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Finite element analysis of stress distribution during metal cold working under the assumption of plasticity and elasticity

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Abstract
Finite Element Analysis (FEA) is a powerful tool for understanding stress distribution in metal cold working processes, particularly under the assumption of plastic and elastic behaviours. This study investigates the stress distribution in metal cold working processes using finite element analysis (FEA), incorporating the effects of material plasticity, material elasticity, tangent modulus, and temperature. The primary objective is to quantitatively assess how variations in tangent modulus (E_t) and temperature (T) influence stress distribution during cold working. A series of simulations were performed using ANSYS mechanical, a commercial finite element software, to model the cold working process on the roller and workpiece. The geometries of the steel roller and rectangular aluminium billet were modelled in ANSYS SpaceClaim while the solution was interfaced and calculated in ANSYS mechanical. Coupled thermal and structural analyses were preformed and the solution algorithms were based on finite element codes. The tangent modulus, a critical parameter influencing plastic deformation, was varied across five levels under the assumption of plasticity; 500 MPa, 750 MPa, 1000 MPa, 1250 MPa, and 1500 MPa. Additionally, the temperature was varied at three levels: 250°C, 300°C, and 350°C to elucidate the influence of temperature during secondary manufacturing process such as metal forming by rolling. These temperature variations were chosen to represent typical preheating conditions used to enhance ductility during cold forming. The material properties, including Young's modulus and Poisson's ratio, were set to 71000MPa and 0.33, respectively. The yield stress was initially set to 280MPa to represent the onset of plastic deformation. The FEA results revealed that Increasing the tangent modulus leads to a more constrained plastic flow, resulting in higher stress concentrations at critical deformation zones. Specifically, a 500 MPa increase in E_t (from 500 MPa to 1000 MPa) resulted in a 15-20% increase in maximum stress values within the deformation zone. Temperature increment from 250°C to 350°C showed a reduction in both the yield and ultimate tensile strength, with ductility improving with increasing temperature. For instance, increasing the temperature to 300°C resulted in ductility measured at over 17% without tensile fracture. These findings offer valuable insights into optimizing cold working processes by carefully selecting the tangent modulus and temperature to achieve desired stress distributions and material flow, which are essential for preventing defects and improving component performance in industrial applications.

Keywords: Finite element analysis; Stress distribution; Cold working; Plastic deformation; Residual stress

1. Introduction

Cold working is a fundamental process in metal forming where plastic deformation occurs below the recrystallization temperature of the material. The intricate relationships between tool shape, material characteristics, and friction conditions cause non-uniform stress distributions in all cold working operations, including rolling, forging, extrusion, and wire drawing. The distribution of stress throughout these processes has a major impact on the metal's ultimate characteristics, including microstructural development, residual stress, and strain hardening. Building accurate Finite Element Analysis (FEA) models requires a solid understanding of the mechanical characteristics of metals during cold working (Hosford & Caddell, 2011).

FEA is a numerical technique for solving complex engineering problems involving the behaviour of materials under external loads. With FEA, a complicated geometry is discretized into smaller, finite elements that are each subject to a set of equations based on boundary conditions and the characteristics of the material. The effectiveness of FEA in cold working is dependent on a number of variables, including element type, mesh density, boundary conditions, and precise material modelling (Dixit & Dixit 2008).

Since the 1980s, computer simulation has gained credibility and acceptance in the metal forming sector. Three modelling scales are available for metal forming study (Kopp et al., 1988). The global modelling scale is the first one, and it just forecasts work or process loads. Analytical techniques are applied in this context. Temperature, strain, and strain rate are examples of thermo-mechanical variables that may be estimated using local scale analysis.

Because it can simulate the intricate geometries of tools and components in forming operations, among other approaches, the Finite Element approaches are frequently employed in metal forming analysis (Button and Roque 2000). FEA has emerged as a powerful computational tool to predict stress, strain, and deformation patterns in cold worked metals; as a result, understanding the stress distribution within the material is crucial to the improvement of mechanical strength and hardness of metals through these processes. FEA offers a potent computational tool for modelling intricate metal forming procedures, enabling a thorough comprehension of stress distribution and deformation behaviour. This skill is critical to the optimization of cold working processes, which include deep drawing, extrusion, and forging, where exact control over material characteristics is necessary to produce components of superior quality. FEA helps minimize flaws like fractures and dimensional errors by properly elucidating how materials behave under various situations. This can result in considerable cost savings and increased product dependability (Khaleed et al., 2014) (Liu et al., 2022c).

The purpose of this study Is to investigate how FEA may be used to model and analyse a variety of cold working processes, including deep drawing, extrusion, and cold forging. The research will concentrate on precisely forecasting stress distribution and material flow during these processes by applying cutting-edge computer techniques. This involves creating models that can replicate particular processes, such upsetting or ring compression tests, which are essential for producing parts with exact mechanical characteristics and geometries (Button & Roque, 2000b).

Examining the behaviour of the material under various loading scenarios is a crucial component of the study. The study will investigate how specimen shape, aspect ratio, and friction affect deformation properties and stress distribution. The goal of the study is to offer insights into improving process parameters for improved performance and lower failure rates by examining the performance of these parameters. For a number of reasons, FEA is economically significant in comprehending the distribution of stress during metal cold working procedures.

Using FEA to optimize processes like cold forging and deep drawing helps manufacturers to save costs considerably. Manufacturers may reduce wasteful material use and manufacturing costs by forecasting stress distribution, deformation and prolonged tool life. Furthermore, FEA lowers the amount of final product defects like cracks or dimensional inaccuracies, which lowers the need for rework and scrap, both of which are essential for sustaining profitability in cutthroat markets (Khaleed et al., 2014).

2. Materials and Methods

2.1 Materials

The materials for this study are mainly computer hardware and software. It entails intricate coupling between advanced engineering software and sophisticated computer capabilities. The materials include ANSYS Mechanical which is finite element-based software, ANSYS SpaceClaim for modelling the geometries. These solution software are widely utilized across various industries, including aerospace, automotive, biomedical, and defence, to enhance product design and testing processes. Another crucial software that was used in this study is the ANSYS workbench. It houses several analysis systems such as thermal systems, structural systems, explicit dynamics, magnetic systems and so many others. ANSYS workbench has the capacity to couple various systems such as thermal and structural in a single investigation. The hardware used in this study is a high-performance computer system with a RAM of 16GB, base speed of 2.8GHz, multi-core (core-i7) CPU, 11th generation and a dedicated GPU for efficient simulations. Other materials for the analysis include the modelled rectangular aluminium billet used as the work piece. Aluminium alloy was chosen due to its favourable properties for cold working, including good ductility and formability. The tool material used to simulate the rollers in the metal forming process is spherical cold worked die steel. The steel is hardened to minimize friction and tool wear during the deformation process and encourage defined properties to simulate realistic tool behaviour.

2.2 Methodology

Launch ANSYS workbench. Set units to metric (Kg, mm, s, C, mA, N, mV). Drag and drop static structural from the systems toolbox into the project schematics environment. A static structural project table will appear. Double-click on the engineering data cell to set the materials and their properties for the analyses. The engineering data tab opens up. Select aluminium alloy from the general materials library. Drag and drop Isotropic elasticity and density from the toolbox into the aluminium alloy.

Then input the values as follows:

Density = $2.77E - 6\ Kg\ mm^{-3}$
Young's Modulus = $71{,}000\ MPa$
Poisson's Ratio = 0.33

To create another variant of the aluminium alloy material that should have a plastic property, right-click on aluminium in the engineering data tab and select Duplicate to create aluminium alloy 2. Then drag and drop bilinear isotropic hardening from the toolbox into aluminium alloy 2. Edit the values as follows:

Yield strength = $280\ MPa$
Tangent modulus= $500\ MPa$

In the project schematics right-click on the geometry cell and select import model to insert the roller and plate geometry**.** Double-click on the model cell to automatically open up the roller and plate objects in ANSYS Mechanical. Now in ANSYS mechanical, in the project outline tool box, expand geometry and browse the geometry directory. Open the model setup, leave the roller material to be structural steel and set the workpiece to be aluminium alloy. Set the roller to rigid body and change the rectangular aluminium alloy to be flexible body. Click on mesh and set global mesh size to 25mm. Then generate mesh.

2.3 Structural loads and boundary conditions

Right-click on static structural and select insert to input remote displacement. Select and apply the roller's face as the geometry for remote displacement and input other settings values. Right-click on static structural again and select insert to insert displacement. Select and apply the bottom face of the plate as the geometry and set its Y-Component to zero to restrict movement in this direction. Right-click on static structural again and select insert to insert displacement. Select and apply the right-side face of the plate as the geometry and set its Z-Component to zero to restrict movement in this direction. Right-click on static structural again and click insert to insert displacement. Select and apply the end face of the plate as the geometry and set its X-Component to zero to restrict movement in this direction. Right-click on the solution and select insert to insert Total Deformation. Repeat the same to insert equivalent elastic strain (von misses) and equivalent stress (von misses). Click on solve to generate the solution. This Result shows the deformation of the plate, exhibiting elastic characteristics.

To observe a result with plastic properties, right-click on static structural project A in ANSYS workbench project schematic and select duplicate. We can rename project A as "without plasticity" and Project B as "with plasticity". Double click on the model cell in project B to open up the analysis in ANSYS Mechanical. Then assign the aluminium Alloy 2 (which has bilinear isotropic Hardening, a plastic property) as the material for the plate geometry. Now click solve again to regenerate a solution with this new analysis setting This Result shows the deformation of the plate, exhibiting plastic characteristics. Repeat the duplication step six more times and resolve varying the tangent modulus value in the engineering data tab from 500MPa to 1500MPa to see the changes in behaviour for each instance. Finally, we apply a thermal condition to the flexible body workpiece for both with plasticity and without plasticity. Each for temperature values of 250 ^{0}C, 300 ^{0}C, and 350 ^{0}C consecutively.

3.0 Result and Discussion

3.1 Simulation of rolling process under the condition of plasticity

By incorporating plasticity, FEA models can more accurately simulate the stresses and strains during and after plastic deformation (Zienkiewicz et al., 2005). These models give a realistic depiction of how metals behave during cold working by taking strain hardening into consideration and adhering to non-linear stress-strain relationships. Plasticity-included models are more effective in predicting residual stresses, which are important in determining the final characteristics of cold-worked metals. (Witek & Milenin, 2017) and (Hill, 1998).

The tangent modulus, a critical parameter influencing plastic deformation, under the assumption of plasticity was varied across five levels; 500 MPa, 750 MPa, 1000 MPa, 1250 MPa, and 1500 MPa.

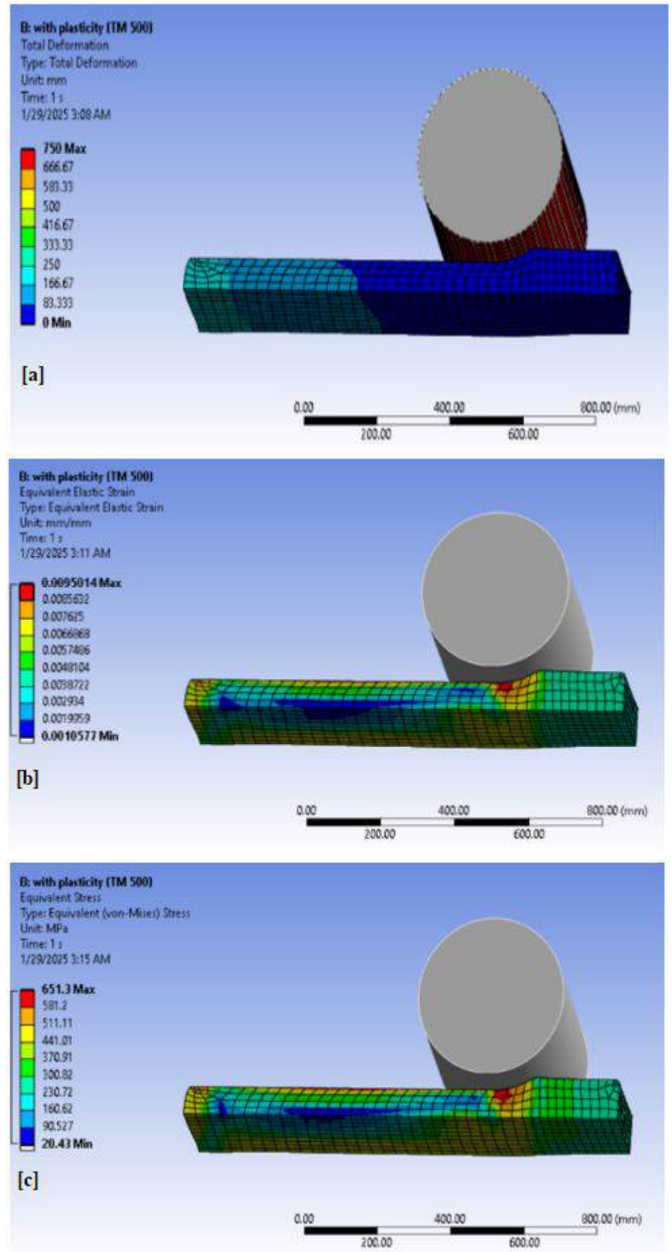


Fig. 1. Results of the simulated workpiece and roller with a tangent modulus of 500MPa under the assumption of plasticity after undergoing (a) Total Deformation (b) Equivalent strain (c) Equivalent stress.

