Forming - Tool materials for forming tools

Manufacturing Technology II
Exercise 8

Laboratory for Machine Tools and Production Engineering
Chair of Manufacturing Technology

Prof. Dr.-Ing. Dr.-Ing. E.h. F. Klocke
Table of Contents

Table of Contents ......................................................................................................2

1 Objectives of the exercise ..................................................................................3

2 Types of stress to which tools are exposed .....................................................4

3 Tool damage and wear .....................................................................................6
   3.1 Types of damage .......................................................................................6
   3.2 Causes of damage and their mechanisms ...............................................6

4 Base material and boundary layer .................................................................10
   4.1 Requirements to be met by forming tools ..............................................10
   4.2 Methods of modifying the subsurface layer selectively .........................12

5 Exercises ...........................................................................................................17
1 Objectives of the exercise

This exercise focuses on the selection of materials suitable for tools used in forming operations.

Each tool is exposed to process-specific stresses which can result in a range of types of damage. Any attempt to ensure that the optimum tool material and method of treatment are selected, must therefore begin with an examination of the load factors involved in the case in question. Process-specific types of damage are therefore explained at the beginning of the exercise. This is followed by a description of the types of damage sustained by tools and of the causes of wear. The demands to be met by the tool material and by the subsurface must be investigated separately. In the last part of the exercise, it will be possible to select the most appropriate material for the case in hand, from the tool construction materials which are available.
2 Types of stress to which tools are exposed

The types of tool load sustained in a range of non-chip forming manufacturing techniques, are shown in Fig. 2.1.

The upper die of cutting tools is exposed to shock-like compressive and bending loads. The cutting and the lateral area is affected by wear strain as a result of friction between the workpiece and the tool. The bottom die is exposed to pressure and is subjected to mainly sliding friction (wear). The face of the upper die and the surface of the lower die should have as high a friction co-efficient as possible, whilst the lateral area of the upper die should have a low friction co-efficient so that the sheet does not move during the cutting operation.

The situation in deep drawing operations is similar. Here, the upper die is exposed mainly to pressure and only to a low level of bending load, the lower die is exposed mainly to friction and to a lesser degree to pressure. As in the cutting operation, care must be taken to ensure that the sheet does not flow at the upper die area. The friction co-efficient should therefore be as high as possible at the rounding of the upper die but low at the rounding of the drawing ring.

In forward extrusion operations, compressive and temperature stresses occur at the upper die and compressive, tensile, friction and thermal stresses at the lower die. Thermal load also develops in cold extrusion operations as a result of the inner friction during material flow.

The situation in the case of reverse extrusion is similar, although the upper die is additionally affected by bending and friction stresses.

The types of stress listed, also occur in varying degrees in other processes such as extrusion, forging, pressure casting and shell casting. The high operating temperatures are particularly liable to cause stresses which are generally masked in forging operations by additional shock stress.
Type of load
- Tensile
- Pressure
- Bending
- Friction
- Temperature
- Impact

**Forging**

**Blanking**

**Deep drawing**

**Forward extrusion**

**Reverse extrusion**

Fig. 2.1: Tool load in various manufacturing processes
3 Tool damage and wear

3.1 Types of damage

The types of damage shown in Fig. 3.1.1, occur as a result of the types of stress previously described. These may render the tool unfit for use and include:

- Wear
- Mechanical crack formation
- Thermal crack formation
- Plastic deformation.

Fig. 3.1.1: Types of damage which affect forming tools

3.2 Causes of damage and their mechanisms

Since wear is the most important type of damage, it makes sense to investigate its causes in more detail.
There is no one material characteristic which provides a conclusive indication in itself, as to the level of wear resistance of that material. This is because in the vast majority of cases, a number of causes interact and combine to cause wear in the tribo-technical systems in industrial practice, (Fig. 3.2.1).

These include:

- Adhesion
- Abrasion
- Surface break-up and
- Tribo-chemical reaction.

