14. Cutting Test on a Steel Bar

(Adapted from the final exam 2024)

A cutting test on a steel bar was performed, and the following values were reported:

- $F_c = 680$ N the shear force
- $F_t = 380$ N the thrust force
- R the resultant force
- F_s the shear force on shear plane
- F the friction force along rake plane
- N the normal force to rake face
- $\phi = 25.0°$ the shear angle
- $\alpha = 10.0°$ the rake angle
- β the mean friction angle

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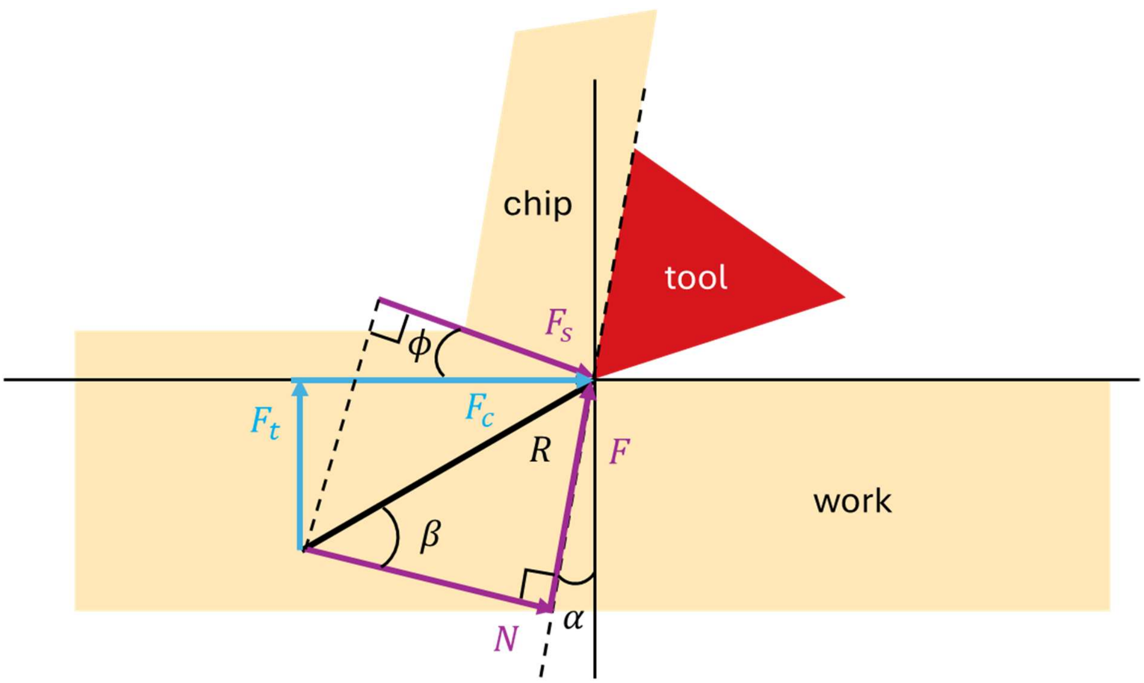
1. Draw a force diagram at the tool-chip-work interface, to scale, to show the graphical relationship between these parameters.



For this test, the following values were noted:

- $w = 3.50$ mm the width of cut
- $t_0 = 0.210$ mm the undeformed chip thickness
- t_c the deformed chip thickness

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2. Compute (a) the reaction force R, (b) the friction angle β, (c) the shear force on shear plane F_s, (d) the friction force along rake face F, (e) the normal force to rake face N, (f) the apparent shear stress τ_s, (g) the apparent friction coefficient μ and (h) the cutting ratio r.

$$R = \sqrt{F_c^2 + F_t^2} \cong 779 \text{ N}$$

$$\beta = \text{atan}\left(\frac{F_t}{F_c}\right) + \alpha = 29.2° + 10.0° = 39.2°$$

Double-check: $F_c = R \cdot cos(\beta - \alpha) = 680 \text{ N}$

$$R = \frac{F_s}{\cos(\phi + \beta - \alpha)} \Leftrightarrow F_s = R \cdot \cos(\phi + \beta - \alpha) \cong 456 \text{ N}$$

$$F = R \cdot \sin(\beta) = 779 \cdot \sin(39.2) \cong 492 \text{ N}$$

$$\tan(\beta) = \frac{F}{N} \Leftrightarrow N = \frac{F}{\tan(\beta)} \cong 603 \text{ N}$$

$$\tau_s = \frac{F_s}{A_s} = F_s \cdot \left(\frac{wt_0}{\sin(\phi)}\right)^{-1} \cong 262 \text{ MPa}$$

