Profilometer images of Nimonic 90 for indentation load of 1000 gf at different dwell time 3 s, (b) 10 s, and (c) 15 s.
Figure 11. 3D Profilometer images of Nimonic 90 for dwell time 10 s at different indentation loads (a) 50 g, (b) 200 g, and (c) 1000 gf.

Figure 9 shows \( R_a \) and \( R_v \) of Nimonic 90 for lower indentation load of 50 g at dwell time of 3 s, 10 s and 15 s. It is clear from Fig 10 that the maximum value of \( R_a \) (0.170 \( \mu \)m) and \( R_v \) (0.650 \( \mu \)m) are obtained at 15 s with lowest value of \( H_v \) (4.896 GPa) under applied load of 50 g. Therefore, higher the value of \( R_a \) and \( R_v \), lower is the value of \( H_v \) and vice-versa. Similar, results of \( R_a \), \( R_v \) and \( H_v \) values are obtained at higher indentation load of 1000 gf for Nimonic 90 as shown in Figure 10. The maximum value of \( R_a \) (0.223 \( \mu \)m) and \( R_v \) (0.850 \( \mu \)m) are obtained at 3s with lowest value of \( H_v \) (4.271 GPa) under applied load of 1000 gf (as specified in Table 1). Figure 11 shows \( R_a \) and \( R_v \) at dwell time of 10 s for Nimonic 90 at indentation load of 50 g, 200 g and 1000 gf. It is evident from Figure 11 and Table 2 that \( R_a \) and \( R_v \) increases with increase in indentation load with the decrease in the \( H_v \) values. The maximum value of \( R_a \) (0.180 \( \mu \)m) and \( R_v \) (0.680 \( \mu \)m) are obtained under applied load of 1000 gf with lowest value of \( H_v \) (4.335 GPa) at dwell time of 10 s as shown in Table 2.

Table 1. The \( R_a \), \( R_v \), and \( H_v \) values of Nimonic 80A and Nimonic 90 at different indentation load and dwell time.

| Materials  | Indentation load (g) | Dwell time (s) | \( R_a \) (\( \mu \)m) | \( R_v \) (\( \mu \)m) | \( H_v \) (GPa) |
|------------|---------------------|----------------|---------------------|---------------------|----------------|
| Nimonic 80A | 50                  | 3              | 0.087               | 0.370               | 5.386          |
|            | 50                  | 8              | 0.228               | 0.734               | 4.855          |
|            | 1000                | 3              | 0.110               | 0.549               | 4.285          |
|            | 1000                | 10             | 0.230               | 0.740               | 4.070          |
|            | 1000                | 15             | 0.210               | 0.713               | 4.176          |
| Nimonic 90 | 50                  | 3              | 0.041               | 0.118               | 5.096          |
|            | 50                  | 10             | 0.112               | 0.537               | 5.021          |
|            | 50                  | 15             | 0.170               | 0.650               | 4.896          |
|            | 1000                | 3              | 0.223               | 0.850               | 4.271          |
|            | 1000                | 10             | 0.180               | 0.680               | 4.335          |
|            | 1000                | 15             | 0.200               | 0.808               | 4.394          |

Table 2. The \( R_a \), \( R_v \), and \( H_v \) values of Nimonic 80A and Nimonic 90 at dwell time of 10 s for different indentation load.

| Materials  | Indentation load (g) | \( R_a \) (\( \mu \)m) | \( R_v \) (\( \mu \)m) | \( H_v \) (GPa) |
|------------|---------------------|---------------------|---------------------|----------------|
| Nimonic 80A | 50                  | 0.210               | 0.622               | 5.138          |
|            | 200                 | 0.210               | 0.647               | 4.532          |
|            | 1000                | 0.230               | 0.740               | 4.070          |
| Nimonic 90 | 50                  | 0.112               | 0.537               | 5.021          |
|            | 200                 | 0.146               | 0.560               | 4.834          |
|            | 1000                | 0.180               | 0.680               | 4.335          |
The variation of $H_V$ with respect to indentation load revealed that $H_V$ values decrease with increase in indentation load, however, the values of $H_V$ with respect to dwell time exhibits marginal variation with increase in dwell time. The values of $R_a$ and $R_v$ increase with increase in indentation load. However, the values of $R_a$ and $R_v$ do not exhibit a definite trend with respect to dwell time. Also the variation of $H_V$ with respect to dwell time exhibits that $H_V$ values show very slight variation with respect to dwell time. The values of $R_a$ and $R_v$ with respect to dwell time do not follow any definite trend that is why researchers had been focusing on indentation load for better study of HV. It is evident from above that different values of $H_V$ have been obtained at different indentation load and dwell time. The optimal value of HV is not available from these values. In order to obtain optimal value of HV for both Nimonic 80A and Nimonic 90, fuzzy logic model is developed.