![Fig. 3.2.1: Causes of wear](image)

Wear inhibiting coatings are frequently equated with hard coatings. This may be true in the case of abrasive wear, in which there is a correlation in many cases between surface hardness and wear resistance. However, this does not apply to other types of wear or to a combination of stresses, since factors other than hardness, such as surface design, toughness etc. are also important.
The most important wear mechanisms and means of reducing wear, are therefore discussed briefly in the following (Fig. 3.2.2).

**Adhesive wear** occurs when bonding forces in the area of the atomic lattice take effect between two metallic materials. The prerequisite for this, is that the lattices of the bodies concerned, are structurally similar and that they approach one another until there is only a short distance between them. Furthermore, the more the lattice structures of the materials concerned differ, the lower is their susceptibility to adhesive wear.

**Abrasive wear** occurs when the harder of the two bodies involved in the wear process, has pronounced roughness beaks, which tear particles of material from the surface of the softer body. Materials which are resistant to abrasive wear, have outstanding hardness in comparison with the abrading material.

When there is **surface breakdown**, the crystal and the structural condition is damaged irreversibly as a result of alternating stresses and which depend on the duration and level of stress involved. Surface breakdown is reduced when the strength of a material is high, whereas stress peaks and notch effects result in an increase.
Tribo-chemical reactions occur when the wear processes take place only in the outermost boundary layer of the bodies involved. This boundary, or interfacial layer can be formed by reactions between the material and the surrounding medium. Consequently, the wear characteristics of the base material itself, have no influence on this process. It is not possible to specify any particular material behaviour in order to avoid the tribo-chemical reaction, since the formation and characteristics of the outer boundary layer are determined to an equal degree by the material and by the surrounding medium. Consequently, the lubricant is the primary determining factor.

The various types of damage sustained by tools, are illustrated in Fig. 3.2.3 by the example of a forging die. In 70% of all cases in which tools become unfit for use, wear is the underlying cause. Mechanical cracking occurs in 25% of all cases.

In contrast, plastic deformation and thermal cracking very rarely mark the end of tool life. These results cannot be transferred directly to other forming operations but wear will be the most common type of wear there too, since shock and temperature stress are generally lower in these operations than in forging.
4 Base material and boundary layer

4.1 Requirements to be met by forming tools

Due to the types of stress listed, there are a number of special requirements which must be met by the base material and the boundary layer of tools. These are shown in Fig. 4.1.1. The focus in the following is on the requirements to be met by the wear and strength characteristics.

![Diagram showing requirements and material characteristics]

**Fig. 4.1.1: Requirements to be met by the base material and the subsurface layer**

Tool steels are classified in terms of a number of different criteria. Depending on their composition, distinctions are drawn between unalloyed, low-alloy and high alloy steels. In many cases, they are also classified by the chilling medium as water, oil and air hardeners or by their use in cold work steel, hot work steel, high-speed steel and hard metals, whose operating temperatures, hardness mechanisms and typical alloying elements are listed in Fig. 4.1.2.
There are metallurgical differences in that the base structure can undergo martensitic hardening to various levels, i.e. additional carbides are formed in the base structure.

In some cases when hard metals are used, particularly in the G group of applications, a degree of the wear resistance is sacrificed in order to achieve a higher level of toughness.

Exacting demands relating to the requirements in terms of tool strength, have frequently resulted in the selection of materials which have a certain level of hardness after heat treatment and therefore of wear resistance. When a high degree of wear resistance is required, this can be achieved via increased hardness only when sacrifices can be made with regard to toughness. In this case, the required increase in hardness can be achieved by increasing the carbon content in the martensite and by increasing the martensite content in the structure.

The martensite content after chilling from the hardening temperature (Austenising temperature), is determined by the degree to which the steel can be hardened. This can be increased by alloying in manganese, nickel, chromium molybdenum, tungsten, vanadium etc.

