THERMAL CUTTING

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Summary

Most materials, including metals, will burn. A number of cutting processes exploit this fact by bringing about the rapid oxidation of material, to form a kerf, or cut. Thermal cutting in this manner offers many advantages over traditional subtractive machining methods such as sawing. As the process does not require the physical contact of a tool with the work surface, cutting forces are almost negligible, rates of material removal are

faster and the mechanics of machine design are simplified. Depending on the source of heat input, there are various processes which can be divided into oxygen, arc and beam cutting processes. Oxygen cutting describes a group of cutting processes used to sever or remove metals by high-temperature exothermic reaction of oxygen with the base metal. In arc cutting, the metal is simply melted by the intense heat of the arc and is then blown away by the force of arc itself or by other gases (such as air or shielded gases). Beam cutting utilizes a beam of light as a heat source. The advantages of these non-contact cutting processes include not having to rely on perishable cutting tools to shape parts or elaborate work holding methods and systems to clamp parts. These processes do, however, use consumable items such as torch tips, gases, and abrasive materials.

1. Introduction

In order to meet the challenges of manufacturing sophisticated components in modern space, transport, nuclear, electronic and computer technology applications many newer manufacturing methods have been developed. Among such processes, metal cutting processes using thermal energy play an important role in modern manufacturing, especially in the metal industries. Such thermal metal cutting processes need a good understanding of physics, mathematics, material science, thermal and fluid science, computers and computational techniques.

Cutting of metals implies severing or removal of metal. Metals may be cut using mechanical means, such as sawing. Some metals also may be cut into two or more pieces with varying contours by using some source of heat that removes a narrow zone in the part to be cut. The heat sources used for welding processes can also mostly be used for cutting purposes. Cutting of metals is an every day practice in industry. It is employed for the following purposes:

- Cutting desired lengths and shapes of (rolled) metal pieces for assembly and other processing operations to be carried out on different machine tools and presses. Many times it is required to cut a gear blank from a plate or a blank is cut from a plate for subsequent forming operations.
- For preparing the edges of plates for welding them together.
- For cutting gates and risers from the castings.
- For salvage work.

Metals may be cut by: mechanical means (machining), chemical reaction (oxidation) - Oxygen cutting, melting (arc action) - Arc cutting. Thermal cutting processes differ from mechanical cutting (machining) in that the cutting action is initiated either by chemical reaction (oxidation) or melting (heat from arc). All cutting processes result in the severing or removal of metals. Oxygen cutting is accomplished through a chemical reaction in which preheated metal is cut, or removed, by rapid oxidation in a stream of pure oxygen. Typical oxygen cutting processes are oxyfuel gas, oxygen lance, chemical flux, and metal powder cutting. Oxyfuel gas cutting and its modifications, chemical flux cutting and metal powder cutting, which are used to cut oxidation-resistant materials, are also discussed in this article.

The cutting of metals using rapid oxidation is perhaps best known through the use of oxyfuel gas cutting. This familiar process, which is still widely used, can be recognized in the flame-cutting torch and gas bottles used by demolition firms, welders and mechanics alike. The equipment is portable, requires no electrical power and, using the appropriate accessories, can also be used for cutting, heating, brazing, soldering and welding. Until the development of plasma and laser cutting techniques, oxyfuel cutting was the most popular means to cut shapes from steel plate and sheet, becoming an essential technique in the fabrication of steel structures of many kinds.

2. Oxygen Cutting

Oxygen cutting describes a group of cutting processes used to sever or remove metals by high-temperature exothermic reaction of oxygen with the base metal. With some oxidation-resistant metals, the reaction can be aided by the use of a chemical flux or metal powder. Typical oxygen cutting processes are oxyfuel gas, oxygen arc, oxygen lance, metal powder and chemical flux cutting.

2.1. Oxyfuel Gas Cutting

Oxyfuel gas cutting processes sever or remove metal by the chemical reaction of oxygen with the metal at elevated temperatures. The necessary temperature is maintained by a flame of fuel gas burning in oxygen. In the case of oxidation resistant metals, the reaction is aided by adding chemical fluxes or metal powders to the cutting stream. The process has been called various other names, such as burning, flame cutting and flame machining. The actual cutting operation is performed by the oxygen stream. The oxygen-fuel gas flame is the mechanism used to raise the base metal to an acceptable preheat temperature range and to maintain the cutting operation. The oxyfuel gas cutting torch is a versatile tool that can be readily taken to the work site. It is used to cut plates up to 2 m thick. Because the cutting oxygen jet has a 360° “cutting edge”, it provides a rapid means of cutting both straight edges as well as curved shapes to required dimensions without expensive handling equipment. Cutting direction can be continuously changed during operation.

