Teaching materials
Guide Notes for Teachers

MISCE project

Mechatronics for Improving and Standardizing Competences in Engineering

Competence: Mechanical systems

Workgroup: RzuT, UNICA, UCLM, UNICAS

This document corresponds to the burnishing exercises for the competence 'Mechanical Systems'.

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1 Introduction

Burnishing is a chipless finishing operation in which a hard tool (often spherical or roller-type) is pressed against the surface of a workpiece, causing plastic deformation that refines the surface topography. When the contact pressure exceeds the material yield strength, the asperities flatten and the grains near the surface are plastically deformed, resulting in a reduction in roughness and improved material properties.

The experimental apparatus developed under the MISCE project integrates a servo-driven crank mechanism, allowing static and dynamic burnishing modes for lathes. Figure 2 shows the schematic of the crank-based mechanism, including the servo motor, crank arms, force sensor, and burnishing head. The system can be attached to a lathe or another machine tool, allowing the workpiece to rotate or translate while the burnisher remains in contact.

Figure 1 outlines the geometric relationships and functional arrangement of the burnishing tool.

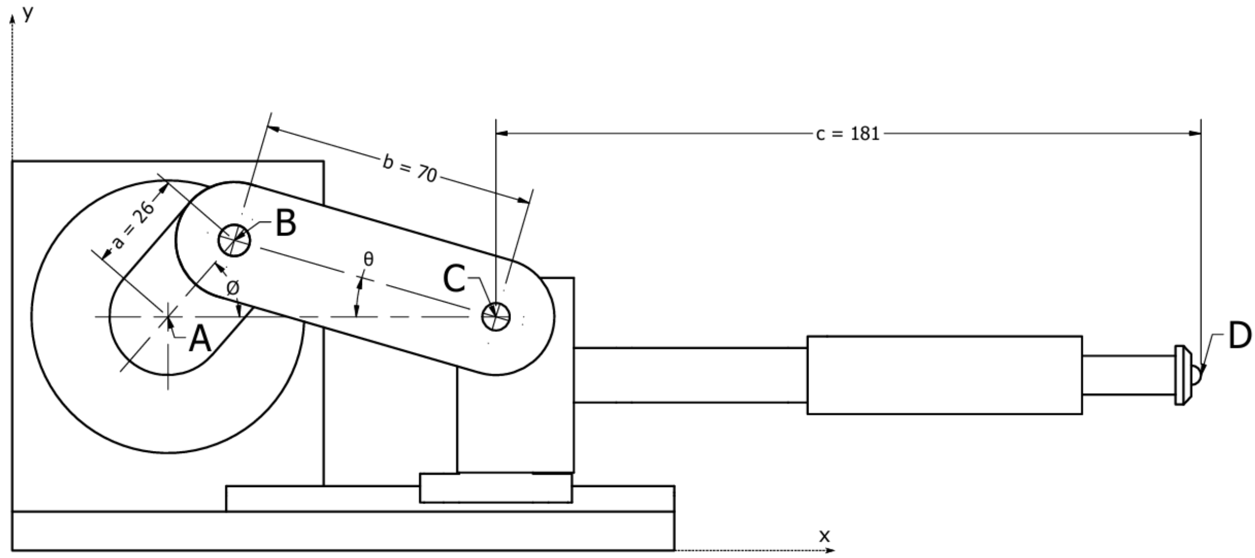

Figure 1 Schematic of the crank-based burnishing mechanism, showing the geometric layout and functional arrangement of components