$$\mu = \tan(\beta) = 0.816$$

$$r = \frac{\sin(\phi)}{\cos(\phi - \alpha)} = 0.438$$

3. The cutting speed was $V = 1.00 \text{ m/s}$ and the mass flow rate $m = 3.50 \text{ g/s}$. Specific heat capacity of the work material is $C = 500 \text{ J/kg/°C}$. Determine the temperature T_s **at the shear plane** assuming 90% of heat is transported with the chip and the original work material temperature was $T_o = 20°\text{C}$.
   - The power dissipated through the chip is $P_{chip} = mC\Delta T$.
   - You can use the law of sines applied to the velocity diagram:
     $$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos(\alpha)} = \frac{V_c}{\sin(\phi)}$$
     where V is the cutting speed, V_s is the speed at which shearing takes place in the shear plane and V_c is the speed of the chip.

We first compute

$$V_s = \frac{\cos(\alpha)}{\cos(\phi - \alpha)} V \cong 1.02 \text{ m/s}$$

As we are considering the temperature at the cutting plane or shear plane, we have

$$P_{shear} = F_s V_s$$

Using the statement about power dissipation, we have

$$P_{chip} = 0.90 P_{shear}$$

$$T = \Delta T + T_o = \frac{0.90 F_s V_s}{mC} + T_o = \frac{0.90 \cdot 456 \cdot 1.02}{0.00350 \cdot 500} + 20 \cong 259°\text{C}$$

4. Where is the maximum temperature in orthogonal cutting located? Note that there are two principal sources of heat: the shear plane and the tool-chip interfaces.

It is reasonable that the maximum temperature in orthogonal cutting is located at about the middle of the tool-chip interface. The chip reaches high temperatures in the primary shear zone; the temperature would decrease from then on as the chip climbs up the rake face of the tool. If no frictional heat was involved, we would thus expect the highest temperature to occur at the shear plane. However, recall that friction at the tool-chip interface also increases the temperature. After the chip is formed it slides up the rake face and temperature begins to build up. Consequently, the temperature due only to frictional heating would be highest at the end of the tool-chip contact. These two opposing effects are additive, and as a result the temperature is highest somewhere in between the tip of the tool and the end of contact zone.

5. Compute the chip velocity V_c and chip thickness t_c.

Chip velocity:

$$V_c = V_s \cdot \frac{\sin(\phi)}{\cos(\alpha)} = V \cdot \frac{\sin(\phi)}{\cos(\phi - \alpha)}$$

$$V_c = 0.438 \text{ m/s}$$

Chip thickness: from the **continuity equation**, $Vt = V_c t_c$ and we can compute

$$t_c = t\frac{V}{V_c} = 0.210 \cdot \frac{1.00}{0.438} \cong 0.479 \text{ mm}$$

6. Answer to the following questions in a few words:
   a. How does the coolant help the cutting process in terms of mechanical properties?

The coolant liquid is transferred into the pores of the processed material reducing its surface toughness and reducing cohesion between particles (thus facilitating fracture). Friction forces decrease as a result of this action of the coolant.

   b. What action may be taken to reduce the rise in coolant temperature in a turning operation, without changing the turning parameters?

The cooling can be improved through steam generation.

7. True or false? Please justify your answers!
   a. For the same depth of cut and rake angle, the type of cutting fluid used has no influence on chip thickness.

The answer is FALSE, because the cutting fluid will influence friction, hence the shear angle and, consequently, the chip thickness.

   b. High-speed cutting can be performed without the use of cutting fluids.

The answer is TRUE. High-speed cutting without cutting fluids can be done using appropriate tool materials and processing parameters. Just think about sawing a metal plate... and recall that in high-speed machining, most of the heat is conveyed from the cutting zone through the chip, so the need for a cutting fluid is less (sparks...).

15. Lead-Frames Manufacturing in Electronics

1. Discuss the optimal choice of material for lead-frames. Which physical properties are relevant in this context and should be optimized? Is there any better material than lead that one could use? Follow the methodology learned in the first exercise. Use the Granta EduPack software to generate a useful Ashby plot (available on the STI-WINDOWS10 virtual machine).