3.1.1 Plastic deformation at Tangent modulus of 500 MPa

The graph in Figs. 2a, b and c show the total deformation, equivalent strain and equivalent stress of a metal under plastic deformation assumption with a tangent modulus of 500 MPa. The X-axis represents time in seconds, covering a 1-second duration, while the Y-axis shows total deformation in mm, equivalent strain in mm/mm, equivalent stress in MPa. For Fig. 2c, the equivalent stress is a scalar value describing the combined effect of stresses acting on the material. The total deformation is plotted for average (red), and maximum (blue), the equivalent strain, equivalent stress is plotted for minimum (blue), average (yellow), and maximum (red), values at various nodes in the finite element model.

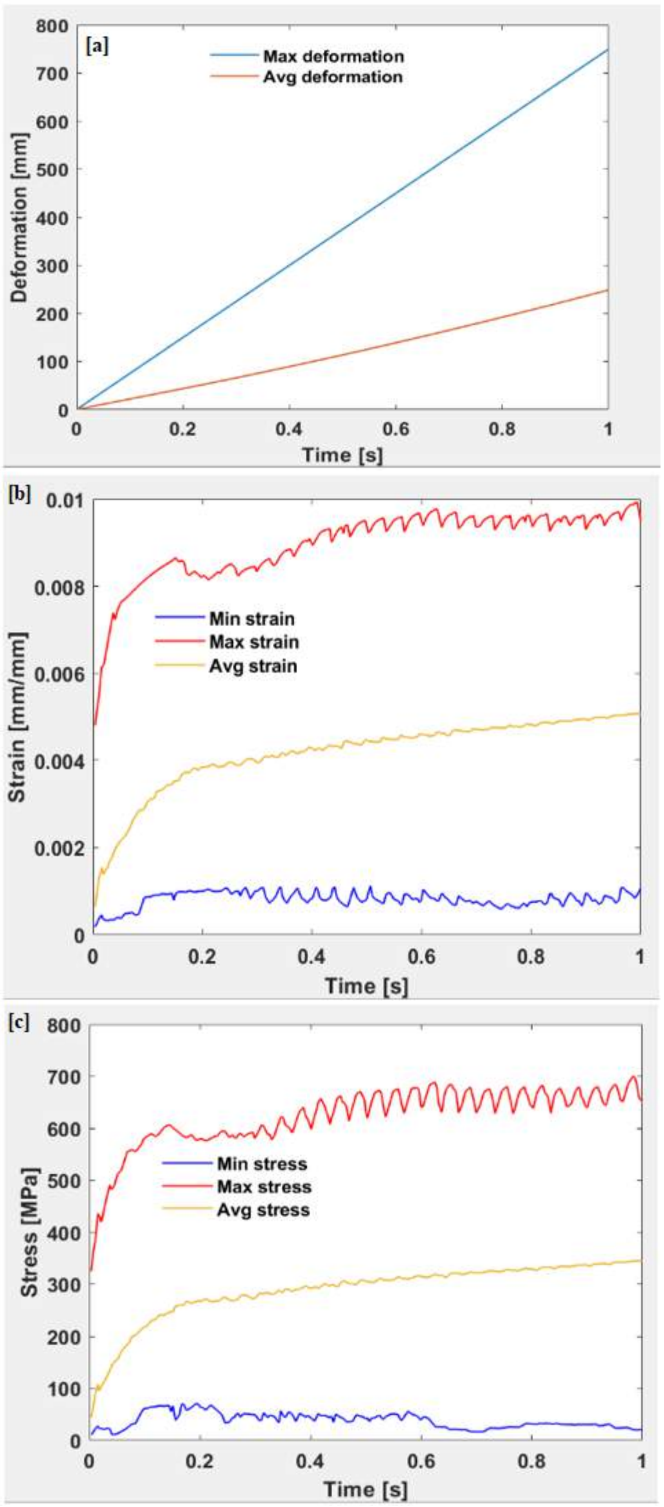


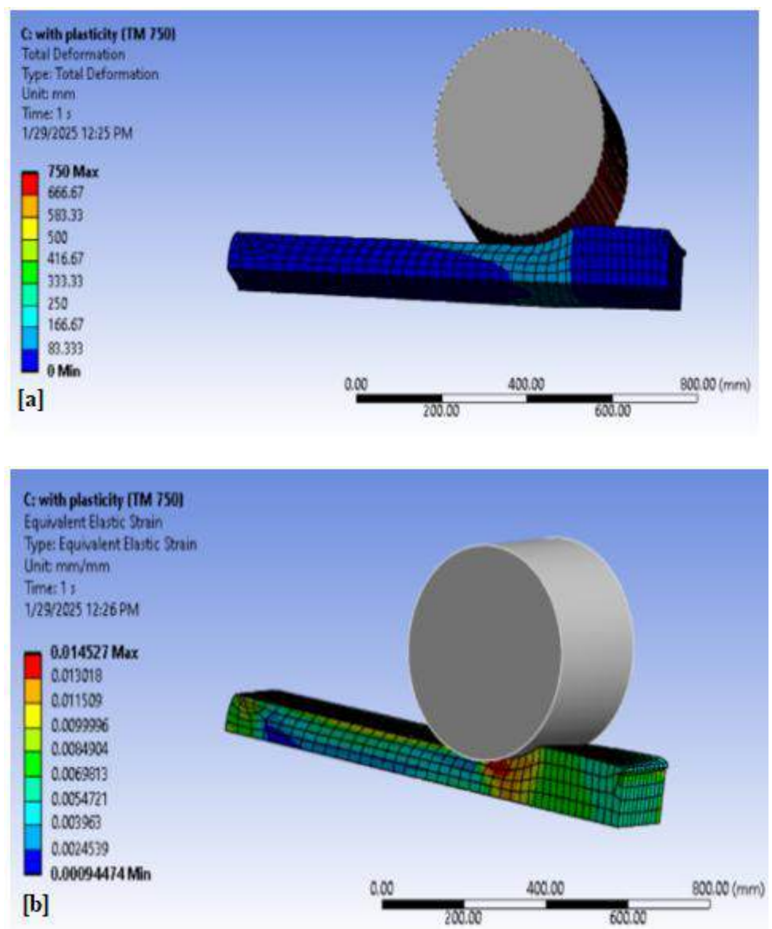
Fig. 2. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 500MPa under the assumption of plasticity.

The assumption of plasticity with a tangent modulus of 500 MPa implies that the material behaves plastically beyond its yield point. The tangent modulus represents the slope of the stress-strain curve in the plastic region. A tangent modulus of 500 MPa indicates a relatively high resistance to plastic deformation.

3.1.1.1 Interpretation of the graph

- Minimum curve line: This line represents the total deformation, equivalent strain, equivalent stress at the point of least stress or strain within the specimen. It shows the smallest amount of deformation, strain and stress experienced by any part of the metal during the process.
- Maximum curve line: This line represents the total deformation, equivalent strain, equivalent stress at the point of highest stress or strain within the specimen. It shows the largest amount of deformation, strain and stress experienced by any part of the metal during the process.
- Average curve line: This line represents the average deformation, equivalent strain, equivalent stress across the entire specimen. It provides an overall measure of the deformation, strain and stress experienced by the metal.

3.1.2 Plastic deformation at Tangent modulus of 750 MPa



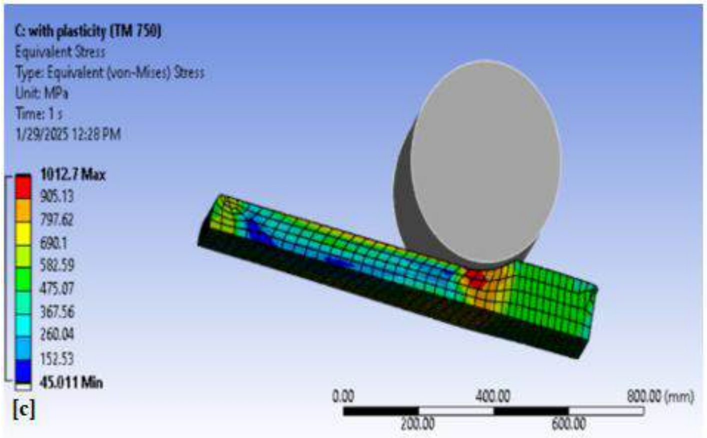
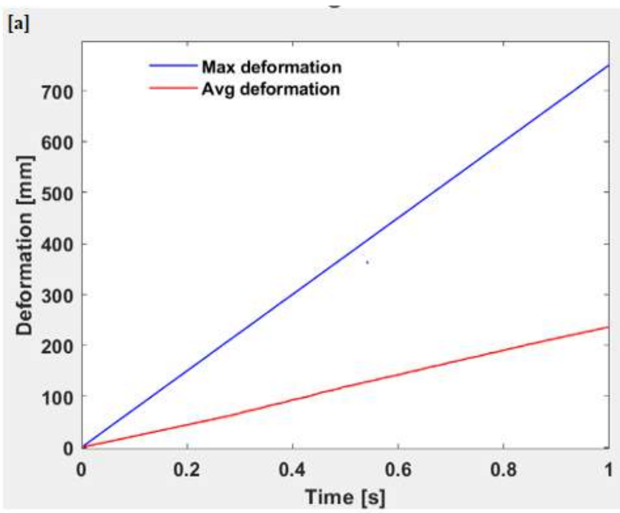
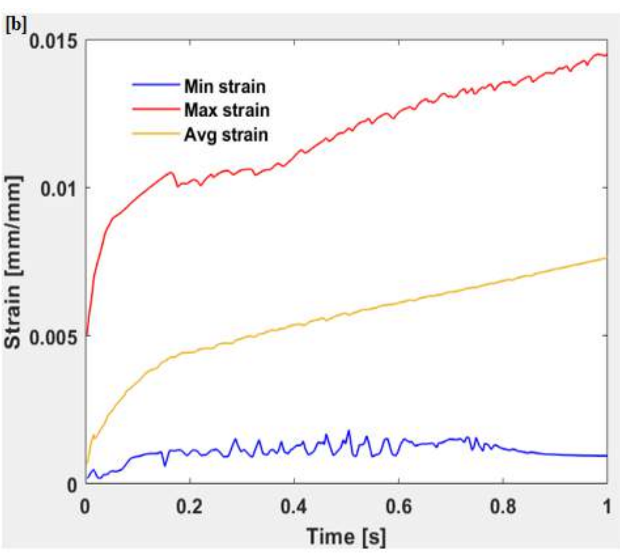


Fig. 3. Diagram of the simulated workpiece and roller with a tangent modulus of 750 MPa under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.





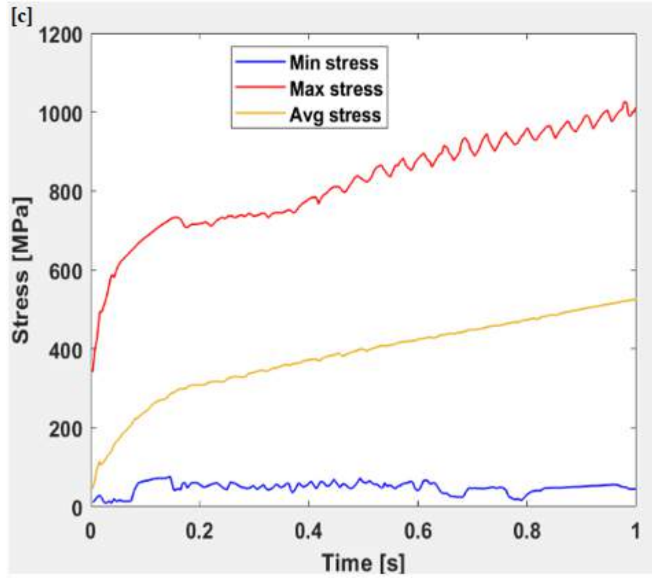


Fig. 4. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 750 MPa under the assumption of plasticity.