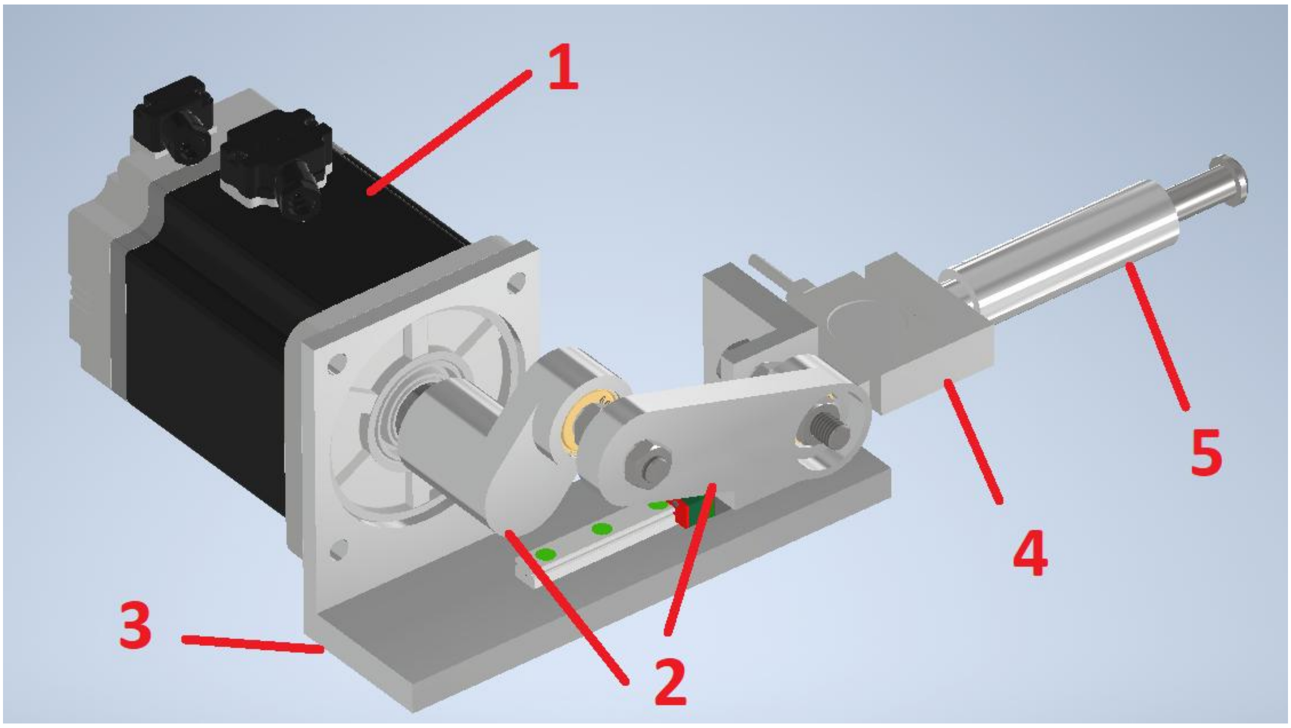

Figure 2 CAD model of the burnisher: (1) servo motor, (2) crank arms, (3) mounting base for attachment to the lathe, (4) EMS110 force sensor, and (5) burnishing head with a spring inside

The burnishing tool has an internal spring, in this case, a compression spring rated for max 211N that plays a central role in maintaining a stable and repeatable load on the spherical tip. In static burnishing mode, this spring ensures a constant contact pressure between the tool and the surface of the workpiece. By adjusting the spring stiffness and its initial compression, it is possible to control the depth of plastic deformation and thus achieve uniform surface finishing.

In static burnishing, spring precompression directly translates into the overall force exerted on the workpiece. In dynamic burnishing, spring precompression also defines the tilt angle φ of the crank arm at the exact moment when the tool engages with the shaft. Precise control of this contact point timing under oscillatory forces is vital for consistent material deformation.

Derivation of the key relationships describing the operation of the burnisher, as illustrated in the figures above is described in sections 2 and 3, in sections 4 and 5 the static and the dynamic burnishing processes are explained.

2 Derivation of the Distance Formula for AD

Below is a step-by-step derivation and the final formula for the distance AD as a function of the given parameters a, b, c, and the angle φ.

2.1 Assumptions and Geometric Description

1. The mechanism consists of three segments:
   - $A \to B$ of length a,
   - $B \to C$ of length b,
   - $C \to D$ of length c.
2. Point A is fixed (e.g., at coordinates $(0,0)$).

3. The angle φ is between segment $A \to B$ and the horizontal axis (x). The coordinate system is defined with A at the origin, the x-axis as horizontal, and the y-axis as vertical.
4. The coordinates of point B can be written as:

$$B_x = a\cos(\varphi), \quad B_y = a\sin(\varphi).$$

5. Point C is connected to B by a rod of length b. Introducing an additional angle θ, representing the angle of segment $B \to C$ with respect to the horizontal axis (x):

$$C_x = B_x + b\cos(\theta) = a\cos(\varphi) + b\cos(\theta),$$

$$C_y = B_y + b\sin(\theta) = a\sin(\varphi) + b\sin(\theta).$$

6. Assume point C moves along a horizontal guide. This means $C_y = 0$, providing a condition to determine θ:

$$a\sin(\varphi) + b\sin(\theta) = 0.$$

Hence:

$$\sin(\theta) = -\frac{a\sin(\varphi)}{b}.$$

7. Using the trigonometric identity $\sin^2(\theta) + \cos^2(\theta) = 1$:

$$\cos^2(\theta) = 1 - \sin^2(\theta) = 1 - \left(\frac{a^2\sin^2(\varphi)}{b^2}\right) = \frac{b^2 - a^2\sin^2(\varphi)}{b^2}.$$

Taking the positive root (assuming a specific orientation of the mechanism):

$$\cos(\theta) = \frac{\sqrt{b^2 - a^2\sin^2(\varphi)}}{b}.$$

8. Substituting:

$$C_x = a\cos(\varphi) + b\cos(\theta) = a\cos(\varphi) + \sqrt{b^2 - a^2\sin^2(\varphi)}.$$

Since $C_y = 0$, point C lies on the x-axis.

9. Point D is located at a horizontal distance c from C (as shown in the diagram). Assuming D is to the right of C:

$$D_x = C_x + c = a\cos(\varphi) + \sqrt{b^2 - a^2\sin^2(\varphi)} + c, \quad D_y = 0.$$

10. The distance AD is simply the length of the vector from $A = (0,0)$ to $D = (D_x, 0)$:

$$AD = \sqrt{(D_x - 0)^2 + (0 - 0)^2} = |D_x| = a\cos(\varphi) + \sqrt{b^2 - a^2\sin^2(\varphi)} + c.$$