3.2. Study of Micro hardness

The most important two types of fuzzy inference methods are Mamdani and Sugeno fuzzy inference [19,20]. Mamdani fuzzy inference is the most commonly used inference method. Mamdani fuzzy inference consists of fuzzification interface, membership functions, fuzzy based rule and defuzzification interface. In the present model, first of all fuzzification of input parameters (indentation load and dwell time) is carried out. The relationship between input and output parameters is referred to the fuzzy based rule construction. Optimization of this research work is based on two input parameters (indentation load and dwell time) and one output parameter (HV values). Table 3 shows fuzzy linguistic variables and range for input and output parameters. The input and output parameters of Fuzzy logic modeling are shown in Figure 12. Graphical representation of input and output membership functions are shown in Figure 13. There are five membership functions which are employed for each input and output variable, i.e., input variable (very low, low, medium, high, very high) and output variable (very low, low, medium, high, very high), as shown in Table 3.

| Parameters | Linguistics variables | Range |
|------------|-----------------------|-------|
| Inputs:    |                       |       |
| A- Load (g)| Very low, low, medium, high, very high | 5 – 1000 |
| B- Time (s)| Very low, low, medium, high, very high | 2 – 16 |
| Output:    |                       |       |
| C- Hardness Nimonic 80A (GPa) | Very low, low, medium, high, very high | 4 – 6.6 |
| D- Hardness Nimonic 90 (GPa) | Very low, low, medium, high, very high | 4.1 – 6.2 |

A set of 42 rules were constructed based on the actual experimental data of $H_V$ for Nimonic 80A and Nimonic 90. The experimental data was simulated in Mat-lab software according to fuzzy logic Mamdani system, as follows:

Rule 1: Load is very low and time is very low then micro-hardness of Nimonic 80A is very high and micro-hardness of Nimonic 90 is medium.

Rule 2: Load is very low and time is very low then micro-hardness of Nimonic 80A is high and micro-hardness of Nimonic 90 is medium.

Rule 3: Load is very low and time is very low then micro-hardness of Nimonic 80A is medium and micro-hardness of Nimonic 90 is medium.

Rule 4: Load is very low and time is very low then micro-hardness of Nimonic 80A is medium and micro-hardness of Nimonic 90 is medium.

Rule N: Load is very high and time is very high then micro-hardness of Nimonic 80A is very low and micro-hardness of Nimonic 90 is medium.

![Figure 12. Schematic representation of fuzzy logic modeling(inputs and outputs parameters).](image-url)
Fuzzification is the conversion of an experimental value to a fuzzy quantity and defuzzification is the conversion of a fuzzy quantity to a predicted value. Researchers utilized various techniques for defuzzifying i.e., mean of maximum value, first of maximum method or last of maximum method, centroid of area, etc., [20,21]. The selected method for this model is centroid of area (COA). COA is used for their capabilities of giving more accurate results as compared to others. The resultant membership function is considering unique value of fuzzy’s rule output.

Fuzzy membership functions of A) Indentation load (g) B) Dwell time (s) are graphically represented in triangular form and C) Vickers hardness (GPa) of Nimonic 80A D) Vickers hardness (GPa) of Nimonic 90 are graphically represented in trapezoidal are shown in Fig. 13. The x axis represents the universe of discourse, whereas, y axis represents the degrees of membership in the [0, 1]. The outputs values depend upon inputs (indentation load and dwell time) parameters are shown in Fig. 14. It is evident from Fig. 14 that one of inputs parameter varies the value of output (micro hardness) changes for Nimonic 80A and Nimonic 90. This model shows the direct relationship between inputs and outputs parameters.

