12.

Thermal Cutting
Thermal cutting processes are applied in different fields of mechanical engineering, shipbuilding and process technology for the production of components and for the preparation of welding edges. The thermal cutting processes are classified into different categories according to DIN 2310, Figure 12.1.

Figure 12.2 shows the classification according to the physics of the cutting process:
- **flame cutting** – the material is mainly oxidised (burnt)
- **fusion cutting** – the material is mainly fused
- **sublimation cutting** – the material is mainly evaporated

The gas jet and/or evaporation expansion is in all processes responsible for the ejection of molten material or emerging reaction products such as slag.

The different energy carriers for the thermal cutting are depicted in Figure 12.3:
- gas,
- electrical gas discharge and
- beams.

Electron beams for thermal cutting are listed in the DIN-Standard, they produce, however, only very small boreholes. Cutting is impossible.
Figure 12.4 depicts the different **methods of thermal cutting with gas** according to DIN 8580. These are:

- flame cutting
- metal powder
- flame cutting
- metal powder
- fusion cutting
- flame planing
- oxygen-lance cutting
- flame gouging or scarfing
- flame cleaning

In **flame cutting** (principle is depicted in Figure 12.5) the material is brought to the ignition temperature by a heating flame and is then burnt in the oxygen stream. During the process the ignition temperature is maintained on the plate top side by the heating flame and below the plate top side by thermal conduction and convection.

However, this process is suited for automation and is, also easy to apply on site. Figure 12.6. shows a **commercial torch** which combines a welding with a cutting torch. By means of different nozzle shapes the process may be adapted to varying materials and plate thicknesses. Hand-held torches or machine-type torches are equipped with different **cutting nozzles**: Standard or **block-type nozzles** (cutting-oxygen pressure 5 bar) are used for hand-held torches and for torches which are fixed to guide carriages.
The **high-speed cutting nozzle** (cutting-oxygen pressure 8 bar) allows higher cutting speeds with increased cutting-oxygen pressure. The **heavy-duty cutting nozzle** (cutting-oxygen pressure 11 bar) is mainly applied for economic cutting with flame-cutting machines. A further development of the heavy-duty nozzle is the **oxygen-shrouded nozzle** which allows even faster and more economic cutting of plates within certain thickness ranges. Gas mixing is either carried out in the torch handle, the cutting attachment, the torch head or in the nozzle (**gas mixing nozzle**); in special cases also outside the torch — in front of the nozzle. As the design of cutting torches is not yet subject to standardisation, many types and systems exist on the market.
The selection of a torch or nozzles important and depends mainly on the cutting thickness, the desired cutting quality, and/or the geometry of the cutting edge. Figure 12.7 gives a survey of the definitions of flame-cutting.

In flame cutting, the thermal conductivity of the material must be low enough to constantly maintain the ignition temperature, Figure 12.8. Moreover, the material must neither melt during the oxidation nor form high-melting oxides, as these would produce difficult cutting surfaces. In accordance, only steel or titanium materials fulfill the conditions for oxygen cutting., Figure 12.9
Steel materials with a C-content of up to approx. 0.45% may be flame-cut without preheating, with a C-content of approx. 1.6% flame-cutting is carried out with preheating, because an increased C-content demands more heat. Carbon accumulates at the cutting surface, so a very high degree of hardness is to be expected. Should the carbon content exceed 0.45% and should the material not have been subject to prior heat treatment, hardening cracks on the cutting surface are regarded as likely.

**Some alloying elements form high-melting oxides** which impair the slag expulsion and influence the thermal conductivity.

The iron-carbon equilibrium diagram illustrates the carbon content-temperature interrelation, Figure 12.10. **As the carbon content increases, the melting temperature is lowered.** That means: from a certain carbon content upwards, the ignition temperature is higher than the melting temperature, i.e., this would be the first violation to the basic requirement in flame cutting.
Steel compositions may influence flame cuttability substantially - the individual alloying elements may show reciprocate effects (reinforcing/weakening), Figure 12.11. The content limits of the alloying constituents are therefore only reference values for the evaluation of the flame cuttability of steels, as the cutting quality is substantially deteriorating, as a rule already with lower alloy contents.