2.2 Final Formula and MATLAB script

Thus, the formula for AD is:

$$\boxed{AD(\varphi) = a\cos(\varphi) + c + \sqrt{b^2 - a^2\sin^2(\varphi)}}.$$

```
% Script 1
% Symbolic derivation of the formula for the distance AD
clear all
```

```
close all


% Assumptions for example values:
a = 26; b = 70; c = 181;
% phi - angular variable


% Points:
% A = (0,0) (fixed)
% B = (a*cos(phi), a*sin(phi))
% C = B + (b*cos(theta), b*sin(theta)) with the condition C_y=0
% D = C_x + c (on the x-axis)
% We are looking for: AD = D_x, since Dy=0 and A=(0,0).


%% Defining symbolic variables
syms a b c phi real
syms theta real


% Position of point B:
Bx = a*cos(phi);
By = a*sin(phi);


% Condition for point C:
% C_y = 0 = a*sin(phi) + b*sin(theta)
sin(theta) = - (a*sin(phi))/b;
sin_theta = -(a*sin(phi))/b;


% Calculating cos(theta) using the trigonometric identity
cos_theta = sqrt(1 - sin_theta^2);


% Position of point C
Cx = a*cos(phi) + b*cos_theta;
Cy = 0;


% Position of point D
Dx = Cx + c;
Dy = 0;


% Distance AD
% AD = Dx, because D_y=0 and A=(0,0)
AD = Dx;
% Simplifying the expression for AD
AD_simplified = simplify(AD);

% Generating a plot of the distance |AD| as a function of angle /phi
```

```
a_val = 26;
b_val = 70;
c_val = 181;
phi_vals = linspace(0, 2*pi, 200);
% Substitute scalar values
AD_numeric = subs(AD_simplified, [a b c], [a_val b_val c_val]);


% Substitute the vector of phi_vals separately
AD_vals = double(subs(AD_numeric, phi, phi_vals));


%% Plot
figure
plot(phi_vals, AD_vals, 'LineWidth', 2)
grid on
xlabel('\phi [rad]')
ylabel('|AD| [mm]')
title('Dependence of distance |AD| on angle \phi')
```

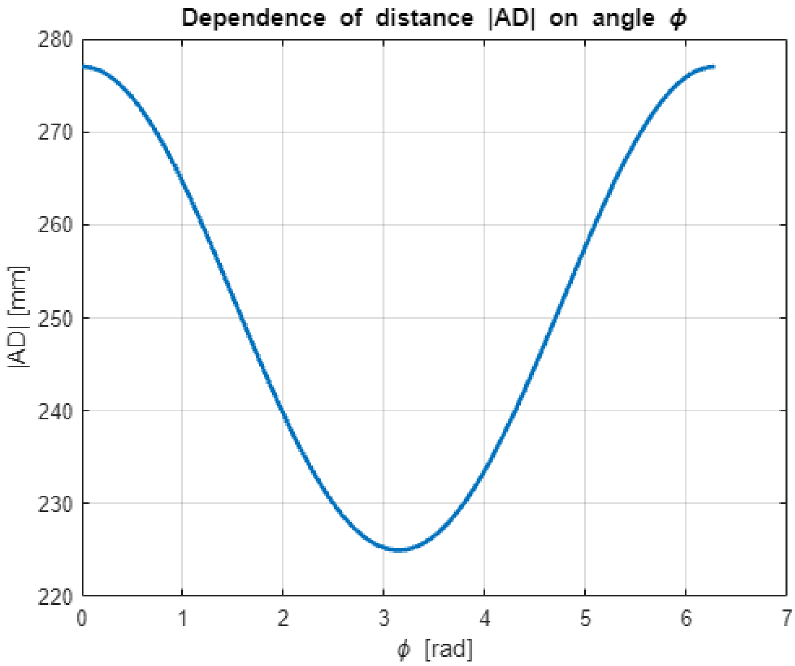

Figure 3 Dependence of distance |AD| on angle φ

3 Derivation of the Velocity of Point D

Below is the derivation of the velocity of point D as a function of the angular velocity $\dot{\varphi}$. At the end, a MATLAB script is presented for visualizing intermediate steps and generating plots.

3.1 Derivation

The expression for the position of point D (on the x-axis) is:

$$D_x(\varphi) = a\cos(\varphi) + c + \sqrt{b^2 - a^2\sin^2(\varphi)}.$$

Point D lies on the x-axis, so its velocity is the derivative of this expression with respect to time:

$$v_D = \frac{dD_x}{dt} = \frac{dD_x}{d\varphi} \cdot \frac{d\varphi}{dt} = \frac{dD_x}{d\varphi} \dot{\varphi}.$$

First, compute the derivative $\frac{dD_x}{d\varphi}$.

3.1.1 Component Derivatives:

$$\frac{d}{d\varphi}[a\cos(\varphi)] = -a\sin(\varphi),$$

$$\frac{d}{d\varphi}[c] = 0,$$

$$\frac{d}{d\varphi}\left[\sqrt{b^2 - a^2\sin^2(\varphi)}\right] = \frac{1}{2\sqrt{b^2 - a^2\sin^2(\varphi)}} \cdot \left(-2a^2\sin(\varphi)\cos(\varphi)\right).$$

Simplifying:

$$\frac{d}{d\varphi}\left[\sqrt{b^2 - a^2\sin^2(\varphi)}\right] = -\frac{a^2\sin(\varphi)\cos(\varphi)}{\sqrt{b^2 - a^2\sin^2(\varphi)}}.$$

Combining these:

$$\frac{dD_x}{d\varphi} = -a\sin(\varphi) - \frac{a^2\sin(\varphi)\cos(\varphi)}{\sqrt{b^2 - a^2\sin^2(\varphi)}}.$$

