Determining Elastic-Plastic Material Properties Using Instrumented Indentation Test and Finite Element Simulation

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ABSTRACT

A new technique that can determine the elastic-plastic properties of metallic materials using an instrumented indentation testing and iterative finite element (FE) simulations is proposed. This non-destructive technique can be applied to isotropic, additively manufactured, and/or surface treated metallic components of various scale. Currently, the measurement of material properties using the instrumented micro- or nano- indentation test is limited to the elastic modulus and surface hardness. A number of experimental and numerical approaches have been suggested for prediction of monotonic properties of metallic materials including yield strength, strain hardening parameters, ultimate strength, and fracture toughness. However, the past efforts to measure the stress-strain behavior using a single instrumented indentation test were not successful because there is no straightforward correlation between force-displacement relation and the elastic-plastic relation. In this study, both experimental data and FE simulation are leveraged to investigate the elastic-plastic stress-strain relation through an interative approach which consists of peak load and residual displacement matching of load-displacement plots from experimental and FE simulated data. This study shows that the residual displacements give the critical information needed to determine material propertites.

Keywords: Instrumented indentation test, Finite element simulation, Elastic-plastic material properties

1 ELASTO PLASTIC MODELS

In any engineering application, one of the most important factors to consider in the selection of a material is its behavior under external excitation prior to and beyond the yield point, or elasto-plastic behavior. Since a material's plastic behavior is generally not linearly proportional to applied load, as is the case in the elastic region, generalized relationships need to be leveraged in order to sufficiently define the mechanical behavior of a material. The general practice for defining the stress-strain behavior of a material is through a monotonic stress-strain curve. This curve contains the stresses associated with each respective strain for uniaxial loading of an isotropic material. Engineers are tasked with determining an appropriate elasto-plastic material properties used in numerical analysis of a engineering system.

For metallic strain-hardening materials, the most popular method for numerical representation of elasto-plastic behavior is the Ramberg-Osgood relationship [1]. This model expresses the total strain (ε) by the sum of an expoential relation for ε_p with a linearly proportional relationship for the elastic strain (ε_e),

$$\varepsilon = \varepsilon_e + \varepsilon_p = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{\frac{1}{n}} \tag{1}$$

This relationship can also be used to effectively determine the 0.2% offset yield stress (σ_0).

$$\sigma_0 = H(0.002)^n \tag{2}$$

Thus, through leverage of the Ramberg-Osgood equation, the full elasto-plastic behavior of a material can be modelled through three parameters: the strength coefficient, the strain hardening exponent, and the Young's Modulus.

2 NANOINDENTATION FOR MATERIAL DETERMINATION

With the development on modern engineering technologies, such as nano-indentation, various methods have been inventigated for the determination of monotonic material propoerties through analysis of the load-indentation curve. Numerous methods have been proposed and accepted for the determination of Young's Modulus through nanoindentation. The most prevelent methods [2, 3] for evaluation of the elastic modulus of the indented material are able to be used in conjunction with Sneddon's relationship [4] for the deterimination of the reduced Young's modulus (E_r) and for correction of inherent experimental errors. for the deterimination of the reduced Young's modulus (E_r) and for correction of inherent experimental errors. These methods are claims that the initial unloading curve ($P > 0.9P_{max}$) can be numerically fit with a linear curve, which will have the slope of the reduced Young's Modulus, as defined by the equation [4],

$$\frac{1}{E_r} = \frac{1-\nu^2}{E} + \frac{1-\nu_i^2}{E_i} \tag{3}$$

where ν_i and E_i are the indenter's Poisson's ratio and Young's Modulus respectively, while ν and E are pertainent to the indented material. Thus, it can be stated that if the material properties as well as the Poisson's ratio of the indentor material are known, the reduced Young's modulus (as deterimined from a numeric fit to the unloading section of the curve) can be utilized to determine the Young's modulus of the indented material.