The assumption of plasticity with a tangent modulus of 750 MPa implies that the material behaves plastically beyond its yield point. The tangent modulus represents the slope of the stress-strain curve in the plastic region. A tangent modulus of 750 MPa indicates a relatively high resistance to plastic deformation. The graph Fig. 4a, b and c show the total deformation, equivalent strain and equivalent stress during the simulation of a metal under plasticity assumptions with a tangent modulus of 750 MPa. The x-axis represents time in seconds, while the y-axis shows the strain in millimeters per millimeter (mm/mm), deformation in mm, equivalent stress in MPa. The total deformation is plotted for average (red), and maximum (blue), the equivalent strain and equivalent stress are plotted for minimum (blue), average (yellow), and maximum (red). For Fig. 4b, the maximum strain starts low but increases steadily, indicating areas of the metal experiencing the highest elastic deformation. The average strain also increases but at a slower rate compared to the maximum strain, suggesting a distributed deformation throughout the material. For Fig. 4c, the red line represents the maximum stress, which increases steadily over time, reaching above 2200 MPa, indicating high localized stress regions where plastic deformation is most intense. The yellow line denotes the average stress, which also rises steadily, showing that overall stress is distributed throughout the metal but at a lower magnitude than the maximum stress. The blue line, representing the minimum stress, remains relatively constant near 10 MPa, indicating constrained or low-stress regions of the material that do not experience significant deformation.

The graph provides valuable insights into the plastic deformation behaviour of the metal during the cold working process. The non-uniform plastic deformation pattern, characterized by the diverging curves, suggests that the material is undergoing plastic deformation as well, which is consistent with the assumption of plasticity used in the simulation.

3.1.3 Plastic deformation at Tangent modulus of 1000 MPa

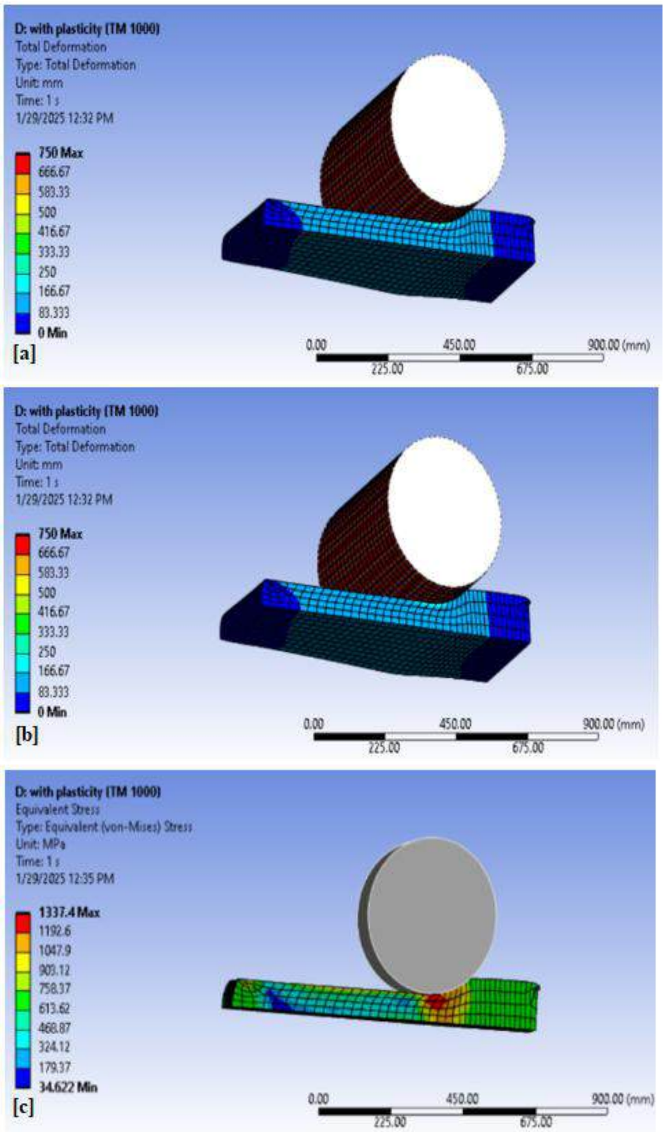


Fig. 5. Diagram of the simulated work piece and roller with a tangent modulus of 1000 MPa under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.

The graph Fig. 6a, b and c show the total deformation, equivalent strain and equivalent stress of a metal under plastic deformation assumptions with a tangent modulus of 1000MPa. The X-axis represents time in seconds, covering a 1-second duration, while the Y-axis shows the strain in millimeters per millimeter (mm/mm), deformation in mm, equivalent stress in MPa. For Fig. 6a, the deformation is plotted for average (red), and maximum (blue) values at various nodes in the finite element model. For fig. 6a and b, the equivalent strain and equivalent stress is plotted for minimum (blue), average (yellow), and maximum (red).

The assumption of plasticity with a tangent modulus of 1000 MPa implies that the material behaves plastically beyond its yield point. The tangent modulus represents the slope of the stress-strain curve in the plastic region. A tangent modulus of 1000MPa indicates a relatively high resistance to plastic deformation.

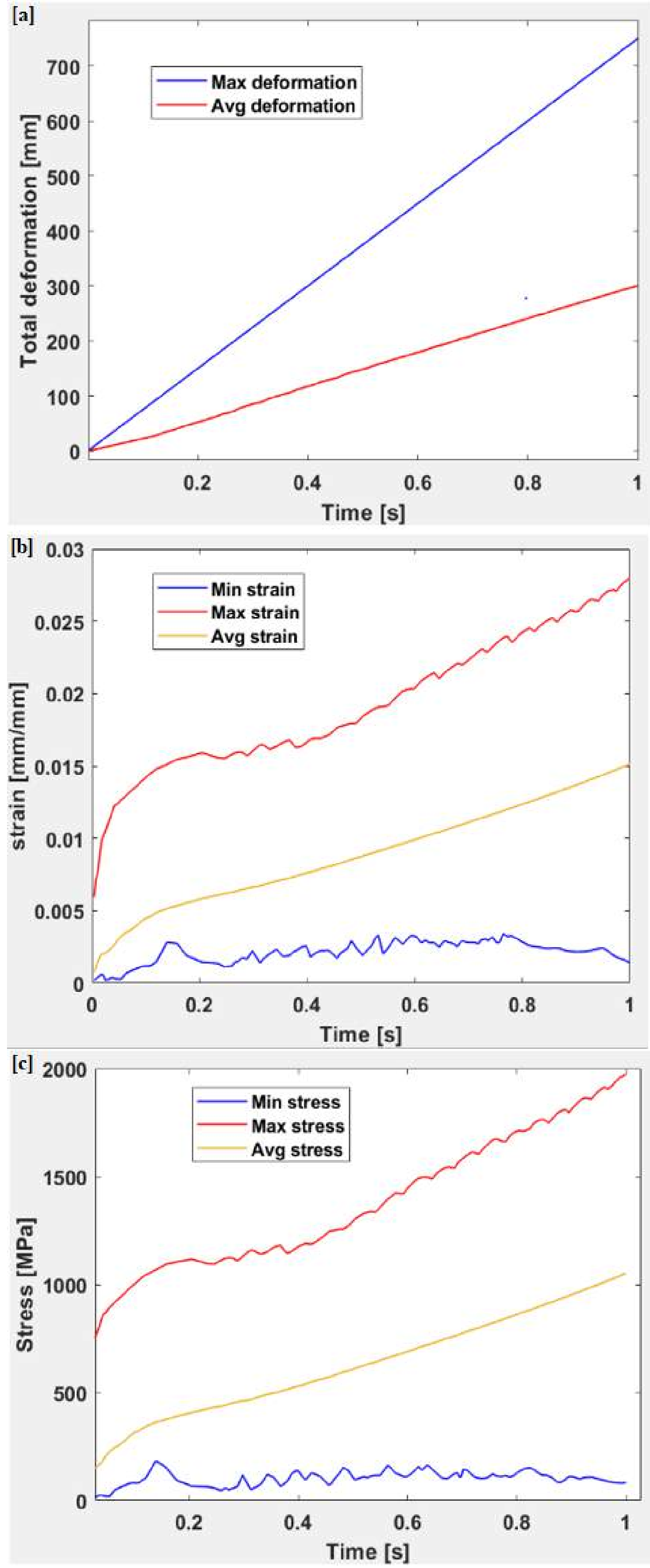


Fig. 6. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 1000 MPa under the assumption of plasticity.

3.1.4 Plastic deformation at Tangent modulus of 1250 MPa

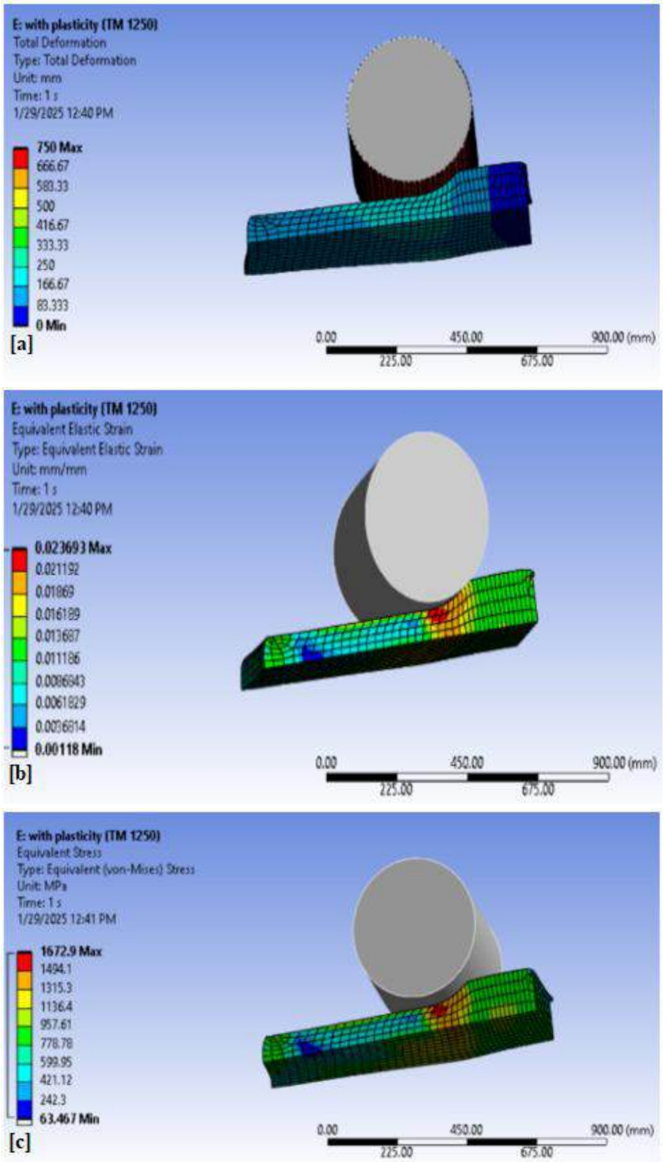
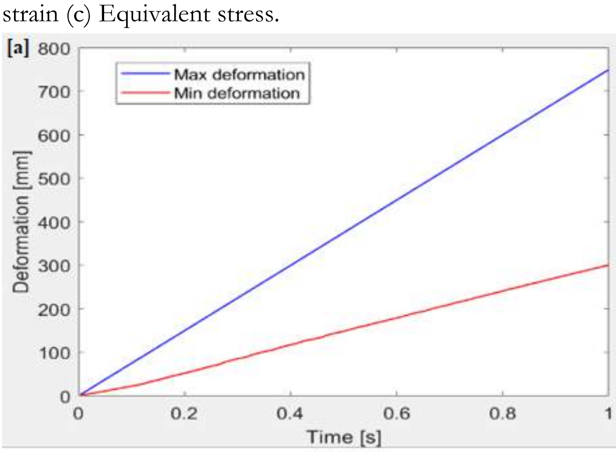


Fig. 7. Diagram of the simulated work piece and roller with a tangent modulus of 1250 MPa under the assumption of plasticity after undergoing (a) Total Deformation (b) Equivalent strain (c) Equivalent stress.