However, when high strength is required in conjunction with high toughness, the hardness of the base structure cannot be increased in order to improve wear resistance. In this case, the wear resistance produced by strength can be increased by ensuring a higher carbide content. However, the proportion of the carbides, and their size, form and distribution can be changed only when there is no risk that toughness will be adversely affected.
The temperatures reached during the operation, are extremely important. The tools are annealed at a temperature in excess of the expected operating temperature in order to reduce the temperature again by an amount which depends on the composition of the steel and the annealing temperature. This eliminates the risk of any unwanted tempering effects when the tool is in use. The hardness of unalloyed steel begins to fall sharply at temperatures above approx. 200°C.

Some of these unwanted effects can be eliminated by alloying the materials with chromium, vanadium and molybdenum.

Fig. 4.1.3 gives an overview of the most frequently used tool materials, their composition and characteristics.

<table>
<thead>
<tr>
<th>cold working steel</th>
<th>X155CrVMo12-1 90MnCrV8</th>
<th>cold extrusion tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot working steel</td>
<td>X38CrMoV5-1 56NiCrMoV7</td>
<td>cold extrusion tools</td>
</tr>
<tr>
<td>high speed steel</td>
<td>HS6-5-2 HS6-5-3-9</td>
<td>cold extrusion tools</td>
</tr>
</tbody>
</table>

**cemented carbide grade**

<table>
<thead>
<tr>
<th>cemented carbide grade</th>
<th>chemical composition</th>
<th>hard.</th>
<th>bending strength</th>
<th>compression strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WC TiC+TaC Co</td>
<td>HV 30</td>
<td>N/mm²</td>
<td>N/mm²</td>
</tr>
<tr>
<td>G30</td>
<td>82 3 15</td>
<td>1200</td>
<td>2400</td>
<td>4100</td>
</tr>
<tr>
<td>G40</td>
<td>77 3 20</td>
<td>1050</td>
<td>2600</td>
<td>3800</td>
</tr>
<tr>
<td>G55</td>
<td>75 - 25</td>
<td>850</td>
<td>2800</td>
<td>3000</td>
</tr>
</tbody>
</table>

**mechanical properties**

- G30: punches, extrusion dies
- G40: extrusion punches (at low bending load), upsetting device, extrusion tools (standard grade of extrusion)
- G55: punches, extrusion dies, upsetting device, extrusion tools (standard grade of extrusion)

**Applications in extrusion tools**

- G30: punches, extrusion dies
- G40: extrusion punches (at low bending load), upsetting device, extrusion tools (standard grade of extrusion)
- G55: punches, extrusion dies, upsetting device, extrusion tools (standard grade of extrusion)

Fig. 4.1.3: Tool materials for extrusion tools

**4.2 Methods of modifying the subsurface layer selectively**

It will be clear from the previous explanations, that the characteristics in the boundary layer of the tool, are very important for wear resistance. A number of techniques can
be used in order to produce these characteristics. The most important of these, will be discussed in the following section.

<table>
<thead>
<tr>
<th>Methods of treating the subsurface layer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hardening of the subsurface layer</strong></td>
</tr>
<tr>
<td><strong>without variation of the chemical composition</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>hardening of subs. layer</td>
</tr>
<tr>
<td>layer thickness max. 5 mm</td>
</tr>
<tr>
<td>hardness max. 66 HRC</td>
</tr>
<tr>
<td>heating by</td>
</tr>
<tr>
<td>- flame</td>
</tr>
<tr>
<td>- induction</td>
</tr>
<tr>
<td>- electron beam</td>
</tr>
<tr>
<td>- laser</td>
</tr>
<tr>
<td>Nitriding</td>
</tr>
<tr>
<td>to a max. depth of 50 µm</td>
</tr>
<tr>
<td>Chromising</td>
</tr>
<tr>
<td>to a max. depth of 10 µm</td>
</tr>
<tr>
<td>Boronising</td>
</tr>
<tr>
<td>to a max. depth of 300 µm</td>
</tr>
<tr>
<td>case hardening</td>
</tr>
</tbody>
</table>