Though leveraging the initial unloading curve has become standard in determination of the Young's modulus of the indented material, methods for determination of the other two parameters which characterize the Ramberg-Osgood relation: the strength coefficient and the strain hardening exponent, have not been as readliy concluded [5-7]. Mata, Anglada, and Alcalá [7] have investigated the degree of pile-up or sink-in which occurs around the site of indentation as an ingredient in numerically caluclating the Ramberg-Osgood parameters of a material's plastic deformation behavior, while Bao and Sun [5] has been relient on the imprint area as a key parameter in the determination of key material properties.

The proposed method will suggest that the remaining two required paremeters: the strength coefficient (H) and the strain hardening coefficient (n) can be determined through an interative procedure which involves matching experimentally yielded results to results gained though finite-element simulations. The proposed method will suggest that the need for any visual post-processing (via electron microscopy) is not required, as is the case in the determination of imprint area and pile-up hight, and that the material parameters can be defined directly from an interative matching process to the experimental data.

3 PROPOSED METHODOLOGY

In the proposed methodology, the force-vs-diplacement curve obtained from an instrumented micro-indentation is iteratively matched by finite-element simulations to determine elastic-plastic material properties. This is illustrated in Figure 1, although the difference in the residual displacements are exaggerated for illustration purpose.

First, the peak of the force-displacement curve obtained from the instrumented micro-indentation (P_{max}) is to be matched by the peak of the curve obtained from the displacement controlled FE simulation ($P_{max,sim}$). The initial FE simulation will be run with assumed starting mechanical properites H_i and n_i. P_{max} will be matched through iteration solely of H, thus when the peaks are matched the iterated FE model will have been analyzed using mecahnical properties of H_{i+1} and n_i. When P_{max} is matched by $P_{max,sim}$ such that the value of ΔP_{max} is sufficiently small,

$$\Delta P_{max} = P_{max} - P_{max,sim} \tag{4}$$

it will be incredibly difficult to realize the differences in loading curves (experimental vs. simulated). However, the differences in unloading curves, especially the difference in the residual displacements (Δh_f), is quantifiable.

$$\Delta h_f = h_f - h_{f,sim} \tag{5}$$

The differences in the residual displacements are very small compared to the magnitude of maximum displacement (h_{max}), but it provides sufficient information to adjust plastic material properties in a similar fashion described above for the strength coefficient.

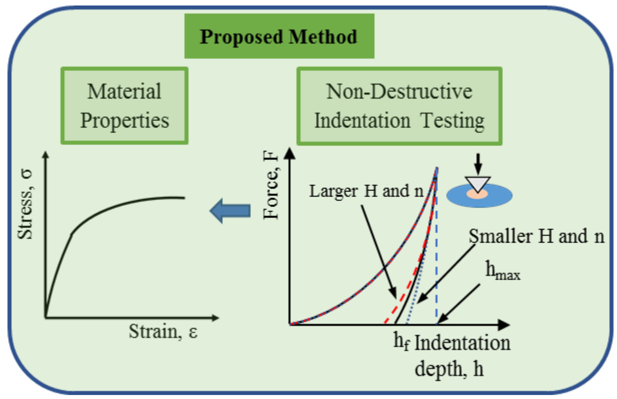

Figure 1 Schematic illustration of proposed method: instrumented indentation test data (black) and iterative finite-element simulations (red and blue).

An identical iteration procedure as described for the strength coefficeint is used to match the residual displacements for minimization of Δh_f. When the residual displacements are matched the iterated FE model will have been analyzed using mecahnical properties of H_{i+1} and n_{i+1}. Once residual displacements are matched, the entire process will need to be repeated to minimize both ΔP_{max} and Δh_f. The simulated material properties with acceptable ΔP_{max} and Δh_f will be taken to be the material properties of the indented material. The algorithm to determine material properties using a loading/unloading force-displacement curve and finite element simulations is illustrated in Figure 2. The developed technique in this study can be used for product design and fast prototyping with confidence in the understanding of material behavior.