3.2 Final Formula and MATLAB script

Introducing $\dot{\varphi}$, the velocity $v_D(\varphi)$ is:

$$\boxed{v_D(\varphi) = \dot{\varphi}\left[-a\sin(\varphi) - \frac{a^2\sin(\varphi)\cos(\varphi)}{\sqrt{b^2 - a^2\sin^2(\varphi)}}\right]}.$$

```
% Script 2
% Derivation of the formula for the velocity of point D


% Define symbolic variables
syms a b c phi phi_prime real


% Position of point D, expressed earlier:
D_x = a*cos(phi) + c + sqrt(b^2 - a^2*sin(phi)^2);


% Derivative dD_x/dphi
dDxdphi = diff(D_x, phi);


% Define angular velocity: phi_prime = dphi/dt
% Velocity of point D:
v_D = dDxdphi * phi_prime;
```

```
% Plots
% Assume example values for a, b, c, and a constant angular velocity phi_prime
a_val = 26;
b_val = 70;
c_val = 181;
phi_prime_val = 1; % [rad/s], for example


phi_vals = linspace(0, 2*pi, 200);


% Calculate AD as a function of phi (distance)
AD_expr = a*cos(phi) + c + sqrt(b^2 - a^2*sin(phi)^2);
AD_numeric = subs(AD_expr, [a b c], [a_val b_val c_val]);
AD_vals = double(subs(AD_numeric, phi, phi_vals));


% Calculate velocity v_D as a function of phi
v_D_expr = subs(v_D, [a b c phi_prime], [a_val b_val c_val phi_prime_val]);
v_D_vals = double(subs(v_D_expr, phi, phi_vals));


% Plot of velocity v_D as a function of phi
figure
plot(phi_vals, v_D_vals, 'LineWidth', 2, 'Color', 'r')
grid on
xlabel('\phi [rad]')
ylabel('v_D [mm/s]')
title('Velocity of point D as a function of \phi')
```

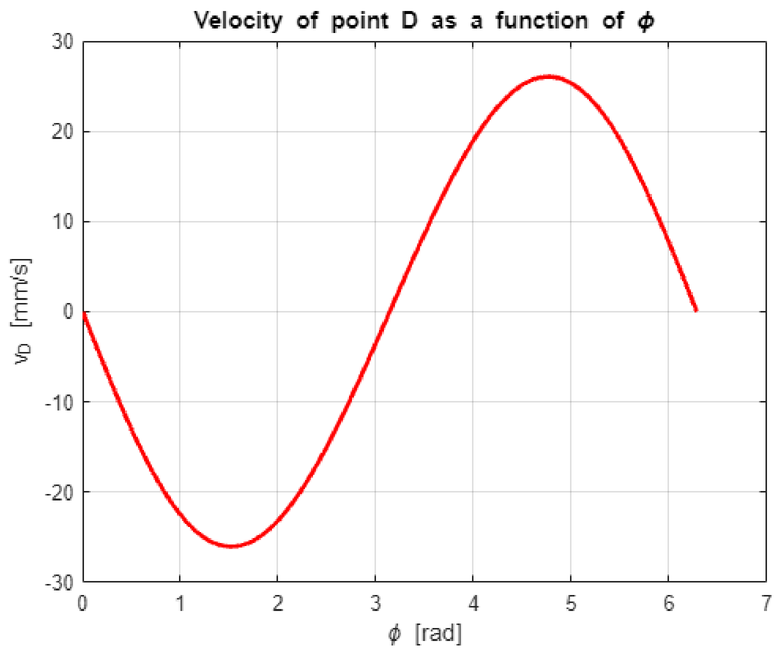

Figure 4 Velocity of point D as a function of φ

```
clear all
```

```
% Determining phi_prime as a function of v_D
% a, b, c given, phi - angle, v_D - constant linear velocity, phi_prime = dphi/dt

syms a b c phi v_D real

% Expression for the position D_x(phi) from previous derivations:
D_x = a*cos(phi) + c + sqrt(b^2 - a^2*sin(phi)^2);

% Derivative dD_x/dphi:
dDxdphi = diff(D_x, phi);

% Expression for v_D:
% v_D = phi_prime * dDxdphi => phi_prime = v_D / dDxdphi
phi_prime = v_D / dDxdphi;

% Assume example values:
a_val = 26;
b_val = 70;
c_val = 181;
v_D_val = 10; % Example constant linear velocity

% Define two ranges of the angle
phi_vals_1 = linspace(0.1, pi - 0.1, 100); % First range <0.1, pi-0.1>
phi_vals_2 = linspace(pi + 0.1, 2*pi - 0.1, 100); % Second range <pi+0.1, 2pi-0.1>

% Combine the two ranges into one vector
phi_vals = [phi_vals_1, phi_vals_2]; % Concatenating vectors

% Use arrayfun to compute a numeric array of values:
phi_prime_numeric = arrayfun(@(ph) double(subs(phi_prime, ...
    [a b c v_D phi], [a_val b_val c_val v_D_val ph])), phi_vals);

% Now phi_prime_numeric is a vector of angular velocity values
% corresponding to the phi values in phi_vals.

figure
plot(phi_vals, phi_prime_numeric, 'LineWidth', 2)
grid on
xlabel('\phi [rad]')
ylabel('\phi'' [rad/s]')
title('Angular velocity \phi'' as a function of \phi for constant v_D = 10 [mm/s]')
```