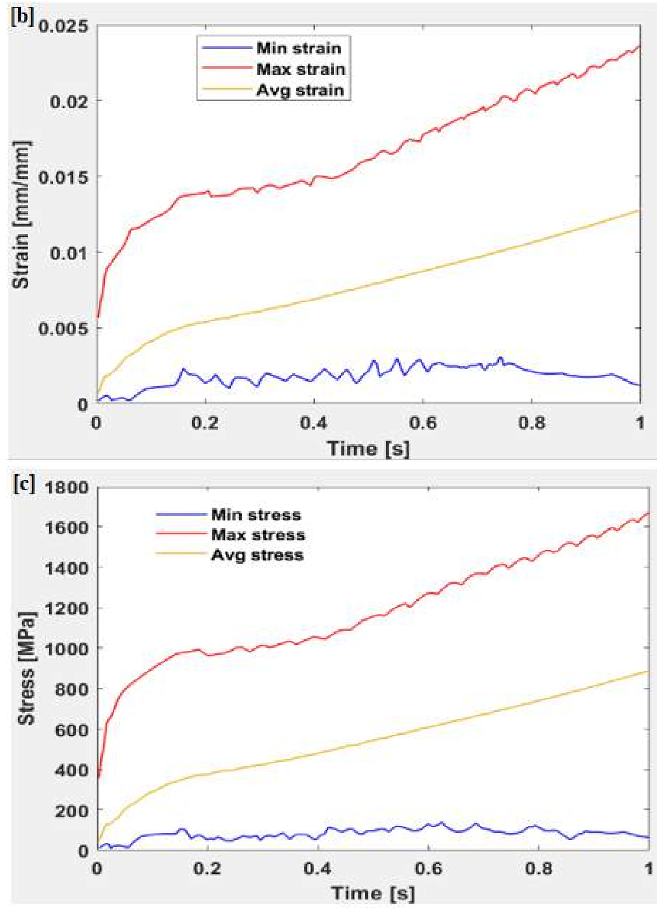


Fig. 8. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 1250 MPa under the assumption of plasticity.

The graph, Fig. 8a, b and c show the total deformation, equivalent strain and equivalent stress during the simulation of a metal under plasticity assumptions with a tangent modulus of 1250 MPa. The x-axis represents time in seconds, while the y-axis shows the strain in millimeters per millimeter (mm/mm), deformation in mm, equivalent stress in MPa. For Fig. 8b, the red line corresponds to the maximum strain, the yellow line indicates the average strain and the blue line shows the minimum strain. The maximum strain starts low but increases steadily, indicating areas of the metal experiencing the highest plastic deformation. The average strain also increases but at a slower rate compared to the maximum strain, suggesting a distributed deformation throughout the material. For Fig. 8c, the red line represents the maximum stress, which increases steadily over time, reaching above 2200 MPa, indicating high localized stress regions where plastic deformation is most intense. The yellow line denotes the average stress, which also rises steadily, showing that overall stress is distributed throughout the metal but at a lower magnitude than the maximum stress. The blue line, representing the minimum stress, remains relatively constant near 10 MPa, indicating constrained or low-stress regions of the material that do not experience significant deformation. For Fig. 8a, the deformation is plotted for minimum (red) and maximum (blue) values at various nodes in the finite element model. The graph provides valuable insights into the plastic deformation behaviour of the metal during the cold working process. The non-uniform plastic deformation pattern, characterized by the diverging curves, suggests that the material is undergoing plastic deformation as well, which is consistent with the assumption of plasticity used in the simulation.

3.1.5 Plastic deformation at Tangent modulus of 1500 MPa

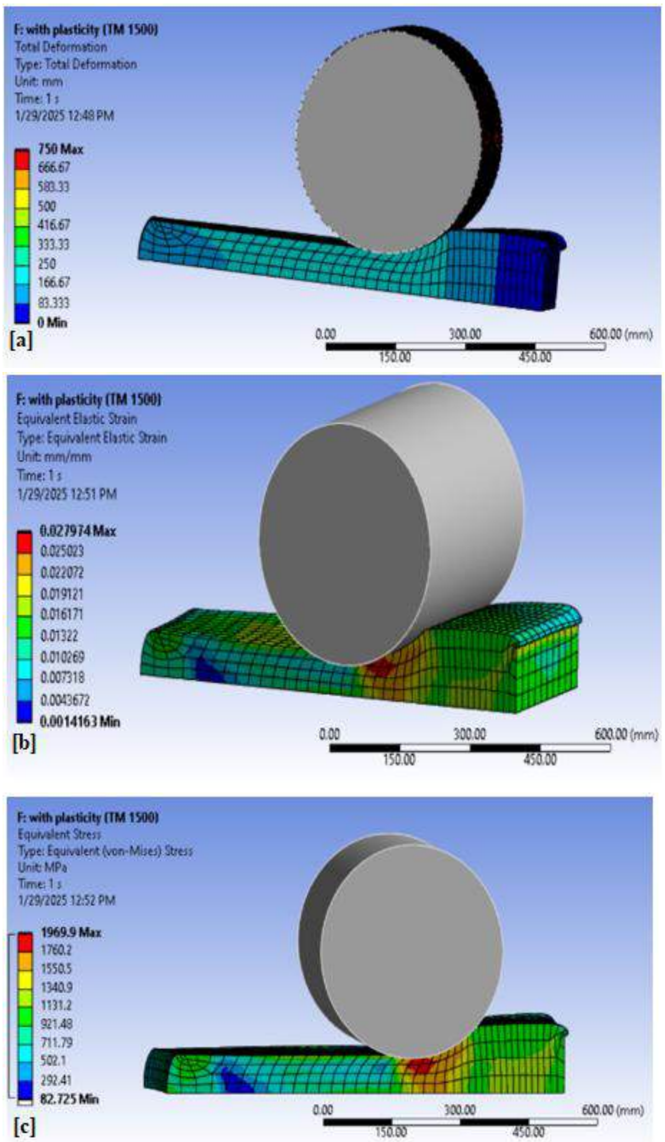
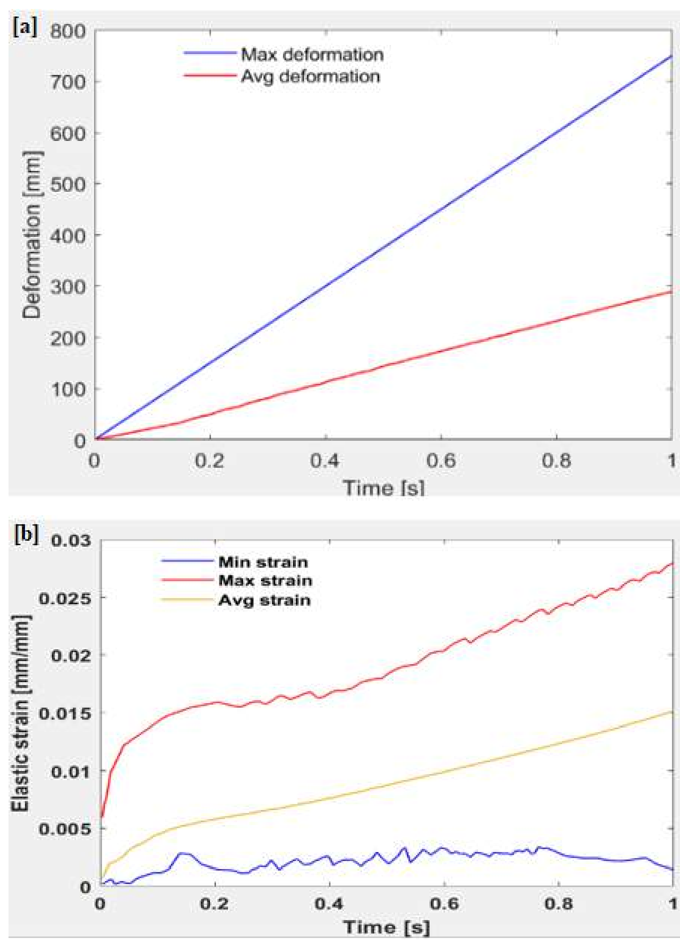


Fig. 9. Diagram of the simulated work piece and roller with a tangent modulus of 1500 MPa under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) Equivalent stress.

The graph, Fig. 10a, b and c show the total deformation, equivalent strain and equivalent stress of a metal under plastic deformation assumptions with a tangent modulus of 1500 MPa. The X-axis represents time in seconds, covering a 1-second duration, while the Y-axis shows strain in millimeters per millimeter (mm/mm), deformation in mm, equivalent stress in MPa. For fig. 10a, the deformation is plotted for average (red) and maximum (blue) values at various nodes in the finite element model. In Fig. 10b, the equivalent elastic strain {mm/mm} a dimensionless parameter indicating strain in the elastic domain. The blue line corresponds to the minimum elastic strain values, the yellow line indicates the average elastic strain values, and the red line represents the maximum elastic strain values. For Fig. 10c, equivalent stress in mega pascal's [MPa], which is a scalar value describing the combined effect of stresses acting on the material. The red line represents the minimum equivalent stress, the blue line indicates the average equivalent stress, and the green line shows the maximum equivalent stress.

The assumption of plasticity with a tangent modulus of 1500 MPa implies that the material behaves plastically beyond its yield point. The tangent modulus represents the slope of the stress-strain curve in the plastic region. A tangent modulus of 1500 MPa indicates a relatively high resistance to plastic deformation.



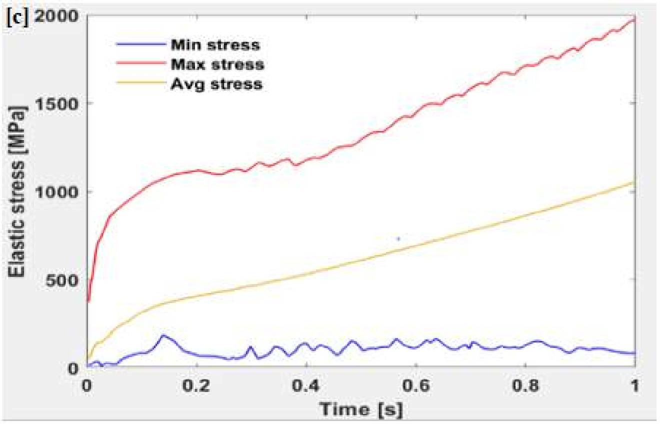
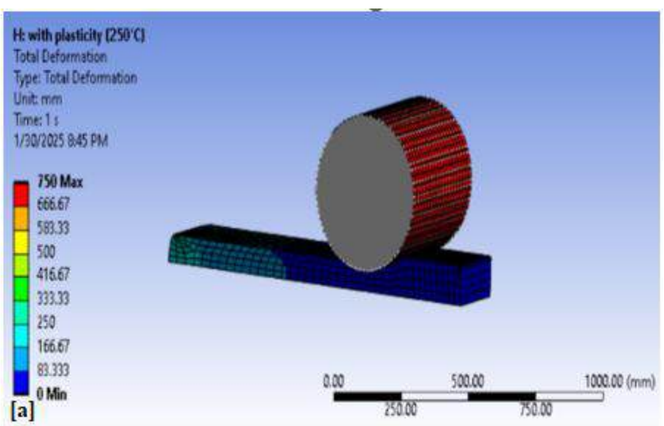
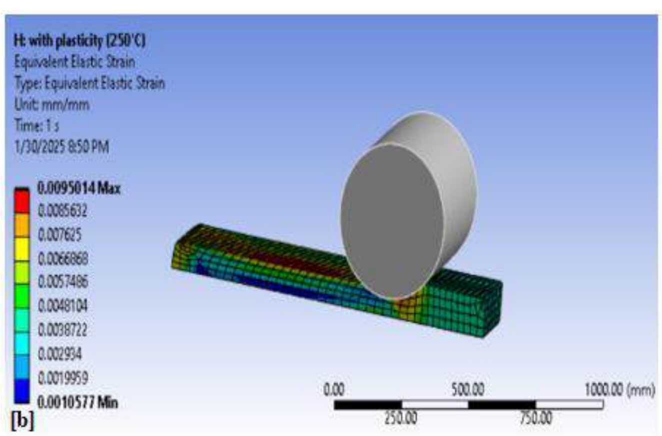


Fig. 10. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 1500 MPa under the assumption of plasticity.