3 RESULTS

In order to proove the validity of this approach numerical experiments have been performed, meaning that the 'experimental data' described in the above methodology is simply a numerical simulation performed with known material properties. The initial, or master, material properties

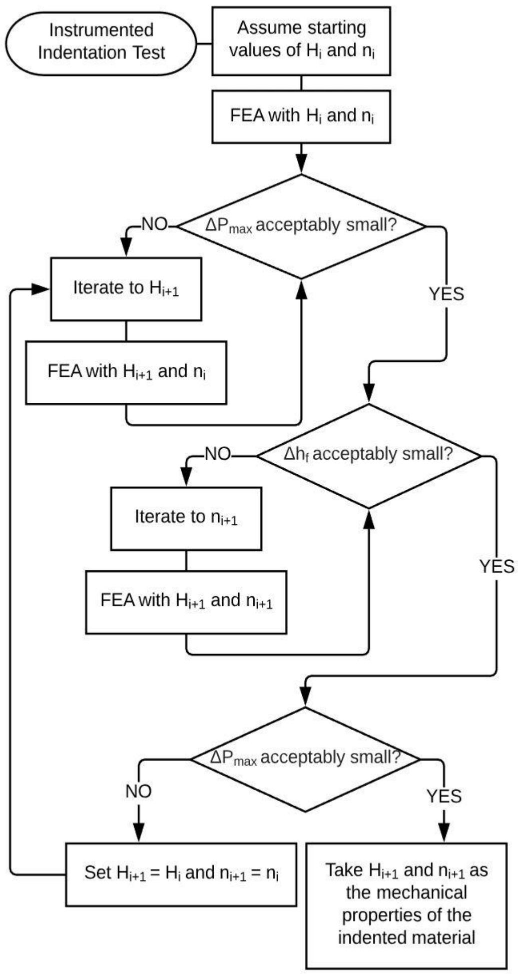

Figure 2 Flow chart algorithem for determination of the material properties of metallic components

were selected to represent AISI 1020 steel and have the values of: $E = 203\ GPa$, $H = 737\ MPa$, and $n = 0.19$ [8]. The axissymmetric FE model was constructed using the commercially availible ABAQUS software and has overall dimensions of 250 x 250 micron. The 2D deformable indented material mesh contains 23,063 CAX4R type elements while the rigid indentor contains 105 RAX2 elements. A structured mesh region was modelled to be large enough to contain the entire plastic contact zone for a maximum indentation depth of 2.5 micron. Frictionless tangential contact between the indentor and the indented material was assumed and the indentor tip was modeled using a 70.3° interior angle to accurately represent the behavior of a Berkovich indentor in the 2D modelling space [9].

The research was performed in order to determine the effect that changing the two input parameters, H and n, would have on a the output load-vs-displacment curve of the FE simulation. These results were compared to the numerically simulated results for the AISI 1020 steel with material properties as shown in Table 1. Among many others, the two additional cases and an example of each iteration are shown in Table 1.

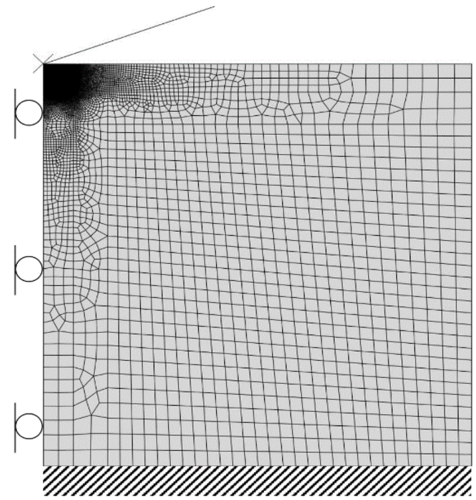

Figure 3 Mesh and boundary conditions for FE model

Table 1. Each run and correspoinding material properties.

	AISI 1020	Iter. 1	Case 1	Iter. 2	Case 2
$E\ (GPa)$	203	203	203	203	203
ν	0.29	0.29	0.29	0.29	0.29
$H\ (MPa)$	737	850	810	810	700
n	0.19	0.22	0.22	0.18	0.18

It is evident form the experimental results that the peak of the load vs displacement curve is not unique to a single pair of input parameters but can rather be matched by a number of combinations of H and n sharing a common Young's modulus and Poisson's ratio. In this research, the residual displacemnts of the load-vs-displacement curve are used an additional information to adjust material properties, as shown in Figure 4.