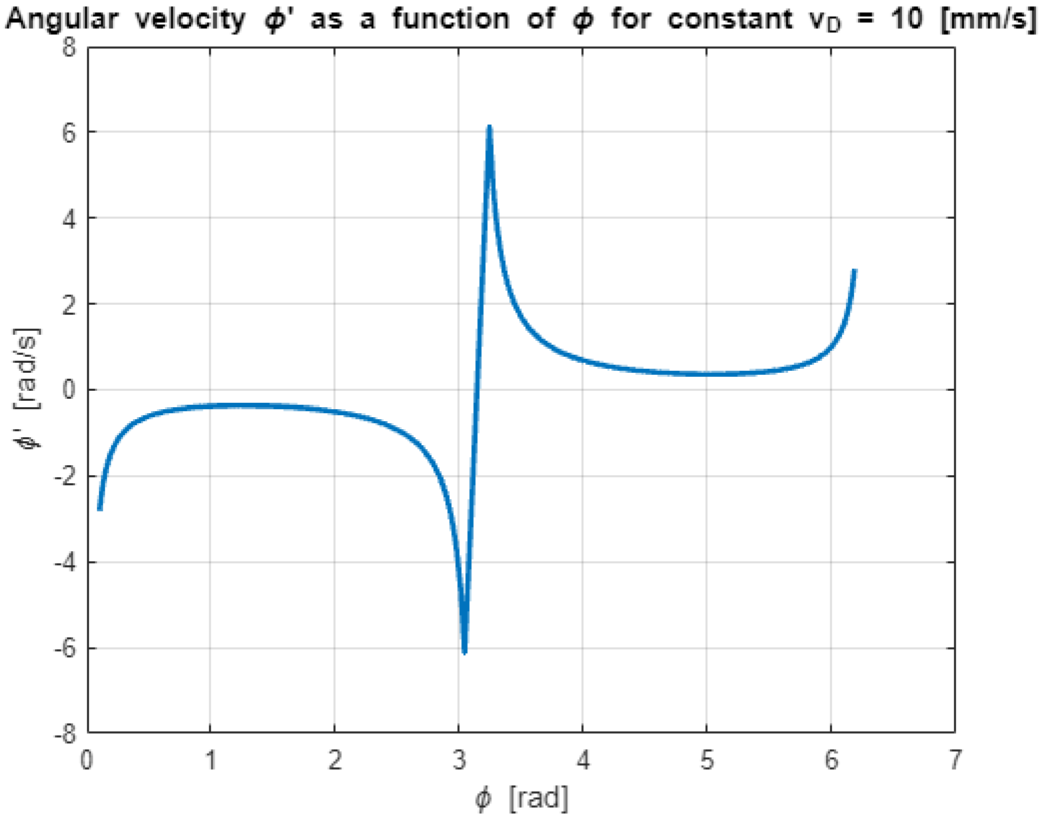

Figure 5 Angular velocity $\dot{\varphi}$ as a function of φ for constant $v_D = 10$ [mm/s]

4 Indentation Depth Under Static Burnishing

This section presents a step-by-step procedure for determining the indentation depth when a steel spherical indenter plastically deforms an aluminum sample under a static load F. In this version, we explicitly show how to solve the Brinell equation for the indentation diameter d.

4.1 Assumptions and Model

- **Burnisher Head:** A sphere with a diameter of $s = 3\,\mathrm{mm}$. The radius of the sphere:

  $$R = \frac{s}{2} = 1.5\,\mathrm{mm} = 0.0015\,\mathrm{m}.$$

- **Mass of the Head:** $m = 20\,\mathrm{g} = 0.02\,\mathrm{kg}$.

4.2 Overview of the Process

- A constant force F is applied via a spherical indenter onto the aluminum sample.
- The resulting plastic indentation on the surface has a measurable (or computable) diameter d.
- Using the Brinell hardness relationship, we link the indentation diameter d to the applied force F.
- Once d is known, the indentation depth δ can be found via spherical geometry.

4.3 Brinell Hardness Equation and solving for d

For a spherical indenter of diameter $D = 2R$ pressed into a material (e.g., aluminum) with an applied force F, the Brinell hardness (HB or BHN) is classically defined by

$$\mathrm{HB} = 0.102 \frac{2\,F}{\pi\,D\left(D - \sqrt{D^2 - d^2}\right)},$$

where

- F is the applied load (in newtons, N),
- D is the indenter diameter (in millimeters, mm),
- d is the measured (or unknown) diameter of the indentation (in mm).

If you know both HB (hardness) and F (applied load) and want to calculate the indentation diameter d, you can rearrange the Brinell equation:

$$d = \sqrt{\frac{0.408F}{\pi D\,\mathrm{HB}} - \left(\frac{0.204F}{\pi D\,\mathrm{HB}}\right)^2}.$$

In practice, you may also solve the original Brinell equation numerically for d, but this closed-form manipulation is a direct approach.

4.4 Indentation Depth via Spherical Geometry

Once d is determined (from either measurement or the rearranged Brinell equation), the indentation depth δ is computed by a simple geometrical formula for a spherical cap:

$$\delta = R - \sqrt{R^2 - \left(\frac{d}{2}\right)^2}.$$

Here,

- R is the radius of the spherical indenter (in mm),
- d is the diameter of the imprint (in mm),
- δ is the depth of the imprint (in mm).

4.5 Step by step procedure

1. Apply the static load F on the aluminum sample with the steel ball indenter by moving the burnisher into the workpiece (read the value of F on the HMI screen)
2. Start the rotation of the aluminium workpiece on the lathe and engage the lathe feed
3. Stop the lathe
4. Perform the steps 1-3 for different values of F applying them to different sections of the workpiece.
5. Dismount the workpiece
6. Calculate and measure the diameter of the indentation d:

- Direct measurement: Use a microscope, profilometer, or optical device to measure d.
- Calculation (Brinell):
  - Take known values of F, HB, and D.
  - Use

$$d = \sqrt{\frac{0.408F}{\pi D\ \mathrm{HB}} - \left(\frac{0.204F}{\pi D\ \mathrm{HB}}\right)^2},$$

  to find d.