3.1.6 Plastic deformation of workpiece at temperature of 250°C





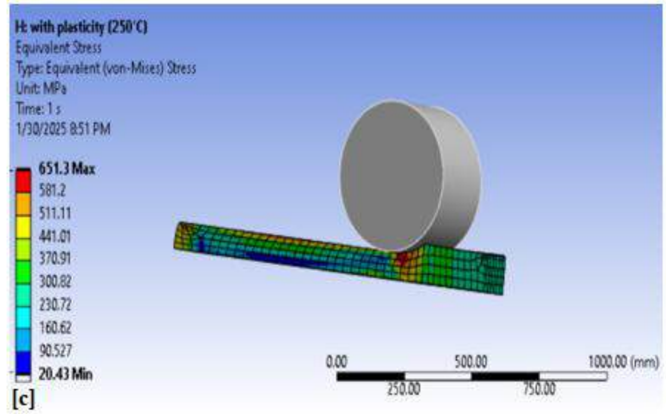


Fig. 11. Diagram of the simulated workpiece and roller at a temperature of 250°C under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.

This graph, Fig. 12a, b and c show the total deformation, equivalent strain and equivalent stress obtained from a finite element simulation of a metal undergoing cold working at 250°C, under the assumption of plasticity. The x-axis represents time (s) from 0 to 1 second, while the y-axis for fig. 12b represents the equivalent elastic strain (mm/mm). The three plotted curves indicate the minimum (blue), average (yellow), and maximum (red) strain values over time.

The maximum strain curve (red) shows a sharp initial increase, indicating rapid strain accumulation in high-stress regions. This is followed by a period of fluctuations and gradual stabilization, suggesting the influence of rolling deformation, material hardening, or contact friction effects. The average strain curve (yellow) follows a similar trend, with a steady increase before reaching a stable state. The minimum strain curve (blue) remains relatively low, indicating regions of the material experiencing negligible elastic strain. For Fig. 12a, this graph represents the total deformation of a metal undergoing cold working at a temperature of 250°C, with deformation values plotted against time in seconds.

At the beginning of the process in Fig. 12c, stress rapidly increases due to the applied force deforming the metal. The maximum stress rises sharply, indicating localized high-stress regions and exhibits periodic fluctuations, suggesting the influence of strain hardening or cyclic loading effects, the average stress also rises but at a more moderate rate which gradually increases and smooths out, indicating progressive deformation and material adaptation, the minimum stress fluctuates, likely due to redistribution of stress and early plastic deformation it fluctuates at a lower level, showing small variations due to localized stress relaxation.

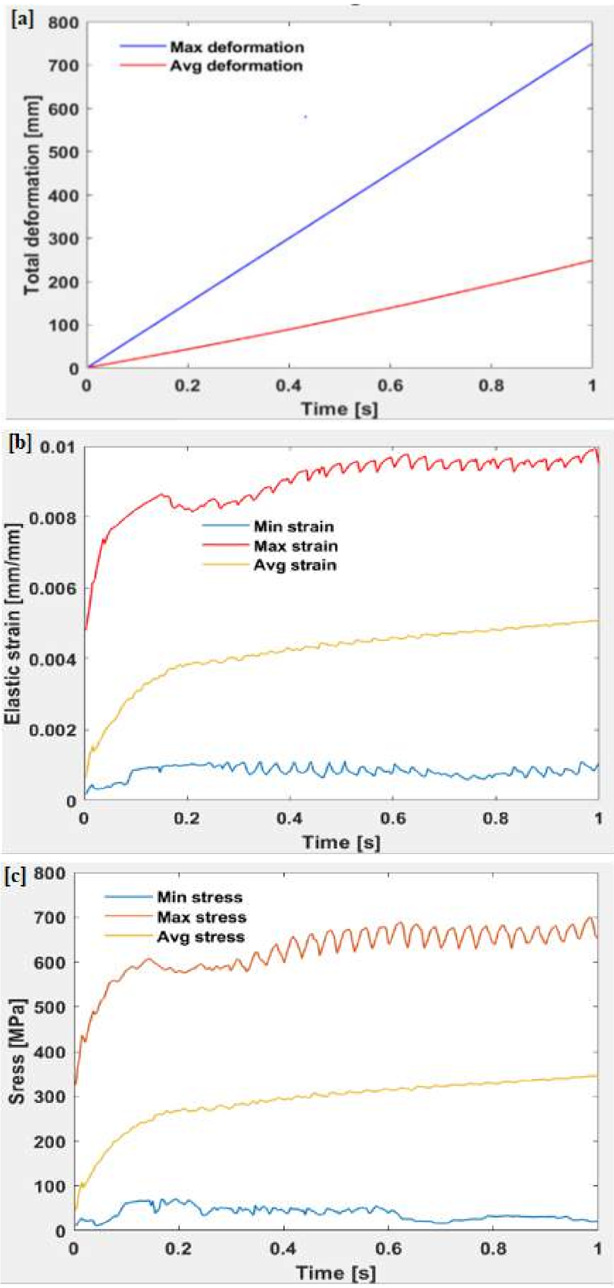
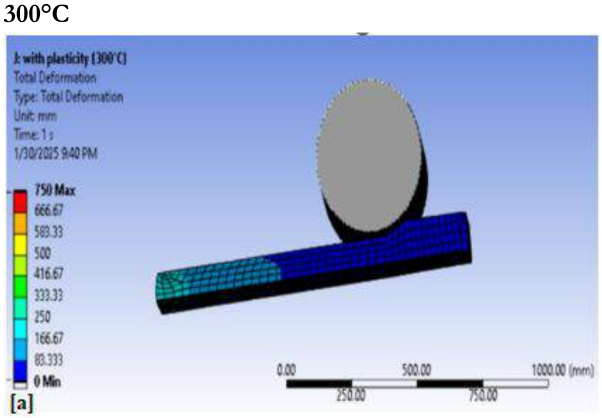


Fig. 12. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 250°C under the assumption of plasticity.

3.1.7 Plastic deformation of workpiece at temperature of 300°C



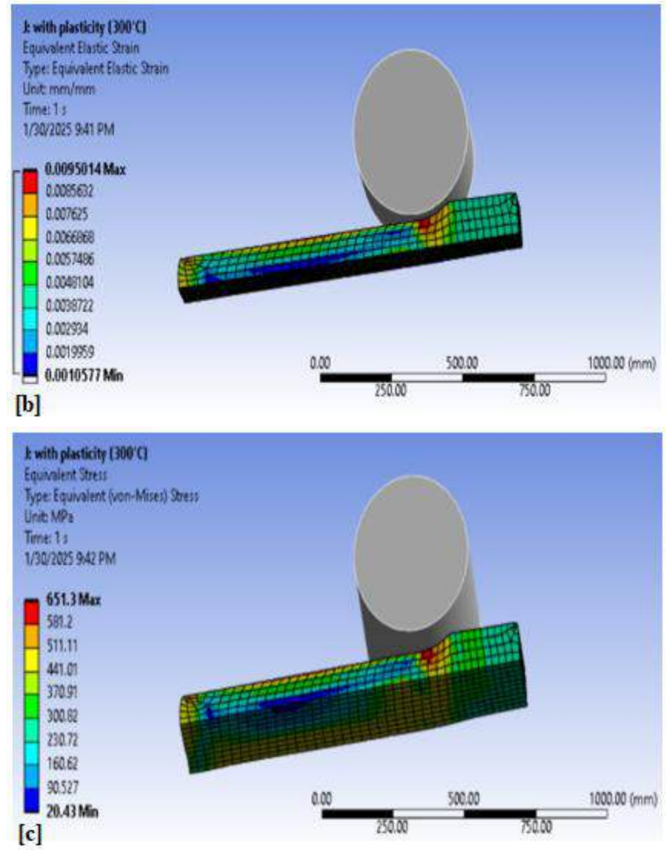
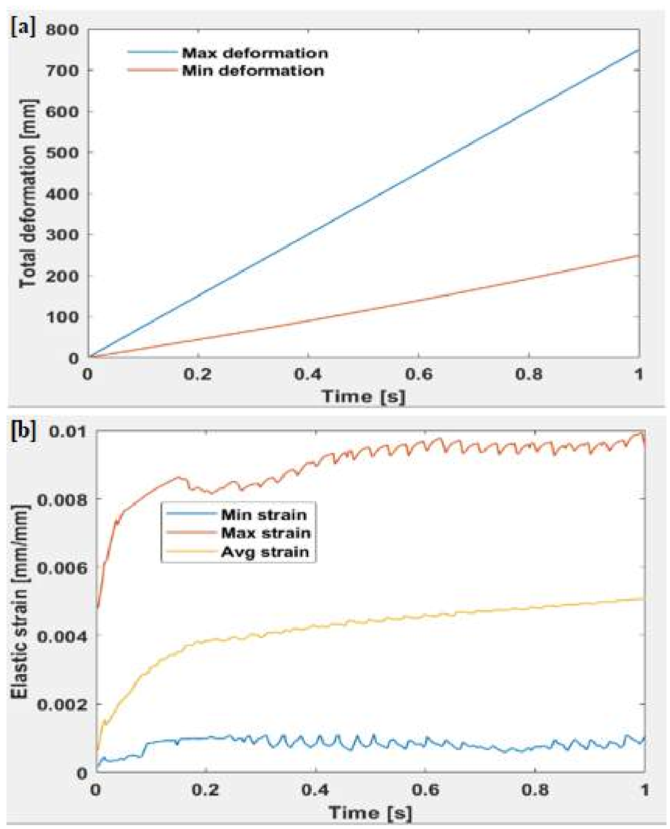


Fig. 13. Diagram of the simulated work piece and roller at a temperature of 300°C under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.



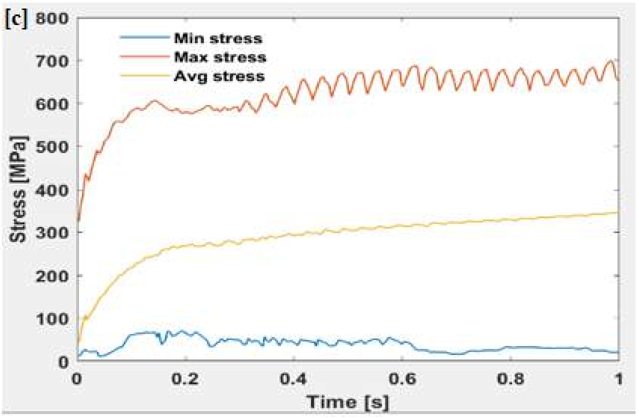


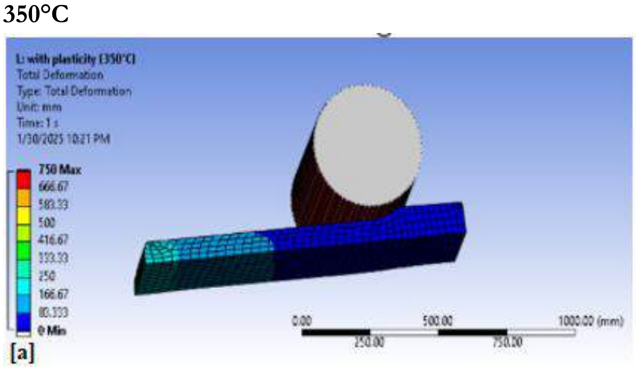
Fig. 14. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 300°C under the assumption of plasticity.

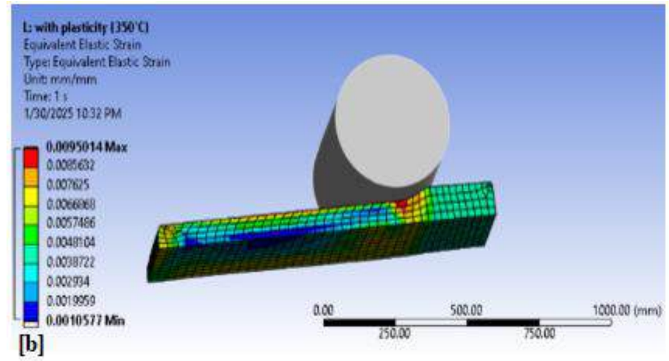
This graph, Fig. 14a, b and c represent the total deformation, equivalent strain and equivalent stress during the cold working process of a metal at 300°C, assuming plasticity. The x-axis represents time (s), while the y-axis represents stress in MPa, strain in millimeters per millimeter (mm/mm), deformation in mm.

The curves in the graph indicate:

- Maximum line curve**:** This increases rapidly showing the most extreme displacement experienced in the material, indicating a consistent loading process and continuous plastic deformation. At the end of the simulation for fig. 14a, the maximum deformation is significantly high, reaching approximately 750 mm.
- Average line curve: This follows a more moderate rate of increase and also follows a linear trend but at a lower magnitude, indicating that the entire material is deforming progressively.
- Minimum line curve: This remains near zero suggesting that some regions of the material are experiencing little to no displacement, meaning that certain fixed boundary points or constrained areas in the material experience negligible movement.