Step 1. We would like to:

- Minimize the contact pads resistance

$$R = \rho_e \cdot \frac{L}{A}$$

- Minimize the force to apply during the forming process, in order to bend the pads efficiently

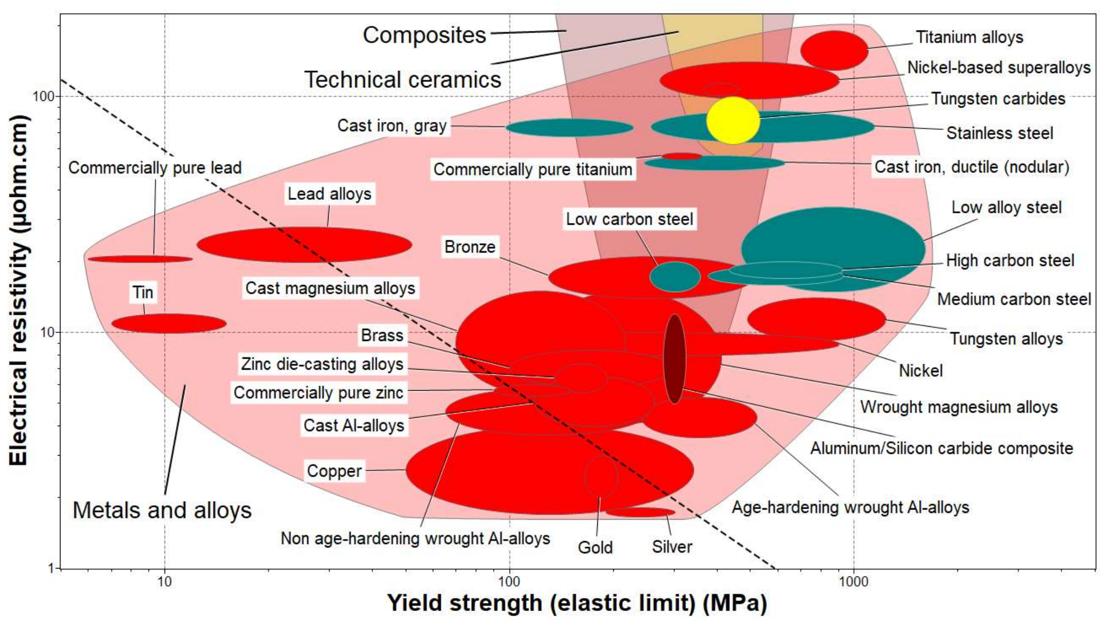
$$F_{perm.strain.} = \sigma_y \cdot A$$

Step 2. Let us define an objective function to optimize:

$$R \cdot F_{perm.strain.} = \rho_e \cdot \sigma_y \cdot L$$

Step 3. As we want to maximize conductivity (or minimize resistivity), while minimizing the yield strength (in relation with ductility), the material parameter function is simply the product of yield strength σ_y and electrical resistivity ρ_e ($C = \sigma_y \cdot \rho_e$); it should be minimized. In particular, remember that the yield strength represents the force to apply before permanently deforming a material. In our case, we want to bend (i.e., permanently deform) the metal pins...

Step 4. We can visualize the function on the Ashby plot that we generated using Granta EduPack. To compare the results with lead, we plot a line passing through the center of the "lead alloys". We see that several metals might be selected instead of lead such as tin, copper, gold or silver.



2. Select four possible processes that would work for producing these parts and discuss for each of them what would be the pros and cons.

Process	Pros	Cons
Laser cutting	• no tooling • versatile (easily reconfigurable) • can achieve high resolution	• serial process • may create heat affected zones • processing time
Electro-discharge machining (EDM)	• high quality • high precision	• serial process • slow : requires passing the wire multiple times • wires are consumables • processing time
Chemical etching	• parallel process • can be high precision	• requires a mask • use of chemicals
Stamping (« estampage »)	• fast : one shot per piece	• requires expensive tooling (stamps)

Another possible process: *water-jet cutting* as well as combination of water-jet and laser…

3. Among your propositions and arguing with logical arguments, propose one process (or two) that are likely to be chosen for such application. Try to guess which process was used for each of the three examples on the figure.

Lead frames typically are high-level production, which would exclude laser processing and EDM for this type of application.

EDM for instance, would not be an optimal use of the process, as the parts are thin (while EDM is good at making high-aspect ratio structures). Note that layers could be stacked up and cut through. However, it remains the difficulty of passing the wire through the structure multiple times to actually cut the contours.

Stamping is a good candidate process as it does one complete lead frame at a time. In fact, this is the process used in the middle and right examples in **Figure 17**. It is a cheap process, even if requires expensive tooling (typically done by EDM). This is acceptable for very high production levels.

Chemical etching is another good candidate. Used in the case of the left example in **Figure 17**. Note that it would also work for the two other examples. It can achieve higher accuracy than stamping but requires handling hazardous chemicals.