7. Compute the indentation depth δ using:

$$\delta = R - \sqrt{R^2 - \left(\frac{d}{2}\right)^2}$$

8. Compare the measurement to the calculations

4.6 Example

The static burnishing tests were carried out on an AW-5754 aluminum shaft (hardness: 75 [HBW], diameter: 106.5 [mm]) mounted on a lathe, operated at 100 [rpm] with a feed of 1 [mm/rev]. Three static burnishing tests were conducted with normal loads of 16, 30, and 45 [N] (see Table I):

Table I. Indentation depth data for static burnishing

Load F[N]	**Calculations** $\delta[\mu m]$	**Measurement** $\delta[\mu m]$
16	6.22	6.2
30	11.64	10.41
45	17.42	16.72

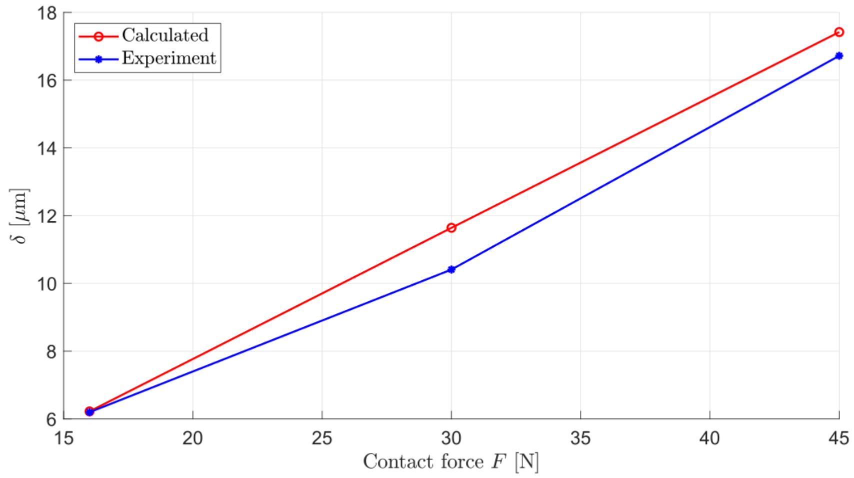

Figure 6 Comparison of calculated vs. experimentally measured indentation depths (δ) in static burnishing.

Static burnishing experiments were conducted with the servo motor set to a fixed angular position so that the normal load on the workpiece remained constant throughout the process. Although the theoretical curves slightly overpredict depths at some intermediate points, the overall correlation with the measured data is strong.

The surface was examined using a Mitutoyo SJ-210 profilometer.

4.7 Practical Notes

- Material Properties: The hardness of aluminum depends on its alloy composition and treatment. Ensure the hardness (HB) corresponds to your specific material condition.
- Indenter Hardness: The steel ball (often tungsten carbide in real Brinell tests) should be significantly harder than aluminum, so it does not deform.
- Accuracy: Surface finish, sample preparation, and force application duration can affect the measured indentation diameter and final results.

This procedure and these formulas enable you to quantify the indentation depth δ under static plastic deformation for an aluminum sample using a steel spherical indenter of radius $R = 3\,\mathrm{mm}$.

5 Indentation Depth Under Dynamic Burnishing

The following calculations assume that the entire kinetic energy of the burnisher head is used for permanent deformation (indentation) in the soft material (aluminum). In practice, to fully determine the force and depth of indentation, material properties (e.g., hardness H or yield strength of aluminum) are required.

5.1 Assumptions and Model

- **Burnisher Head:** A sphere with a diameter of $s = 3\,\mathrm{mm}$. The radius of the sphere:

$$R = \frac{s}{2} = 1.5\,\mathrm{mm} = 0.0015\,\mathrm{m}.$$

- **Mass of the Head:** $m = 20\,\mathrm{g} = 0.02\,\mathrm{kg}.$

- **Impact Velocity:** v_d (assumed to be known and constant).

The burnisher head presses into aluminum, creating an indentation. It is assumed that the process is dominated by plastic deformation, and the concept of hardness (H) is used. Hardness H (in Pa) is defined as:

$$H = \frac{F}{A},$$

where F is the force and A is the contact area at the indentation state.

5.2 Contact Area

For small spherical indentations, the contact area can be approximated as:

$$a(\delta) \approx \sqrt{2R\delta},$$

where δ is the depth of the indentation. The contact area is then given by:

$$A(\delta) = \pi a(\delta)^2 = \pi(2R\delta).$$

5.3 Force Pressing the Sphere

The force pressing the sphere at an indentation depth δ is given by the definition of hardness:

$$F(\delta) = H \cdot A(\delta) = H \cdot \pi(2R\delta) = 2\pi RH\delta.$$

5.4 Kinetic Energy and Indentation Depth

The kinetic energy of the burnisher head before impact is:

$$E = \frac{1}{2}mv_d^2.$$

This energy is entirely used for deformation:

$$E = \int_0^\delta F(\delta)\, d\delta.$$

Substituting $F(\delta) = 2\pi RH\delta$:

$$E = \int_0^\delta 2\pi RH\delta\, d\delta = 2\pi RH\frac{\delta^2}{2} = \pi RH\delta^2.$$

Equating the two expressions for energy:

$$\frac{1}{2}mv_d^2 = \pi RH\delta^2.$$

Solving for δ:

$$\delta = \sqrt{\frac{mv_d^2}{2\pi RH}}.$$

5.5 Maximum Force

The maximum force (achieved at the maximum indentation depth δ) is:

$$F_{\text{max}} = F(\delta) = 2\pi RH\delta = 2\pi RH\sqrt{\frac{mv_d^2}{2\pi RH}}.$$