3.1.8 Plastic deformation of workpiece at temperature of 350°C





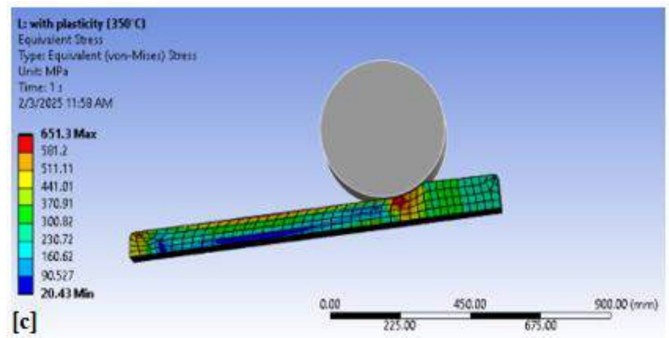
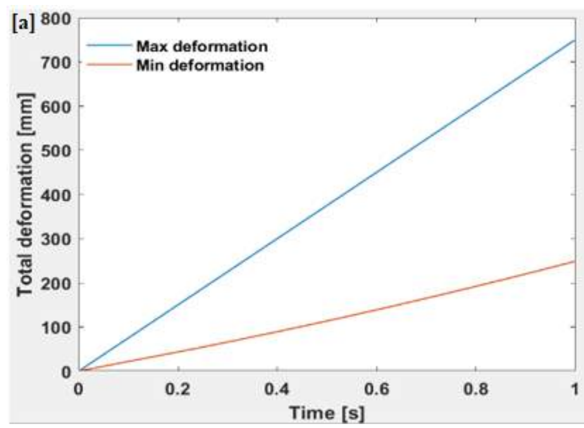
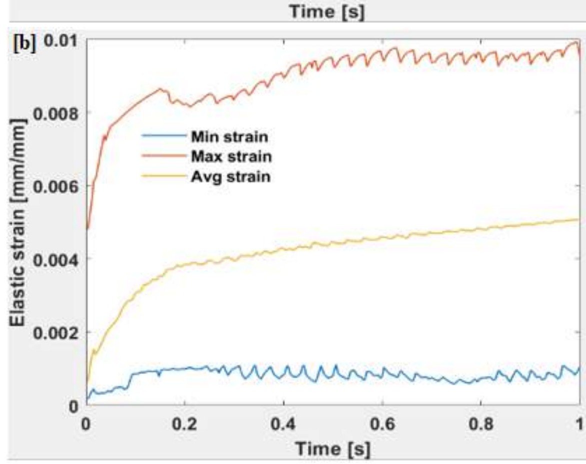


Fig. 15. Diagram of the simulated workpiece and roller at a temperature of 350°C under the assumption of plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.





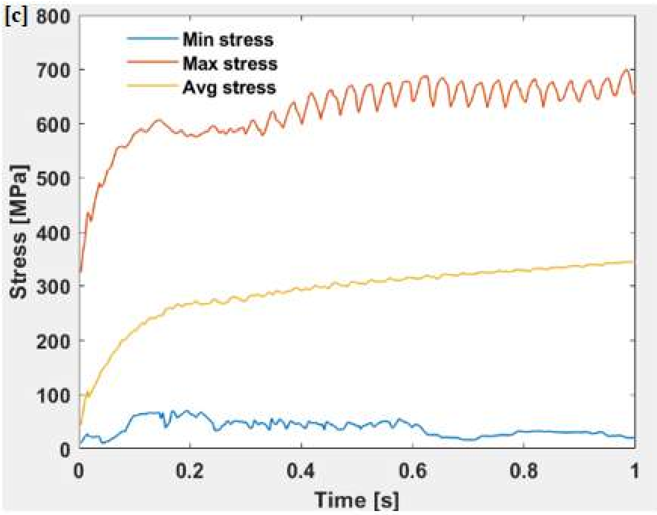


Fig. 16. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 350°C under the assumption of plasticity.

This graph, Fig. 16a, b and c represent the total deformation, equivalent strain and equivalent stress of a metal undergoing cold working at 350°C, assuming plasticity. The x-axis represents time (s), This axis represents the progression of the cold working process. The time scale is from 0 to 1 second. while the y-axis represents deformation in millimetres (mm), stress in MPa, strain in millimetres per millimetre (mm/mm), which indicate the amount of deformation, stress and strain the metal has undergone. In Fig. 16a, the values range from 0 to 750 mm indicating the extent of shape change.

3.1.8.1 Interpretation of the graph

- Minimum line curve**:** This is the deformation, stress and strain experienced by any point in the workpiece at a given time. This could be near zero indicating areas where the material is constrained or experiences less plastic deformation.
- Average line curve: This is the average deformation, stress and strain of the workpiece at a given time. This gives an overall sense of how much the material has been plastically deformed on average.
- Maximum line curve: This is crucial for identifying areas where the material might be susceptible to failure or require further analysis. The maximum line curve is consistently above the other two curves, indicating that certain regions of the material experience higher deformation, stress and strain than others.

3.2 Simulation of rolling process under the condition of elasticity

3.2.1 Elasticity deformation at Tangent modulus of 500 MPa

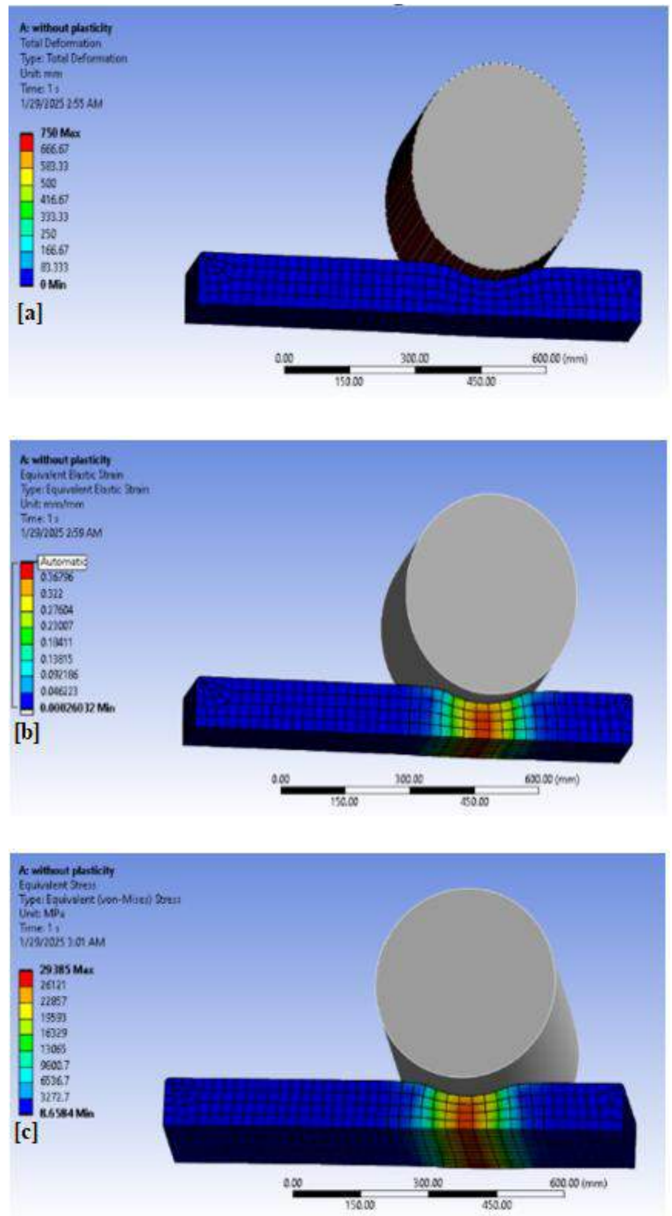
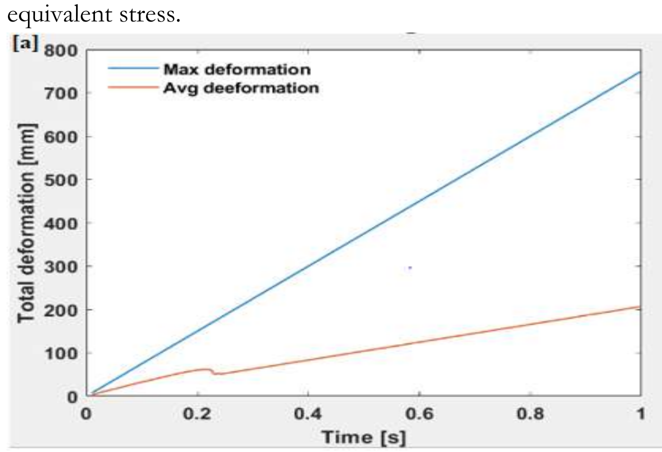


Fig. 17. Diagram of the simulated workpiece and roller with a tangent modulus of 500 MPa under the assumption of elasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.



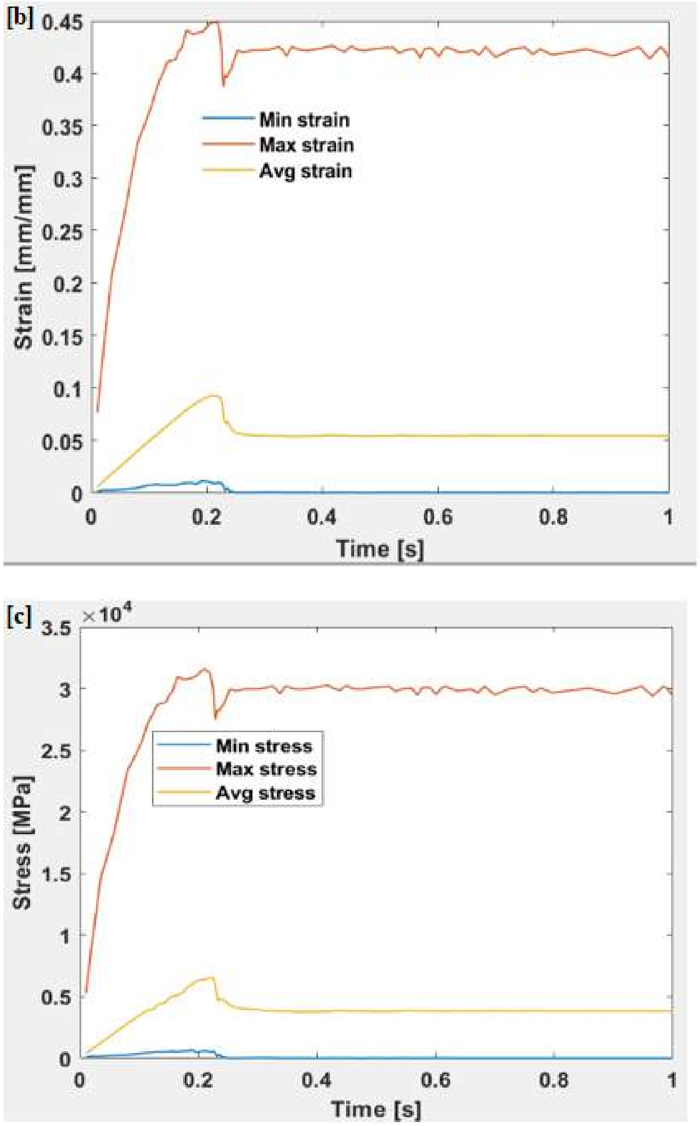
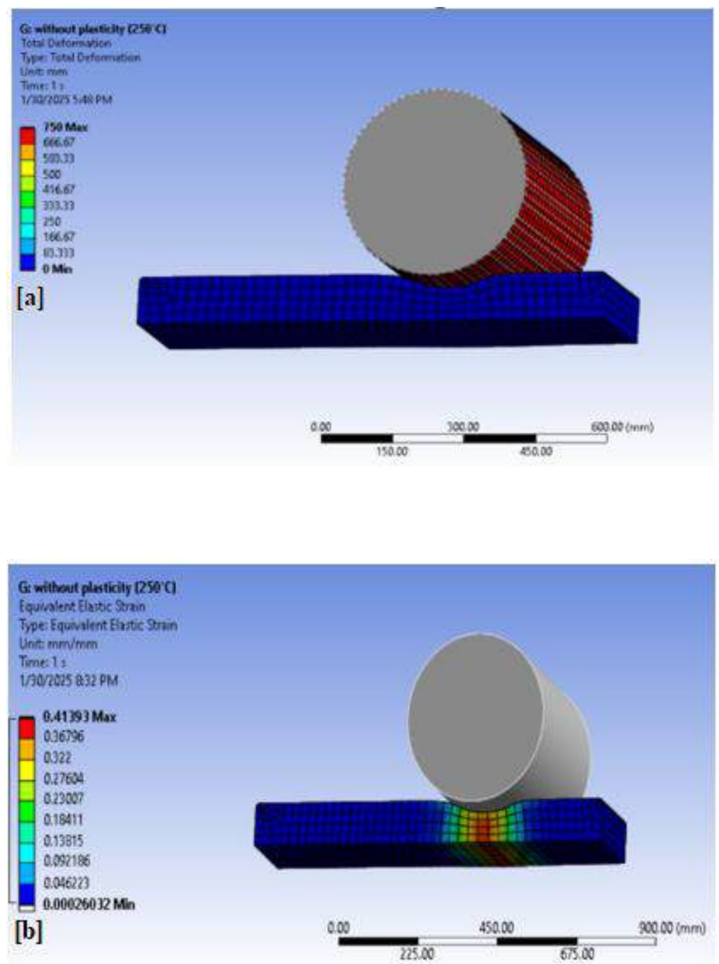


Fig. 18. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress with a tangent modulus of 500 MPa under the assumption of elasticity.