Fig. 4.2.1: Methods of treating the subsurface layer

- **Subsurface hardness**

In this process only one subsurface with a certain thickness (up to a maximum of 5 mm) is hardened selectively. A distinction is drawn between subsurface hardening methods which modify the chemical composition of the subsurface layer (e.g. case hardening, nitriding, treating with boron, chromising) and those which do not modify the chemical composition. Hardness values of up to 66 HRC are achieved, depending on the carbon content of the material and on the depth of the hardening process. The material can be heated by induction, conduction, flame, electron beam or laser. The workpieces most frequently treated using this method, are those which require selective, localised increased resistance to wear in order to ensure toughness. This process is not used for tools which are subjected to high levels of load due to the insufficiently high grain strength.

- **Nitriding**

The concentration of nitrogen in the subsurface in the nitriding operation results in increased hardness due to the lattice distortion. The progression and degree of the increased hardness achieved in identical operations, depends largely on the type of tool steel used. The thickness of the coating is usually 1 µm to 25 µm, occasionally
reaching 50 µm and its hardness can be as high as 1500 HV. High abrasion resistance and good sliding properties of the coating have a positive effect on cold work steel used for drawing, cutting and blanking tools, which are required to have high levels of compression and wear resistance in conjunction with a low level of susceptibility to adhesion. Hot working steel types used in die-casting, pressing and cutting tools at operating temperatures in excess of 250°C, are nitrided, in order to improve the subsurface tempering properties. At temperatures above 500°C, further diffusion can produce a gradual degradation of the nitration coating, which may require to be coated again with nitride after a certain operating time. Any dimensional changes as a result of nitriding are very small, however distortion may occur as a result of incorrect treatment. In the case of unalloyed, steel with a low carbon content, the boundary layer can also be rendered wear resistant by conducting carbonising and nitrogenising (carbon-nitriding) operations simultaneously.

- **Chromising**

The chromising operation is similar to the boronising operation in that chromium is added to the subsurface. In the case of materials containing over 0.6% C, a chromium-carbide layer, which usually measures between 5 µm and 10 µm develops. The chromising operation is conducted at temperatures of between 950°C - 1050°C, the hardness of the layer is approx. 2000 HV. The chromium carbide coating is characterised by a low level of susceptibility to adhesion and reaction, a reduced coefficient of friction and high resistance to friction.

- **Boronising**

In boronising operations, the subsurface of the ferrous materials is enriched with boron, producing a boron layer between 10 µm and 300 µm thick, depending on the treatment temperature and duration and on the material concerned. This results in an increase in volume. After heating and holding at the hardening temperature, boronised parts are generally cooled in a water bath, since salt water cooling can result in cracking due to the sudden cooling effect. The hardness of the boron coating can rise to 2500 HV depending on the steel. Boron treatment has become a technologically and economically satisfactory process only in recent years. Virtually all ferrous products can be boronised. Only high-speed steel should not be treated with boron since it cannot subsequently be hardened. The increase in volume in boronising operations is generally 20% to 25% of the diffusion depth, but can account for up to 80% of the coating thickness in the case of high-alloy materials. Consequently, it should be taken into account when the part is designed.
Case hardening
Case hardening is a subsurface hardening process in which the chemical composition of the subsurface is modified. Depending on how much martensite is required, the subsurface is first carbonised and then hardened. This process is helpful only when the C-content of the steel concerned is below 0.2%.

Example of double hardening with core refining and process-annealing for C10 DIN 17210 carbon steel:

Case-hardening occurs in powders which release C-gas at temperatures of between 880°C and 930°C (higher temperatures reduce the case-hardening time). The workpiece is subsequently cooled slowly in powder (in order to compensate for the stresses at the structural boundaries). It is then re-heated to temperatures of 880°C to 930°C and chilled in oil with a temperature of 20°C in order to refine the core. The workpiece is then process-annealed at a temperature of between 650°C and 680°C and cooled slowly in the furnace, in order to reduce the stresses at the crystalline boundaries again. After cooling, it is heated rapidly to a temperature between 780°C and 800°C, then chilled in water with a temperature of 20°C (re-crystallisation, grain refining and hardening the outer layer; tempering the core). An other option is to temper the workpiece for one hour at a temperature of between 150°C and 175°C in order to relax the upper layer.