Simplifying:

$$F_{\text{max}} = v_d\sqrt{2\pi RHm}.$$

The velocity v_D was calculated in section 3.2 and is equal to:

$$v_D(\varphi) = \dot{\varphi}\left[-a\sin(\varphi) - \frac{a^2\sin(\varphi)\cos(\varphi)}{\sqrt{b^2 - a^2\sin^2(\varphi)}}\right]$$

5.6 Summary of Key Formulas and MATLAB script

- **Depth of indentation:**

$$\boxed{\delta = \sqrt{\frac{mv_d^2}{2\pi RH}}}.$$

- **Maximum force:**

$$\boxed{F_{\text{max}} = v_d\sqrt{2\pi RHm}}.$$

```
% Script 3
% Determining force and indentation depth


%% Symbolic data
syms m v_d R H real
syms delta real


% Kinetic energy
E = (1/2)*m*v_d^2;


% Energy equation:
% E = pi*R*H*delta^2
% delta^2 = E/(pi*R*H)
% delta = sqrt(E/(pi*R*H))


delta_expr = sqrt(E/(pi*R*H));


% Maximum force:
% F_max = F(delta) = 2*pi*R*H*delta
F_max_expr = 2*pi*R*H*delta_expr;


%% Substituting example values
m_val = 0.02;      % kg
v_d_val = 1;        % m/s
```

```
R_val = 0.0015;     % m (radius 1.5mm)
H_val = 5e8;        % Pa


delta_num = double(subs(delta_expr, [m v_d R H], [m_val v_d_val R_val H_val]));
F_max_num = double(subs(F_max_expr, [m v_d R H], [m_val v_d_val R_val H_val]));


%% Plotting dependence on velocity v_d
v_d_values = linspace(0.1, 3, 100);


% Here, delta_expr and F_max_expr are single scalar expressions
% For each v_d, substitute values to get a scalar result


delta_values = arrayfun(@(vd) double(subs(delta_expr, [m R H v_d], [m_val R_val
H_val vd])), v_d_values);
F_values = arrayfun(@(vd) double(subs(F_max_expr, [m R H v_d], [m_val R_val H_val
vd])), v_d_values);


figure
subplot(2,1,1)
plot(v_d_values, delta_values*1000, 'LineWidth', 2)
grid on
xlabel('v_d [m/s]')
ylabel('delta [mm]')
title('Indentation depth as a function of velocity')


subplot(2,1,2)
plot(v_d_values, F_values, 'LineWidth', 2, 'Color', 'r')
grid on
xlabel('v_d [m/s]')
ylabel('F_{max} [N]')
title('Maximum force as a function of velocity')
```

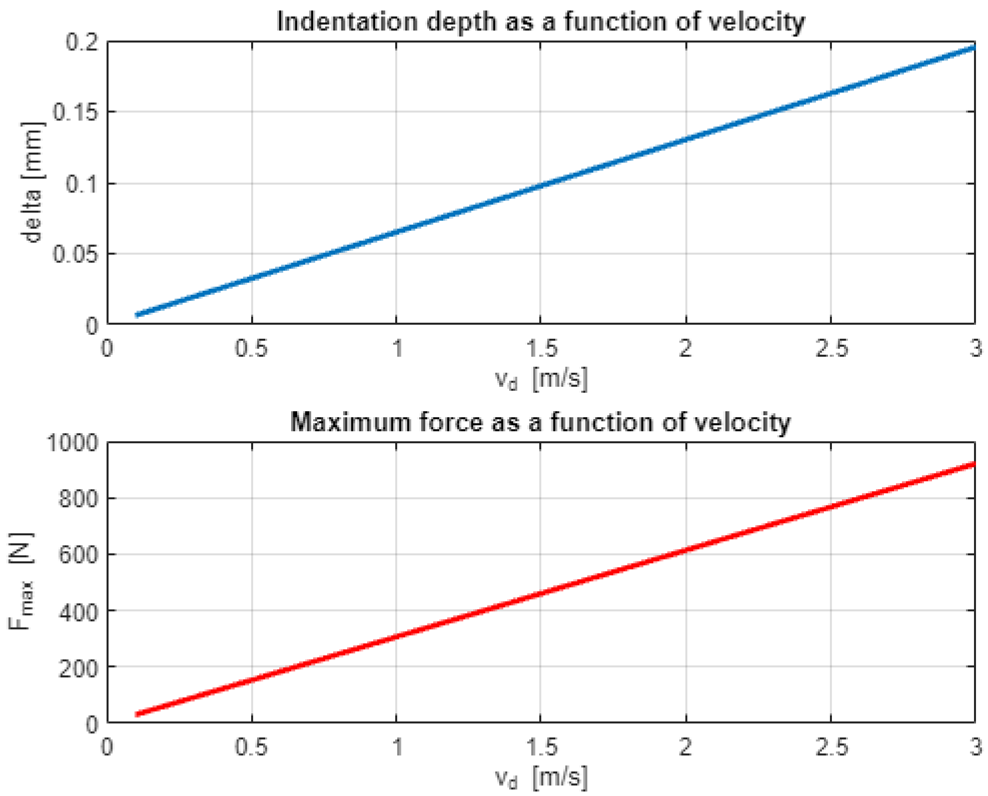

Figure 7 Indentation depth and maximum force as a function of velocity

5.7 Step by step procedure

1. Move the tip of the burnisher towards the workpiece until it makes contact. Read the value of force F (or spring deformation Δ) when the mechanism's arms are fully extended (this represents the additional static force applied to the workpiece by inner spring compression).
2. Set the servo angular velocity to, for example, $\dot{\varphi} =$ **500 rpm**
3. Start the rotation and engage the lathe feed.
4. Stop the lathe and the servo
5. Perform the steps 1-3 for different values of F or Δ and servo rpm, applying them to different sections of the workpiece.
6. Dismount the workpiece
7. Calculate and measure the velocity v_D and the depth of the indentation :