The graph, Fig. 18a, b and c represent the total deformation, equivalent strain and equivalent stress over time for a metal undergoing cold working under the assumption of elasticity. The x-axis represents time in seconds, while the y-axis represents total deformation in millimetres, strain in millimetres per millimetre (mm/mm), equivalent stress in MPa. Fig. 18a, the maximum deformation increases almost linearly with time, reaching approximately 750 mm at 1s, indicating a continuous increase in strain without yielding, which supports the assumption of elasticity. The average deformation follows a non-linear pattern initially, with a noticeable deviation around 0.1 – 0.2 s, before settling into a steady linear increase, suggesting an early-stage transient effect. In fig. 18b, the maximum strain increases sharply in the early stage, reaching approximately 0.42 mm/mm around 0.2s before stabilizing, indicating a rapid initial stress buildup followed by an elastic equilibrium. The average strain follows a similar trend but with a much lower peak, reaching around 0.07 mm/mm before stabilizing, which suggests that most regions experience moderate strain while localized areas experience significantly higher deformation. The minimum strain remains close to zero throughout the simulation, indicating that certain regions experience negligible deformation, possibly due to boundary conditions or regions constrained by external forces. Fig. 18c, the maximum stress increases sharply in the early stage, reaching approximately 30,000 MPa (30 GPa) around 0.2s before stabilizing, indicating a rapid initial load application followed by stress redistribution and equilibrium. The average stress follows a similar trend but peaks at a significantly lower value of around 500 MPa, reflecting the overall stress distribution in the material. The minimum stress remains close to zero, suggesting that certain regions experience negligible stress, likely due to boundary conditions or constrained areas.

3.2.2 Elasticity deformation of workpiece at temperature of 250°C



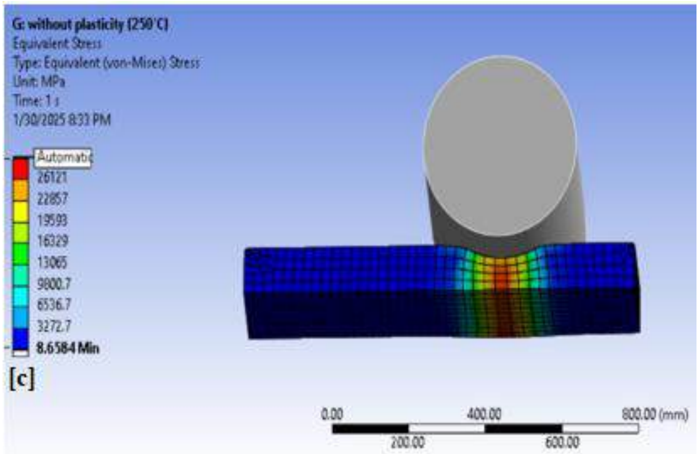
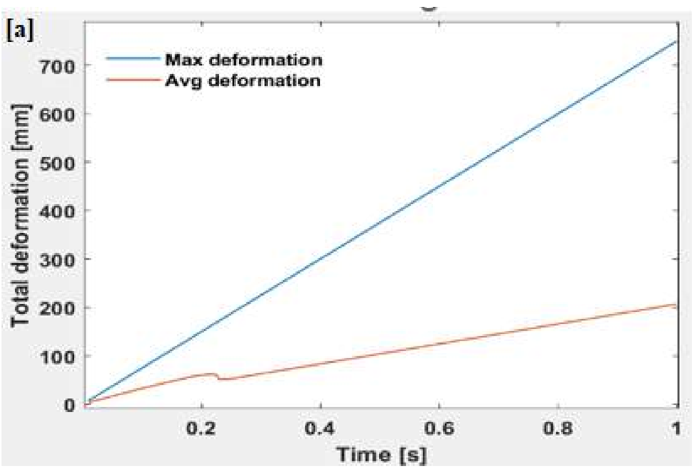
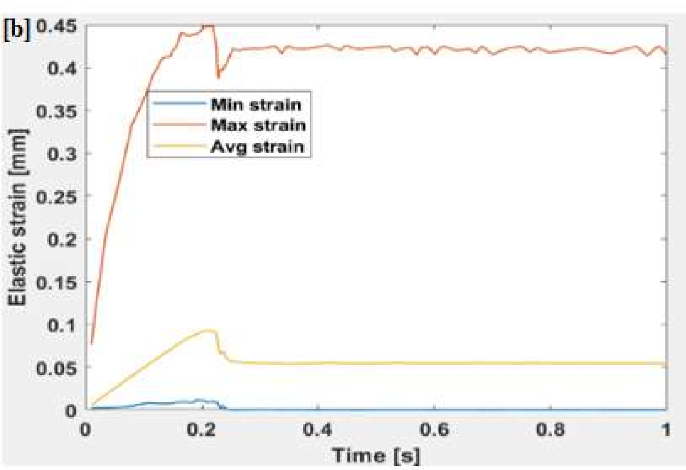


Fig. 19. Diagram of the simulated work piece and roller at a temperature of 250°C under the assumption of non-plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.





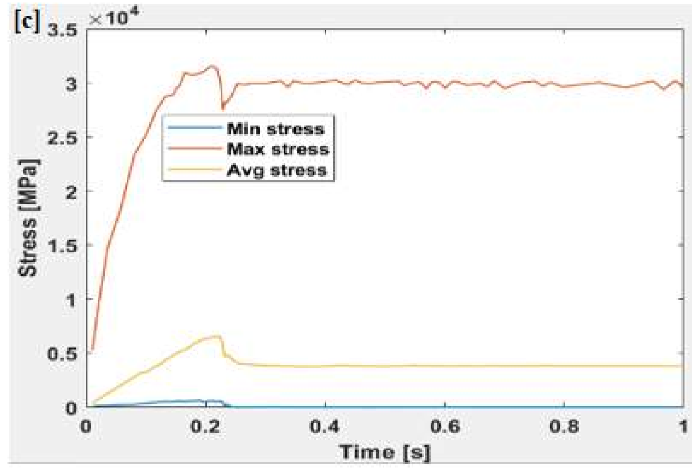


Fig. 20. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 250°C under the assumption of non-plasticity.

The graph, Fig. 20a, b and c represent the total deformation, equivalent strain and equivalent stress of a metal during cold working under the assumption of elasticity at a temperature of 250°C. The x-axis represents time in seconds, while the y-axis represents total deformation in millimeters, strain in millimeters per millimeter (mm/mm), equivalent stress in MPa. For Fig. 20a, the maximum deformation increases linearly over time, reaching approximately 750 mm at 1 second, indicating that certain regions experience significantly higher displacement due to localized stress concentrations.

The average deformation follows a similar but lower trend, reaching around 200 mm, reflecting the overall material displacement. For Fig. 20b, the maximum strain rapidly increases in the initial stage, reaching approximately 0.43 mm/mm within the first 0.2 seconds before stabilizing, suggesting a rapid material response to applied stress. The average strain follows a similar trend, reaching a peak of about 0.07 mm/mm before stabilizing at a lower value. The minimum strain remains close to zero throughout, indicating regions experiencing negligible deformation.

In Fig. 20c, the maximum stress increases sharply, reaching approximately 30,000 MPa (30 GPa) within the first 0.2 seconds before stabilizing. The average stress follows a similar trend but peaks at a much lower value, around 500 MPa, indicating that most of the material experiences moderate stress levels. The minimum stress remains near zero throughout, suggesting certain regions undergo minimal or no stress.

3.2.3 Elasticity deformation of workpiece at temperature of 300°C

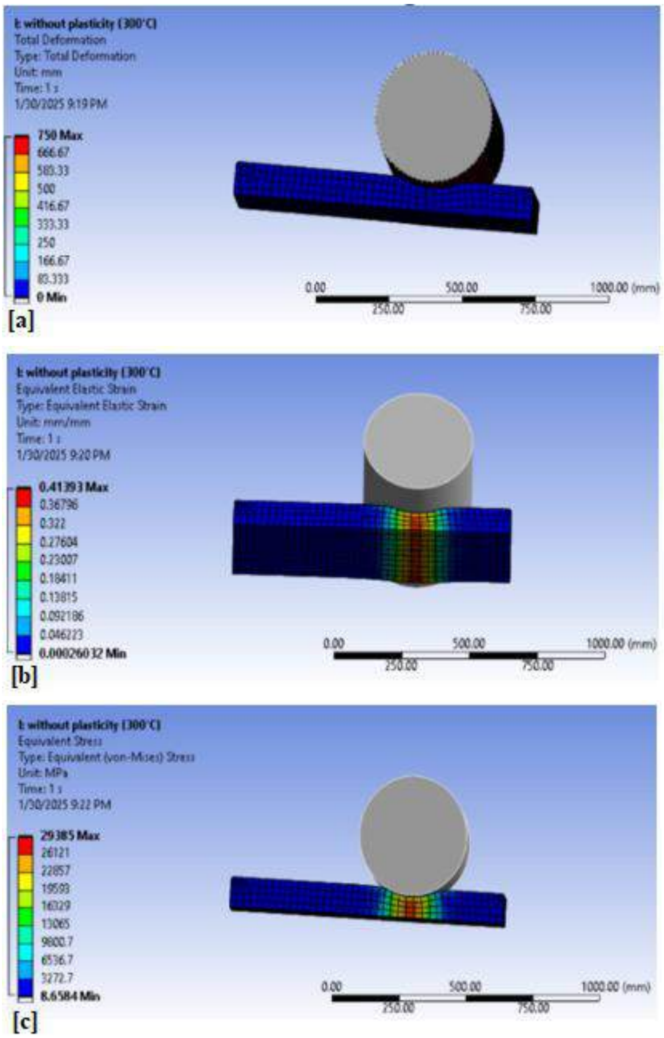
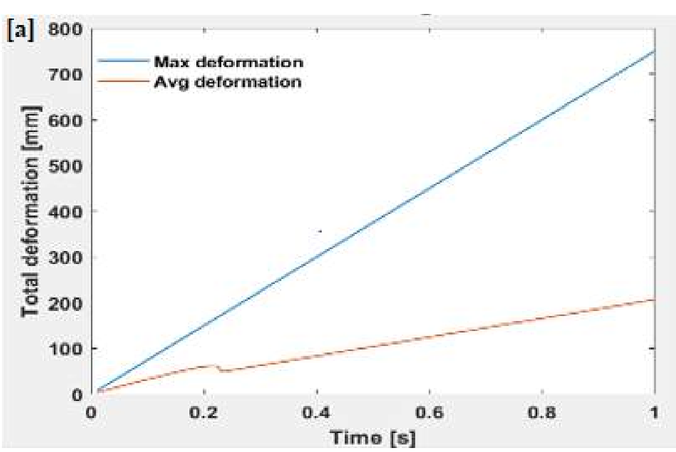


Fig. 21. Diagram of the simulated work piece and roller at a temperature of 300°C under the assumption of non-plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.