![Figure 13. Membership function of A) Indentation load (g) B) Dwell time (s) C) Vickers hardness (GPa) of Nimonic 80A D) Vickers hardness (GPa) of Nimonic 90.](image)

![Figure 14. Schematic representation of Fuzzy logic reasoning procedure.](image)

![Figure 15. The predicted surface hardness in relation to change of indentation load and dwell time of (a) Nimonic 80A, and (b) Nimonic 90 by fuzzy logic model.](image)
time, however, it do not show any definite trend for Nimonic 80A and Nimonic 90. Both the experimental values and the predicted values by fuzzy logic model exhibit the same behavior. At constant indentation load, the surface hardness behavior of particular dwell time 3 s differ from the surface hardness behavior obtained at dwell times of 5s, 8s, 10 s etc., for Nimonic 80A and Nimonic 90.

Figure 16. Experimental and Fuzzy logic Vickers hardness values of Nimonic 80A and Nimonic 90 at indentation load (a) 50 g, (b) 200 g, and (c) 1000 gf with indentation time.

Figure 17. Fuzzy model accuracy and error %ages values of Nimonic 80A at indentation load 50 g, 200g and 1000 gf with indentation time.

Figure 18. Fuzzy model accuracy and error % values of Nimonic 90 at indentation load 50 g, 200 g and 1000 gf with indentation time.

The behavior of all experimental values and fuzzy logic predicting values at different indentation load and dwell time are shown in Figure 16. It is clear from Figure 16 that at particular indentation load of 50 g, 200 g and 1000 gf, the differences between experimental and predicted values of HV are very small and the behaviors of HV with respect to dwell time for both values are same. It is evident from Figure 16 that predicted values are greater than experimental values and the micro hardness of material is more than the bulk hardness of that material. Fuzzy logic accuracy and error %age graphs of Nimonic 80A and Nimonic 90 with respect to indentation time at different load are shown in Figure 17 and Figure 18. It is clear from Figure 17 and Figure 18 that the minimum fuzzy error %age was observed to be 3.05; at indentation load 50 g and dwell time 10s in case of Nimonic 80A, whereas, fuzzy error %age was observed to be 1.80, at indentation load 200 g and dwell time 12 s, in case of Nimonic 90. Therefore,
optimal values of HV are 5.138 GPa and 4.939 GPa for Nimonic 80A and Nimonic 90. This paper shows that all the predicted values are very close to the experimental values. Hence using this method, fuzzy logic modeling, provides very efficient results for HV of Nimonic 80A and Nimonic 90.

4. Conclusion

In the present research work micro-hardness tests were carried out on Nimonic 80A and Nimonic 90 to study the influence of indentation load and dwell time. The important observations of the study are summarized as under:

1. The Hv values gradually decreases with increase in indentation load. At lower load of 50 g, high Hv values are obtained and at higher load of 1000 gf, low Hv value are obtained for dwell of 3 to 15 s. By gradually increasing the indentation load for Nimonic 80A and Nimonic 90, we can obtain their bulk hardness value. The values of Hv marginally vary with increase in dwell time. However, no definite trend was obtained in Hv values with respect to dwell time.

2. The Rv and Rr values increases with increase in indentation load. The Rv and Rr values shows no definite trend with respect to dwell time. Higher the value of Rv, lower is the value of Hv with respect to dwell time and vice-versa. Therefore, the values of Rv,Rr and Hv shows clear trend with respect to indentation load that is why researchers have been focusing on indentation load for better study of Hv.

3. ‘Fuzzy logic predictive model’ has proved to be an efficient method to determine most appropriate values for HV with respect to indentation load and dwell time. This mathematical model was used to achieve accurate and precise results, validated by the experimental values. The ‘minimum fuzzy error %age’ was observed to be 3.05; at indentation load 50 g and dwell time 10 s in case of Nimonic 80A, whereas, ‘fuzzy error %age’ was observed to be 1.80, at indentation load 200 g and dwell time 12 s, in case of Nimonic 90. Therefore, optimal values of HV are 5.138 GPa and 4.939 GPa for Nimonic 80A and Nimonic 90. This indicates that fuzzy logic prediction model predicted the micro hardness of Nimonic 80A and Nimonic 90 with great accuracy.

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