$$v_D(\varphi) = \dot{\varphi}\left[-a\sin(\varphi) - \frac{a^2\sin(\varphi)\cos(\varphi)}{\sqrt{b^2 - a^2\sin^2(\varphi)}}\right],$$

$$\delta = \sqrt{\frac{mv_d^2}{2\pi RH}}.$$

8. Compare the measurement of δ to the calculations

5.8 Example

The static burnishing tests were carried out on the same aluminum shaft as in static burnishing. Twelve dynamic burnishing tests with the 30g burnisher head were performed, measuring the final indentation depth δ at four different servo angular velocities $\dot{\varphi}$ = 100, 250, 350, 500 [rpm] and three preset spring compressions Δ = 1, 2.5, 5 [mm]. (see Table II):

Table III. Indentation depth data for dynamic burnishing

Angular velocity $\dot{\varphi}$[rpm]	**Spring deformation** Δ [mm]	**Calculations** $\delta[\mu m]$	**Measurement** $\delta[\mu m]$
100	1	8.37	8.96
250	1	10.69	8.84
350	1	12.24	11.83
500	1	14.56	15.48
100	2.5	11.48	10.92
250	2.5	14.99	13.95
350	2.5	17.33	16.74
500	2.5	20.84	19.40
100	5	16.58	14.48
250	5	21.18	16.91
350	5	24.25	23.57
500	5	28.86	35.70

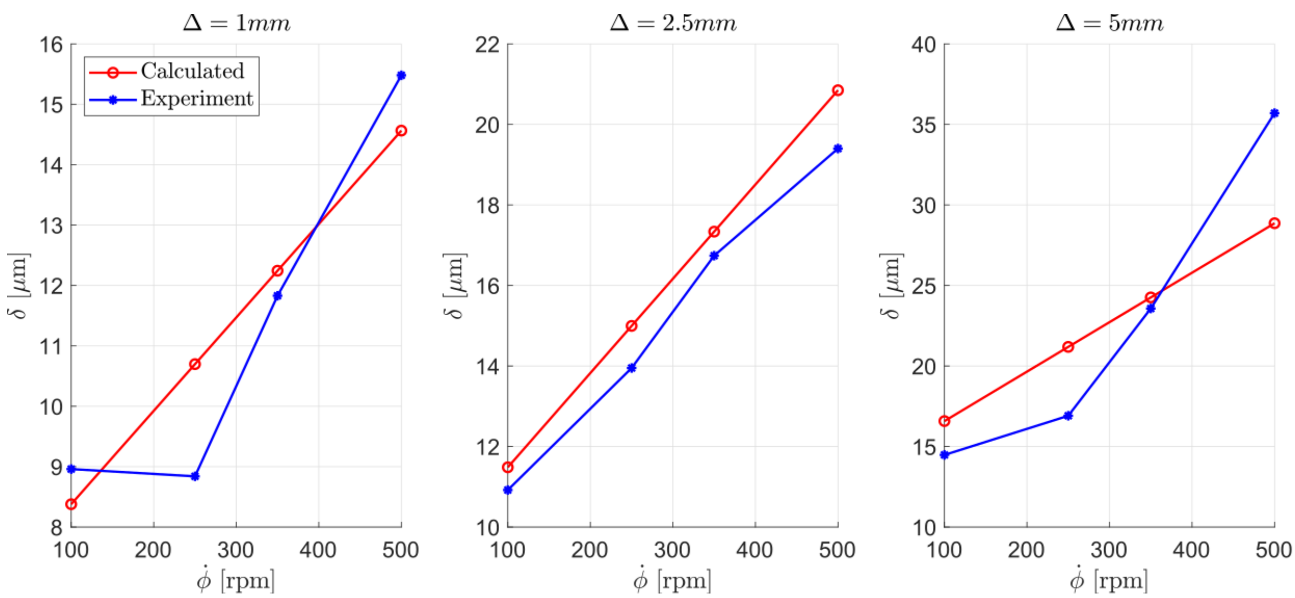

Figure 8 Comparison of calculated vs. experimentally measured indentation depths (δ) in dynamic burnishing for three levels of initial spring compression (Δ).

The figure 8 illustrates the correlation between dynamic burnishing parameters, specifically servomotor angular velocity $\dot{\varphi}$, initial spring compression Δ and the resulting indentation depth in aluminum. As the angular velocity increases, the higher the relative velocity of the burnisher head imparts a greater kinetic energy to the contact interface, causing deeper plastic deformation. Likewise, elevating the spring compression amplifies the normal force, further promoting material flow under the spherical tool and thereby increasing the observed indentation. Minor deviations between experimental measurements and theoretical predictions probably arise from factors such as friction, slight misalignments in the linkage, and localized heating effects. However, the overall consistency between the modeled and measured data affirms that higher angular velocity and larger spring preload systematically lead to more pronounced surface densification under dynamic burnishing conditions.

5.9 Practical Notes

- In dynamic burnishing, the contact between the burnisher head and the workpiece is maintained until the mechanism arm is fully extended. This means that the deformation is not only a result of the impact but also includes additional static deformation.