By an arrangement of one or several nozzles already during the cutting phase a weld preparation may be carried out and certain welding grooves be produced. Figure 12.12 shows torch arrangements for
- the square butt weld,
- the single V butt weld,
- the single V butt weld with root face,
- the double V butt weld and
- the double V butt weld with root face.

Maximum allowable contents of alloy-elements:

- carbon: up to 1.6 %
- silicon: up to 2.5 % with max. 0.2 %C
- manganese: up to 13 % and 1.3 % C
- chromium: up to 1.5 %
- tungsten: up to 10 % and 5 % Cr, 0.2 % Ni, 0.8 % C
- nickel: up to 7.0 % and/or up to 35 % with min. 0.3 % C
- copper: up to 0.7 %
- molybdenum: up to 0.8 %, with higher proportions of W, Cr and C not suitable for cutting
It has to be considered that, particularly in cases where flame cutting is applied for weld preparations, flame cutting-related defects may lead to increased **weld dressing work. Slag adhesion** or **chains of molten globules** have to be removed in order to guarantee process safety and part accuracy for the subsequent processes. Figure 12.13 gives a survey of **possible defects in flame cutting.**

In order to **improve the flame-cutting capacity** and/or cutting of materials which are normally not to be flame-cut the powder flame cutting process may be applied. Here, in addition to the cutting oxygen, iron powder is blown into the cutting gap. In the flame, the iron powder oxidises very fast and adds further energy to the process. Through the additional energy input the **high-melting oxides of the high-alloy materials are molten.** Figure 12.14 shows a diagrammatic representation of a **metal powder cutting arrangement.**

<table>
<thead>
<tr>
<th>Possible Flame Cutting Defects</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>edge defect:</strong></td>
</tr>
<tr>
<td>edge rounding</td>
</tr>
<tr>
<td>chain of fused globules</td>
</tr>
<tr>
<td>edge overhang</td>
</tr>
<tr>
<td><strong>cut face defects:</strong></td>
</tr>
<tr>
<td>kerf constriction or extension</td>
</tr>
<tr>
<td>angular deviation</td>
</tr>
<tr>
<td>step at lower edge of the cut</td>
</tr>
<tr>
<td>excessive depth of cutting grooves</td>
</tr>
<tr>
<td><strong>cratering:</strong></td>
</tr>
<tr>
<td>sporadic craterings</td>
</tr>
<tr>
<td>connected craterings</td>
</tr>
<tr>
<td>cratering areas</td>
</tr>
<tr>
<td><strong>adherent slag:</strong></td>
</tr>
<tr>
<td>slag adhearing to bottom cut edge</td>
</tr>
<tr>
<td><strong>cracks:</strong></td>
</tr>
<tr>
<td>face cracks</td>
</tr>
<tr>
<td>cracks below the cut face</td>
</tr>
</tbody>
</table>

![Figure 12.13](image1)  
Possible Flame Cutting Defects

![Figure 12.14](image2)  
Metal Powder Flame Cutting
Figure 12.15 shows the principle of **flame gouging** and **scarfing**. Both methods are suited for the weld preparation; material is removed but not cut. This way, root passes may be grooved out or fillets for welding may be produced later.