Coating
The primary function of the coating of hard material is to prevent contact between the material and the tool during the machining operation and thus to reduce tool wear caused by adhesive and abrasive wear, surface break-down and tribo-chemical reactions on the surface of the cutting material. These processes interact and combine over wide areas and both their causes and their effect on wear are difficult to distinguish from one another in most cases.

Whilst the layer of hard material improves the wear resistance of the coated cutting material, reduces adhesion between the tool and prevents diffusion, the function of the substrate as the carrier of the layer of hard material, is to ensure good adhesion and to lend the composite object consisting of a substrate and a layer, sufficient levels of thermal strength and toughness.

The characteristics of hard material layers are determined by their chemical composition and by their structure, which itself depends on the depositing conditions. Characteristics such as the chemical composition, morphology, structure, texture, residual stress and therefore formation enthalpy, micro-hardness, the thermal
expansion coefficient and the oxidation resistance can also be modified within certain limits by changing the conditions of deposition.
5 Exercises

The selection of a suitable tool material is an important factor in calculating the economic efficiency of the warm reverse extrusion operation (550 °C), in the run-up to deciding whether this technique should be used within the production process. Suitable tool materials can be identified on the basis of an analysis of the types of stress encountered.

a) Which loads affect the punch and the lower die in warm reverse extrusion operations?

<table>
<thead>
<tr>
<th>Tool part</th>
<th>Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punch</td>
<td></td>
</tr>
<tr>
<td>Lower die</td>
<td></td>
</tr>
</tbody>
</table>

b) Wear is the form of damage resulting from the types of load, which occurs most frequently and which can render a warm reverse extrusion tool unfit for use. List and explain briefly the four wear mechanisms which are responsible for this.

<table>
<thead>
<tr>
<th>Causes of wear</th>
<th>Wear mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adhesion</td>
<td></td>
</tr>
<tr>
<td>Abrasion</td>
<td></td>
</tr>
</tbody>
</table>
Surface breakdown

Tribo-chemical reaction
c) Mark the zones in the diagram below, which are susceptible to wear in reverse extrusion operations and label the mechanisms responsible, as listed in Task b).

Reverse extrusion

![Diagram of reverse extrusion process]

d) List three requirements to be met by each of the following: Tool material and sub-surface

Base material:

1.

2.

Subsurface layer:

1.

2.

3.
e) The following four materials are used as tool construction materials. State the operating temperature for each one. The following four materials are used as tool construction materials. State the operating temperature for each one.

<table>
<thead>
<tr>
<th>Tool material</th>
<th>Operating temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cold work steel</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Hot forming tool steel,</strong></td>
<td></td>
</tr>
<tr>
<td><strong>HSS</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Cemented carbide</strong></td>
<td></td>
</tr>
</tbody>
</table>

f) Select two suitable tool construction materials from the list of materials below for the upper die and two for the extrusion die (please underline the two most suitable materials in each case).

<table>
<thead>
<tr>
<th>Tool part</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper die</td>
<td>St70</td>
</tr>
<tr>
<td></td>
<td>X30WCrV9-3</td>
</tr>
<tr>
<td></td>
<td>C15 (case-hardened)</td>
</tr>
<tr>
<td></td>
<td>S6-5-2</td>
</tr>
<tr>
<td></td>
<td>100Cr6</td>
</tr>
<tr>
<td></td>
<td>G30</td>
</tr>
<tr>
<td>Lower die</td>
<td>C35N</td>
</tr>
<tr>
<td></td>
<td>G55</td>
</tr>
<tr>
<td></td>
<td>Ck15 (chromised)</td>
</tr>
</tbody>
</table>
C70W2
X65WCrMoV9-4