2.1.1. Principles of Operation

The oxyfuel gas cutting process employs a torch with a tip (nozzle). The functions of a torch are to produce preheat flames by mixing the gas and the oxygen in the correct proportions and to supply a concentrated stream of high-purity oxygen to the reaction zone. The oxygen oxidizes the hot metal and also blows the molten reaction products from the joint. Features of cutting torches are shown in Figure 1.

The cutting torch mixes the fuel and the oxygen for the preheating flames and aims the oxygen jet into the cut. The torch cutting tip contains a number of preheat flame ports and a center passage for the cutting oxygen as shown in Figure 2.

The preheat flames are used to heat the metal to a temperature where the metal will react with the cutting oxygen. The oxygen jet rapidly oxidizes most of the metal in a narrow section to make the cut. Metal oxides and molten metal are expelled from the cut by the kinetic energy of the oxygen stream. Moving the torch across the work piece at a proper rate, produces a continuous cutting action. The torch may be moved manually or by a mechanized carriage. The accuracy of a manual operation depends largely on the skill of the operator. Mechanized operation generally improves the accuracy and speed of the cut and the finish of the cut surfaces.

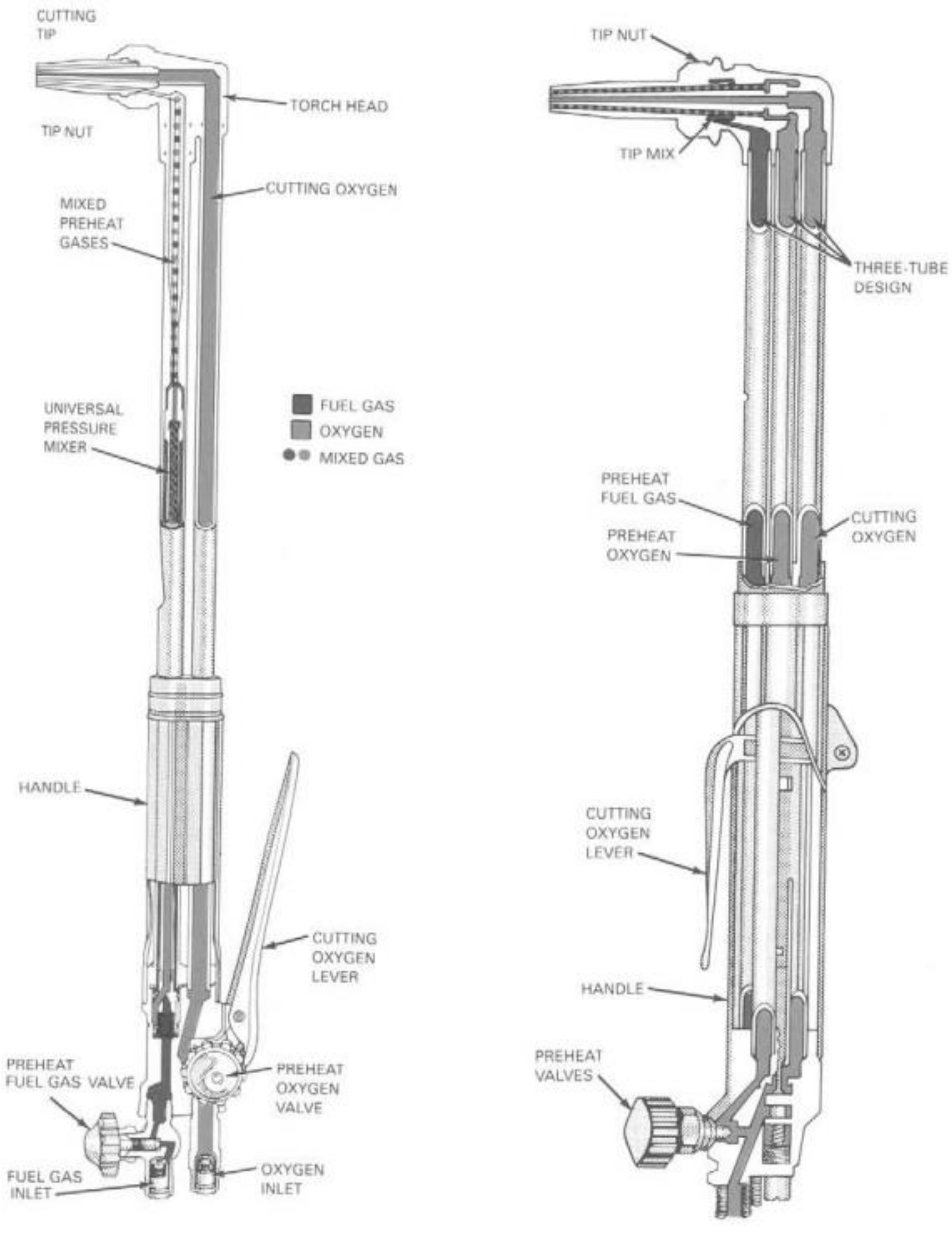

Figure 1. Features of cutting torches

There are four basic requirements for oxyfuel gas cutting:

1. The ignition temperature of the material must be lower than its melting point otherwise the material would melt and flow away before cutting could take place