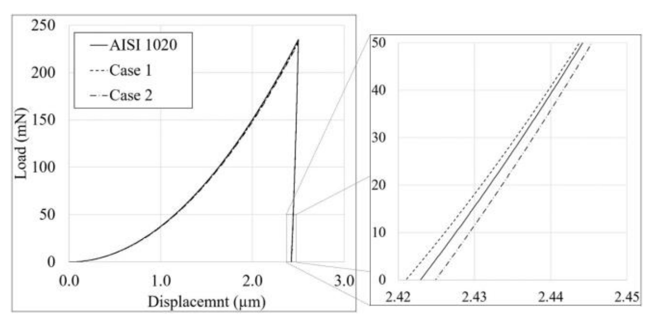

Figure 4 Simulated load vs. displacement curves with magnified residual displacement effects

When a simulated material has a higher H and n value than the properties of AISI 1020 steel, and the values of P_{max} are matched, this the residual displacement will be less than that of the AISI 1020 steel such that $h_{f,sim} < h_f$. In addition, then the simulated material has a lower H and n value than the properties of AISI 1020 steel, and the values of P_{max} are matched, the resiual displacement will be greater than that of the AISI 1020 such that $h_{f,sim} > h_f$. This indicates that in order to use FE simulated P-h curves for determination of experimental monotonic material properties, H and n, than the parameter that must be considered in the adjustment of the material properties is the residual displacemnt.

Although the framwork is prooving to be a very promising method for relieable and non-destructive determination of key material parameters, one instance that needs to be further investigated is the influence of the grain structure. Figure 5 shows scatter in insturmented indentation test data on E8620 steel. Because of the localized responses of the instrumented micro- or nano- indentation, the experimental data is depended on the grain structure on intened area.

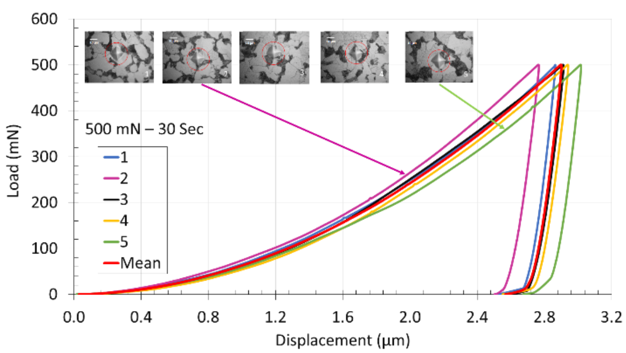

Figure 5 Scatter in instrumented indentation tests on E8620 steel

CONCLUSION

A promising new iterative technique is proposed which can determine the elastic-plastic properties of metallic materials using a dual approch of instrumented indentation testing and finite element (FE) simulation. This methodology promises to leverage cutting-edge, non-destructive nano-indentation techniques and can be expanded to be applied to isotropic, additively manufactured, and surface treated metallic components. This proposed methodology will allow for quick, and reliable determiation of material properties, such as strength coefficient and strain hardening exponent, which are currently unachievable through nano-indentation techniqes without the application of costly and labor intensive microscopy procedures. In this proposed methodology, both experimental data and FE simulation are leveraged to investigate the elastic-plastic stress-strain relation through an interative approach which consists of peak load and residual displacement matching of load-displacement plots from experimental and FE simulated data. Further research will include in-depth investigations into the effects of the grain structures of the indented materials, as well as how the iterative process can be miminized.

In closing, the methodology in this research proposed that it is possible to determine the three key paremters of the Ramberg-Osgood equation; H, n, and E, through simple non-destructive nano-indentation techniques which will allow engineers a new approach to material property determination which is nowadays unachievable due to the restrictions of detructive testing and labor-intensive surface processing techniques.

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