Figure 12.16 shows the methods of **thermal cutting processes by electrical gas discharge**:
- plasma cutting with **non-transferred arc**
- plasma cutting with **transferred arc**
- plasma cutting with **transferred arc and secondary gas flow**
- plasma cutting with **transferred arc and water injection**
- **arc air gouging** (represented diagrammatically)
- **arc oxygen cutting** (represented diagrammatically)
In **plasma cutting** the entire workpiece must be heated to the melting temperature by the plasma jet. The nozzle forms the plasma jet only in a restricted way and limits thus the cutting ability of plate to a thickness of approx. 150 mm, Figure 12.17. Characteristic for the plasma cut are the **cone-shaped formation of the kerf** and the rounded edges in the plasma jet entry zone which were caused by the hot gas shield that envelops the plasma jet. These process-specific disadvantages may be significantly reduced or limited to just one side of the plate (high quality or scrap side), respectively, by the inclination of the torch and/or water addition. With the plasma cutting process, all **electrically conductive** materials may be separated. Nonconductive materials, or similar materials, may be separated by the emerging plasma flame, but only with limited ability.

In order to cool and to reduce the emissions, plasma torches may be surrounded by **additional gas or water curtains** which also serve as arc constriction, Figure 12.18. In **dry plasma cutting** where Ar/H\(_2\), N\(_2\), or air are used, harmful substances always develop which not only have to be sucked off very carefully but which
also must be disposed of.

In water-induced plasma cutting (plasma arc cutting in water or under water) gases, dust, also the noise, and the UV radiation are, for the most part, held back by the water. A further, positive effect is the cooling of the cutting surface, Figure 12.18. Careful disposal of the residues is here inevitable.

Figure 12.19 gives a survey of the different cutting methods using a water bath.

Figure 12.20 shows a torch which is equipped with an additional gas supply, the so-called secondary gas. The secondary gas shields the plasma jet and increases the transition resistance at the nozzle front. The so-called “double and/or parasite arcs” are avoided and nozzle life is increased.
Thanks to new electrode materials, compressed air and even pure oxygen may be applied as plasma gas – therefore, in flame cutting, the burning of unalloyed steel may be used for increased capacity and quality. The selection of the plasma forming gases depends on the requirements of the cutting process. Plasma forming media are argon, helium, hydrogen, nitrogen, air, oxygen or water.

The advantage of the use of oxygen as plasma gas is in the achievable cutting speeds within the plate thickness range of approx. 3 – 12 mm (400 A, WIPC). In the steel plate thickness range of approx. 1 – 10 mm the application of 40 A-compressed air units is recommended. In comparison with 400 A WIPC systems, these allow vertical and significantly narrower cutting kerfs, but with lower cutting speeds. Figure 12.21 shows different cutting speeds for different units and plasma gases.

In the thermal cutting processes with beams only the laser is used as the jet generator for cutting, Figure 12.22.
Variations of the laser beam cutting process:
- laser beam combustion cutting, Figure 12.25
- laser beam fusion cutting, Figure 12.26
- laser beam sublimation cutting, Figure 12.27.

The **process sequence in laser beam combustion cutting** is comparable to oxygen cutting. The material is heated to the ignition temperature and subsequently burnt in the oxygen stream, Figure 12.23. Due to the concentrated energy input almost all metals in the plate thickness range of up to approx. 2 mm may be cut. In addition, it is possible to achieve very good bur-free cutting qualities for stainless steels (thickness of up to approx. 8 mm) and for structural steels (thickness of up to 12 mm). Very narrow and parallel cutting kerfs are characteristic for laser beam cutting of structural steels.

In laser beam cutting, either oxygen (additional energy contribution for oxidising materials) or an inactive cutting gas may be applied depending on the cutting job. Besides, the very high beam powers (pulsed/superpulsed mode of operation) allow a direct evaporation of the material (sublimation). In **laser beam combustion cutting** and **laser beam sublimation**...
Thermal Cutting  the reflexion of the laser beam of more than 90 % on the workpiece surface decreases unevenly when the process starts. In laser beam fusion cutting remains the reflexion on the molten material, however, at more than 90%! Figure 12.24 shows the absorption factor of the laser light in dependence on the temperature. This factor mainly depends on the wave length of the used laser light. When the melting point of the material has been reached, the absorption factor increases unevenly and reaches values of more than 80%.