2. The oxide melting point must be lower than that of the surrounding material so that it can be mechanically blown away by the oxygen jet
3. The oxidation reaction between the oxygen jet and the metal must be sufficient to maintain the ignition temperature
4. A minimum of gaseous reaction products should be produced so as not to dilute the cutting oxygen

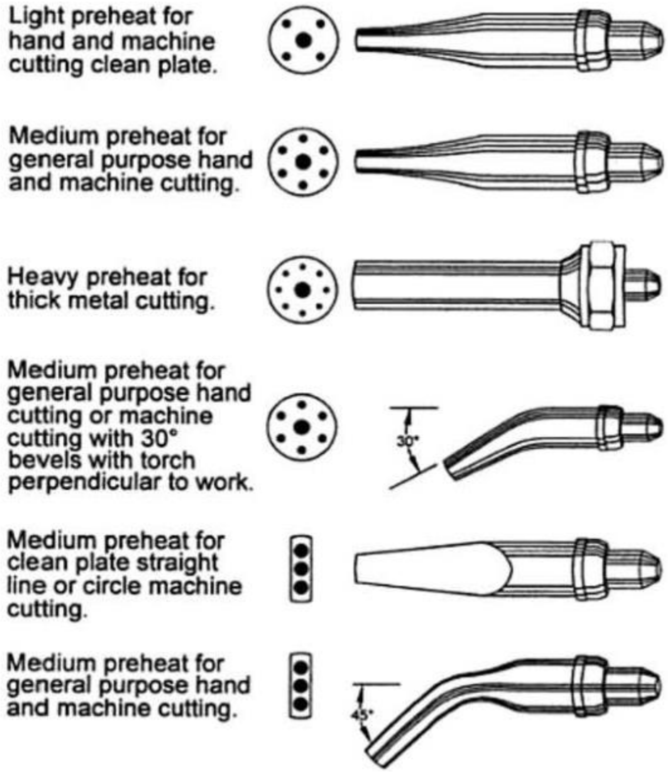

Figure 2. Special purpose oxyfuel cutting tips

As stainless steel, cast iron and non-ferrous metals form refractory oxides; i.e. the oxide melting point is higher than the material melting point, powder must be injected into the flame to form a low melting point of the oxides (fluid slag).

When a piece is cut by an oxyfuel cutting process, a narrow width of metal is progressively removed. The width of the cut is called a kerf, as shown in Figure 3.

Control of the kerf is important in cutting operations where dimensional accuracy of the part and squareness of the cut edges are significant factors in quality control. With the oxyfuel gas cutting process, kerf width is a function of the size of oxygen port, type of tip used, speed of cutting and flow rates of cutting oxygen and preheating gases. As material thickness increases, oxygen flow rates must usually be increased. Cutting tips with larger cutting oxygen ports are required to handle the higher flow rates. Consequently, the width of the kerf increases as the material thickness being cut increases. Kerf width is especially important in shape cutting. Compensation must be made for kerf width in the layout of the work, or the design of the template. Generally, on materials up to 50 mm thick, kerf width can be maintained within +0.4mm.