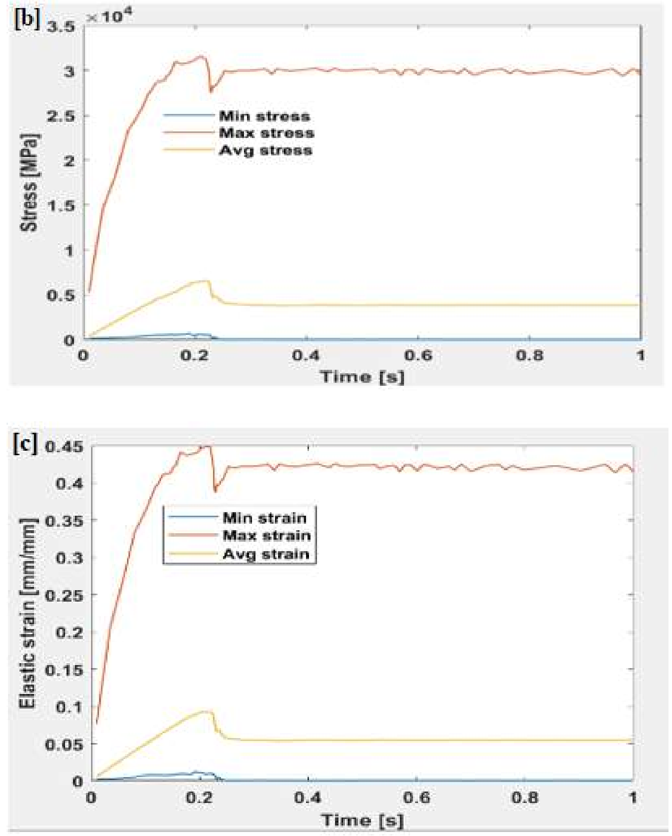


Fig. 22. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 300°C under the assumption of non-plasticity.

The graph, Fig. 22a, b and c represent the total deformation, equivalent strain and equivalent stress of a metal during cold working under the assumption of elasticity at a temperature of 300°C. The x-axis represents time (in seconds), while the y-axis represents total deformation in millimeters, strain in millimeters per millimeter (mm/mm), equivalent stress in MPa. In Fig. 22a, the maximum deformation increases linearly throughout the process, reaching approximately 750 mm at 1 second, indicating continuous elongation of certain regions of the metal. The average deformation follows a similar trend but at a significantly lower magnitude, reaching around 150 mm, suggesting that most of the material undergoes moderate deformation while localized regions experience much higher displacement. For Fig. 22b, the maximum strain exhibits a rapid increase within the first 0.2 seconds, peaking at approximately 0.45 mm/mm before stabilizing, indicating the highest localized deformation in the material. The average strain follows a similar but much lower trajectory, peaking near 0.06 mm/mm and maintaining a steady state after the initial rise, suggesting uniform deformation across most regions with localized areas experiencing higher strain. The minimum strain remains close to zero, indicating regions with negligible elastic deformation. For Fig. 22c, the maximum stress rises steeply within the first 0.2 seconds, reaching approximately 31,000 MPa before stabilizing, indicating the peak stress concentration in localized regions of the material. The average stress follows a similar trend, increasing initially before stabilizing around 500 MPa, suggesting a uniform stress distribution across most regions. The minimum stress remains close to zero, indicating areas with negligible stress.

3.2.4 Elasticity deformation of workpiece at temperature of 350°C

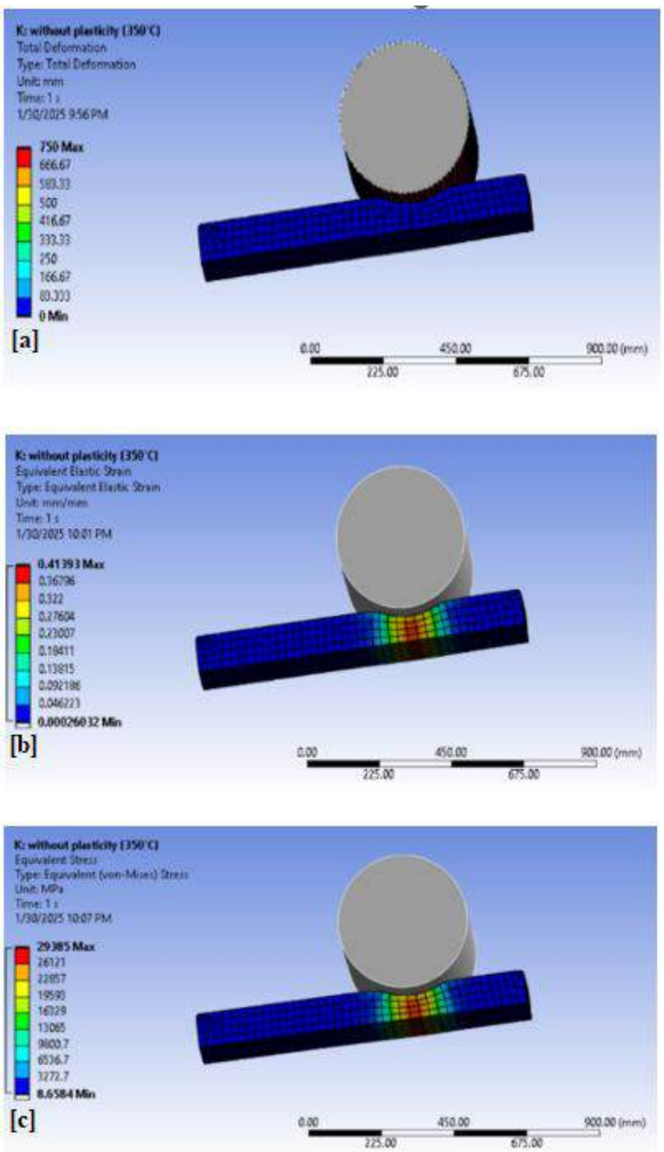


Fig. 23. Diagram of the simulated workpiece and roller at a temperature of 350°C under the assumption of non-plasticity after undergoing (a) total deformation (b) equivalent strain (c) equivalent stress.

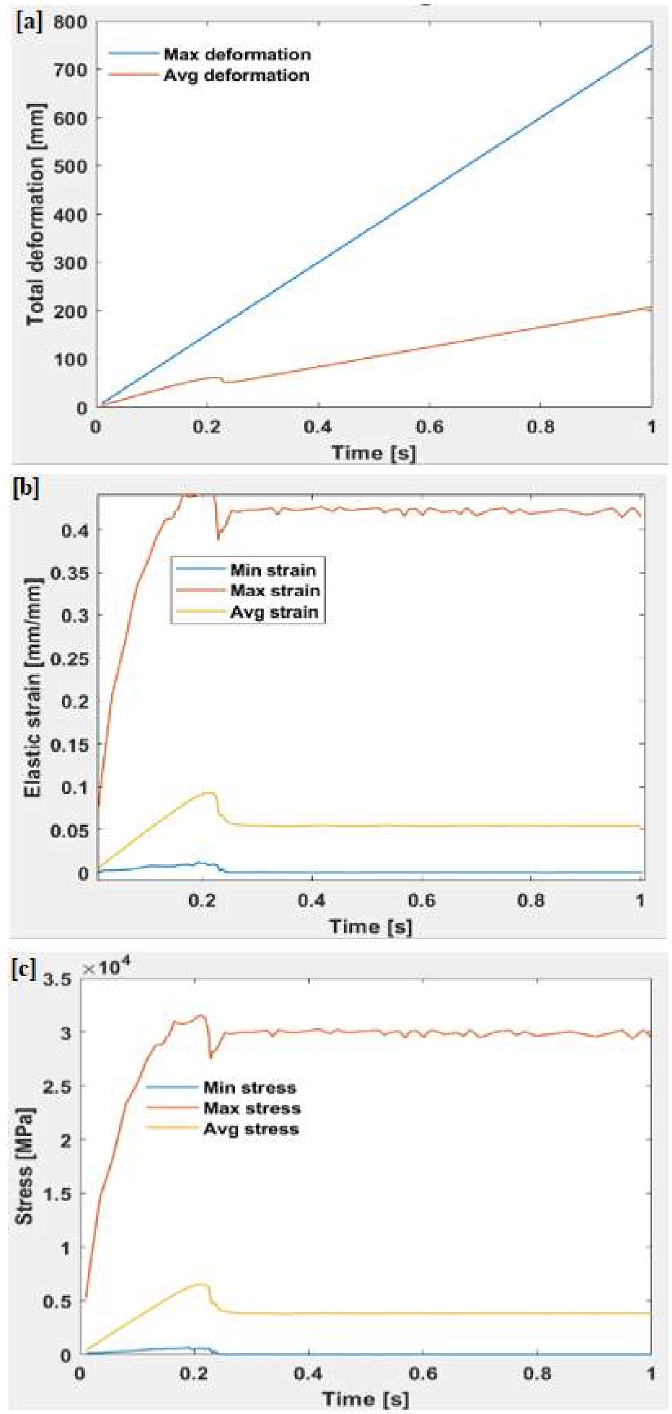


Fig. 24. Graph of (a) total deformation (b) equivalent strain (c) equivalent stress at a temperature of 350°C under the assumption of non-plasticity.

The graph, Fig. 24a, b and c represent the total deformation, equivalent strain and equivalent stress behaviour of a metal during cold working under the assumption of elasticity at a temperature of 350°C. The x-axis represents time in seconds, while the y-axis represents total deformation in millimeters, strain in millimeters per millimeter (mm/mm), equivalent stress in MPa. For Fig. 24a, the maximum deformation increases almost linearly over time, reaching approximately 750 mm at 1 second, signifying regions experiencing the highest displacement under applied loads. The average deformation follows a similar trend but at a lower magnitude, reaching about 200 mm at 1 second, indicating the overall displacement behaviour of the material. In Fig. 24b, the max strain (red curve) represents the highest elastic strain experienced in the material, increasing rapidly within the first 0.2 seconds and stabilizing around 0.42 mm/mm, indicating that the regions of maximum deformation undergo significant elastic stretching before reaching a steady state. Average strain (yellow curve) represents the overall elastic strain behaviour across the metal, increasing initially and stabilizing at approximately 0.05 mm/mm, showing the average elastic response of the material. Minimum strain (blue curve) remains close to zero throughout the simulation, indicating that certain regions of the metal experience negligible elastic deformation. For Fig. 24c, the maximum stress (red curve) shows the highest stress within the material, increasing sharply in the first 0.2 seconds to approximately 31,000 MPa before stabilizing, indicating a rapid elastic response to applied load. Average stress (yellow curve) represents the overall stress distribution in the material, rising initially to around 5000 MPa and stabilizing after 0.2 seconds, providing insight into the average stress state. Minimum stress (blue curve) remains close to zero throughout the simulation, indicating areas experiencing negligible stress.

4.0. Conclusion

The conclusions derived from the finite element analysis of stress distribution during metal cold working under the implementation of plasticity and elasticity are as follows:

Tangent modulus significantly influences the stress distribution within the workpiece when it is varied from 500 MPa, 750 MPa, 1000MPa, 1250 MPa and 1500 MPa. Lower tangent modulus values, such as 500 MPa and 750 MPa, resulted in greater deformation and broader stress distribution, while higher values, such as 1250 MPa and 1500 MPa, led to increased material stiffness, localized stress concentrations, and increased resistance to deformation, leading to distinct stress profiles that are critical for understanding material performance during cold working operation. Each increment in tangent modulus demonstrated a corresponding change in stress distribution within the material.

Higher temperatures reduced material yield strength, facilitated easier deformation, and promoted uniform stress distribution. At 350°C, stress concentration was notably reduced, whereas at 250°C, increased resistance to deformation was observed, potentially contributing to higher tool wear and energy requirements.

The results indicated that elevated temperatures enhanced ductility and reduced stress concentrations, facilitating smoother material flow and improving overall process efficiency. The interaction between tangent modulus and temperature highlighted the complexity of stress behaviour during cold working. Combinations of lower tangent modulus and higher temperatures minimized stress concentrations and facilitated plastic flow, whereas higher modulus and lower temperatures intensified stress concentrations.

Declaration Statement

The authors agreed with total interest to submit the manuscript entitled, 'Finite element analysis of stress distribution during metal cold working under the assumption of plasticity and elasticity' for publication in your reputable Institution without conflict of interest be it design and implementation, respect towards society, resources and research output and conduct without deceptive acts.

Conflict of Interest

The authors declare no conflict of interest**.**

Author Contribution

Egole C.P.: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Nzebuka, G. C: Writing – review & editing, Visualization, Investigation, Formal analysis, Data curation. Mbamara, F. A: Writing – review & editing, Writing – original draft, Resources, Project administration, Investigation, Formal analysis, Data curation. Ajawobu, D. N.: Writing – review & editing, Resources, Methodology, Investigation. Ugwuegbu C.C.: Writing – review & editing, Resources, Investigation. Anaele J.U.: Writing – review & editing, Resources. Arukalam I.O.: Methodology development. Ndukwe A.I.: Technical editorial and typesetting Uche,R: Projection administration, general supervision and English Language editing.

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