During laser beam combustion cutting of structural steel high cutting speeds are achieved due to the exothermal energy input and the low laser beam powers, Figure 12.25. In the above-mentioned case (dependent on beam quality, focusing, etc.), above a beam power of approx. 3.3 kW, spontaneous evaporation of the material takes place and allows sublimation cutting. Significantly higher laser powers are necessary to fuse the material and blow it out with an inert gas, as the reflexion loss remains constant.
Important influence quantities for the cutting speed and quality in laser beam cutting are the focus intensity, the position of the focus point in relation to the plate surface and the formation of the cutting gas flow. A prerequisite for a high intensity in the focus is the high beam quality (Gaussian intensity distribution in the beam) with a high beam power and suitable focussing optics.

Laser beam cutting of contours, especially of pointed corners and narrow root faces, requires adaptation of the beam power in order to avoid heat accumulation and burning of the material. In such a case the beam power might be reduced in the continuous wave (CW) operating mode. With a decreasing beam efficiency decreases the cuttable plate thickness as well. Better suited is the switching of the laser to pulse mode (standard equipment of HF-excited lasers) where pulse height can be selected right up to the height of the continuous wave. A super pulse equipment (increased excitation) allows significantly higher pulse efficiencies to be selected than those achieved with CW. Further fields of application for the pulse and super pulse operation mode are punching and laser beam sublimation cutting.
Laser beam cutting of aluminium plates thicker than appx. 2 mm does not produce bur-free results due to a high reflection property, high heat conductivity and large temperature differences between Al and Al₂O₃. The addition of iron powder allows the flame cutting of stainless steels (energy input and improvement of the molten-metal viscosity). The cutting quality, however, does not meet high standards.

Figure 12.28 shows a comparison of the different plate thicknesses which were cut using different processes. For the plate thickness range of up to 12 mm (steel plate), laser beam cutting is the approved precision cutting process. Plasma cutting of plates > 3 mm allows higher cutting speeds, in comparison to laser beam cutting, the cutting quality, however, is significantly lower. Flame cutting is used for cutting plates > 3 mm, the cutting speeds are, in comparison to plasma cutting, significantly lower. With an increasing plate thickness the difference in the cutting speed is reduced. Plates with a thickness of more than 40 mm may be cut even faster using the flame cutting process.

Figure 12.29 shows the cutting speeds of some thermal cutting processes.
Apart from technological aspects, financial considerations as well determine the application of a certain cutting method. Figures 12.30 and 12.31 show a comparison of the costs of flame cutting, plasma arc and laser beam cutting – the costs per m/cutting length and the costs per operating hour. The high investment costs for a laser beam cutting equipment might be a deterrent to exploit the high cutting qualities obtainable with this process.

<table>
<thead>
<tr>
<th></th>
<th>flame cutting (6-8 torches)</th>
<th>plasma cutting (plasma 300A)</th>
<th>laser beam cutting (laser 1500W)</th>
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</thead>
<tbody>
<tr>
<td>investment total (replacement value) €</td>
<td>170,000.00</td>
<td>220,000.00</td>
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<tr>
<td>calculation for a 6-year-accounting depreciation €/h</td>
<td>23.50</td>
<td>29.00</td>
<td>65.00</td>
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<tr>
<td>maintenance costs €/h</td>
<td>3.50</td>
<td>4.00</td>
<td>10.00</td>
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<tr>
<td>energy costs €/h</td>
<td>1.00</td>
<td>2.50</td>
<td>2.50</td>
</tr>
<tr>
<td>production cost unit rate costs/1 operating hour €/h</td>
<td>65.00</td>
<td>75.00</td>
<td>130.00</td>
</tr>
</tbody>
</table>

1 shift, 1600h/year, 80% availability, utilisation time 1280h/year

Figure 12.31