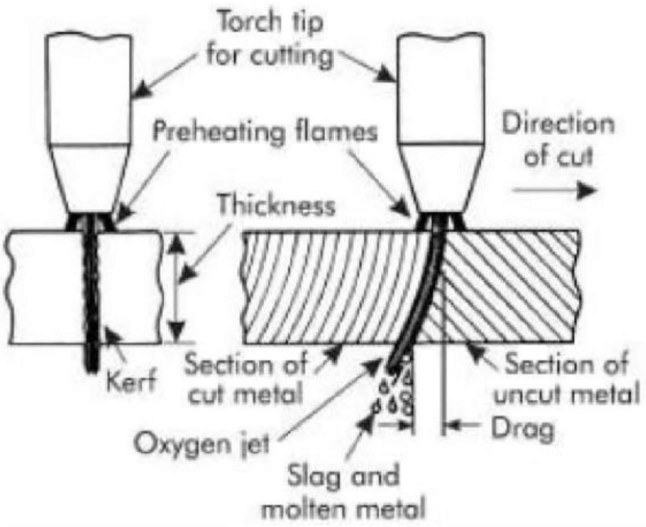

Figure 3. Principles of oxyfuel cutting

When the speed of the cutting torch is adjusted so that the oxygen stream enters the top of the kerf and exits from the bottom of the kerf along the axis of the tip, the cut will have zero drag. If the speed of the cutting is increased or if the oxygen flow is decreased, the oxygen available in the lower regions of the cut decreases. With less oxygen available, the oxidation reaction rate decreases and also the oxygen jet has less energy to carry the reaction products out of the kerf. As a result, the most distant part of the cutting stream lags behind the portion nearest to the torch tip. The length of this lag, measured along the line of cut, is referred to as the drag. This is shown in Figure 3. Drag may also be expressed as a percentage of the cut thickness. A 10% drag means that the far side of the cut lags the near side of the cut by a distance equal to 10% of the material thickness. Cutting speeds below those recommended for the best quality cuts usually result in irregularities in the kerf. The oxygen stream inconsistently oxidizes and washes away additional material from each side of the cut. Excessive preheat flame results in undesirable melting and widening of the kerf at the top.

The process of oxygen cutting is based on the ability of high-purity oxygen to combine rapidly with iron when it is heated to its ignition temperature, above 870°C. The iron is rapidly oxidized by the high-purity oxygen and heat is liberated by several reactions. The balanced chemical reactions for these reactions are as following:

$$\mathrm{Fe} + \mathrm{O} \rightarrow \mathrm{FeO} + \mathrm{heat}\left(267\mathrm{kJ}\right) \qquad (1)$$

$$3\mathrm{Fe} + 2\mathrm{O}_2 \rightarrow \mathrm{Fe}_3\mathrm{O}_4 + \mathrm{heat}\left(1120\mathrm{kJ}\right) \qquad (2)$$

$$2\mathrm{Fe} + 1.5\mathrm{O}_2 \rightarrow \mathrm{Fe}_2\mathrm{O}_3 + \mathrm{heat}\left(825\mathrm{kJ}\right) \qquad (3)$$

The tremendous heat release of the second reaction predominates over that of the first reaction, which is supplementary in most cutting applications. The third reaction occurs to some extent in heavier cutting applications. Theoretically, $1\mathrm{m}^3$ of oxygen is required to oxidize about $430\mathrm{cm}^3$ of Fe. Actually, about 30-40% of the metal is melted and blown away without being oxidized and removal of 600cm^3 or more of iron per 1m^3 of oxygen is not uncommon performance. In actual operations, the consumption of cutting oxygen per unit mass of iron varies with the thickness of the metal. Oxygen consumption per unit mass is higher than the ideal stoichiometric reaction for thicknesses less than approximately 40mm and it is lower for greater thicknesses. For thicker sections, the oxygen consumption is lower than the ideal stoichiometric reaction because only part of the iron is completely oxidized to Fe_3O_4. Some unoxidized or partly oxidized iron is removed by the kinetic energy of the rapidly moving oxygen stream. The heat generated by the iron-oxygen reaction at the focal point of the cutting reaction (the hot spot) must be sufficient to continuously preheat the material to the ignition temperature. Allowing for the loss of heat by radiation and conduction, there is ample heat to sustain the reaction. In actual practice, the top surface of the material is frequently covered by mill scale or rust. That layer must be melted away by the preheating flames to expose a clean metal surface to the oxygen stream. Preheating flames help to sustain the cutting reaction by providing heat to the surface. They also shield the oxygen stream from turbulent interaction with air. The alloying elements normally found in carbon steels are oxidized or dissolved in the slag without markedly interfering with the cutting process. When alloying elements are present in steels in appreciable amounts, their effect on the cutting process must be considered. Steels containing minor additions of oxidation resistant elements, such as nickel and chromium, can still be oxygen cut. However, when oxidation resistant elements are present in large quantities, modifications of the cutting technique are required to sustain the cutting action. This is true for stainless steels.

Oxygen

Oxygen used for cutting operations should have a purity of 99.5% or higher. Lower purity reduces the efficiency of the cutting operation. A 1% decrease in purity of oxygen will result in a decrease of 15% in cutting speed and an increase of about 25% in consumption of cutting oxygen. The quality of the cut will be impaired and the amount and tenacity of the adhering slag will increase. With oxygen purities below 95%, the familiar cutting action disappears and it becomes a melt-and-wash action that is usually unacceptable.

2.1.2 Preheating Fuels

Functions of the preheating flames in the cutting operation are the following:
1. Raising the temperature of the steel to the ignition point
2. Adding heat to the work to maintain the cutting reaction
3. Providing a protective shield between the cutting oxygen stream and the atmosphere
4. Dislodging from the upper surface of the steel any rust, scale, paint or other foreign substance that would stop or retard the normal forward progress of the cutting action.

A preheat intensity that raises the steel to the ignition temperature rapidly will usually be adequate to maintain cutting action at high travel speeds. However, the quality of the cut will not be the best. High-quality cutting can be carried out at considerably lower preheat intensities that those normally required for rapid heating. On larger cutting machines, dual range gas controls are provided that limit high-intensity preheating to the starting operation. Then the preheat flames are reduced to lower intensity during the cutting operation, to save fuel and oxygen and provide a better cut surface. A number of commercially available fuel gases are used with oxygen to provide the preheating flames. Some have proprietary compositions. Fuel gases are generally selected because of availability and cost.

The following are some general factors for consideration when selecting a preheat fuel:
1. Time required for preheating when starting cuts on square edges and rounded corners and also when piercing holes for cut starts
2. Effect on cutting speeds for straight line, shape and bevel cutting
3. Effect of the above factors on work output
4. Cost and availability of the fuel in cylinder, bulk and pipeline volumes
5. Cost of the preheat oxygen required to burn the fuel gas efficiency
6. Ability to use the fuel efficiently for other operations, such as welding, heating, brazing if required
7. Safety in transporting and handling the fuel gas containers

For best performance and safety, the torches and tips should be designed for the particular fuel selected.

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Biographical Sketches

Branko Bauer has received his diploma of Engineering (Dipl.Ing.) from the University of Zagreb, Faculty of mechanical engineering and naval architecture, Department of Welded Structures, Chair of Welding, Croatia in 1997. He began to work at the Faculty of mechanical engineering and naval architecture, Zagreb in 1997. He obtained a certificate of European Welding Engineer after completing course according EWF program in 1999. After completing further studies he obtained a Master of Science (M.Sc.) degree in 2002, and he earned a PhD-degree (Dr.sc.) in 2006. At the Welding department of the Faculty he is in charge of research in laser beam welding and cutting. In 2007 he was appointed Assistant professor at the Faculty of mechanical engineering and naval architecture in Zagreb. He has published more than 30 scientific and technical papers.

Maja Remenar has received her diploma of Engineering (Mag.Ing.Mech.) from the University of Zagreb, Faculty of mechanical engineering and naval architecture, Department of Quality, Chair of Non-Destructive Testing, Croatia in 2008. She started her first employment in 2009, on the Faculty of Mechanical Engineering, University of Zagreb, as an Assistant at the Department of Welded Structures. In academic year 2009/2010 she started postgraduate studies on the Faculty. In her work she participates in academic activities and scientific activities related to welding and thermal cutting processes.