

4. Properties of Cutting Fluids

4.1 Functions of cutting fluids

Cutting fluids consist of those liquids and gases that are applied to the tool and the material being machined to facilitate the cutting operation. Vast quantities are used annually to accomplish a number of objectives. (Boston, 1952)

- 1) To prevent the tool from overheating, i.e. so that no temperature is reached where the tool's hardness and resistance to abrasion are reduced, thus decreasing the tool life.
- 2) To keep the work cool, preventing machining that results in inaccurate final dimensions.
- 3) To reduce power consumption, wear on the tool, and the generation of heat, by affecting the cutting process. This investigation wishes to establish a relationship between the surface chemistry of the lubricants involved and how they can accomplish reducing the contact length on the rake face of the tool where most of the heat during cutting is produced.
- 4) To provide a good surface finish on the work.
- 5) To aid in providing a satisfactory chip formation (related to contact length)
- 6) To wash away the chips/clear the swarf from the cutting area.
- 7) To prevent corrosion of the work, the tool and the machine.

The desirable properties of cutting fluids in general are (Boston, 1952)

- 1) High thermal conductivity for cooling
- 2) Good lubricating qualities
- 3) High flash point, should not entail a fire hazard
- 4) Must not produce a gummy or solid precipitate at ordinary working temperatures
- 5) Be stable against oxidation.
- 6) Must not promote corrosion or discoloration of the work material.
- 7) Must afford some corrosion protection to newly formed surfaces.
- 8) The components of the lubricant must not become rancid easily
- 9) No unpleasant odour must develop from continued use
- 10) Must not cause skin irritation or contamination
- 11) A viscosity that will permit free flow from the work and dripping from the chips.

4.2 Types of cutting fluids

Cutting fluids may be divided into four main categories (FVTC, 2000) :

- i- straight or neat cutting oils
- ii- water miscible or water-based fluids
- iii- gases
- iv- and paste or solid lubricants

The water-based fluids act mainly as coolants and the neat cutting oils act mainly as lubricants. There are many variants of both types. Fatty acids are often incorporated in the neat oils. Until recently both the emulsions or soluble oils as they are also called and the neat oils, contained chlorine and sulphur additives that improved lubrication under

extremely difficult conditions. Chlorine affects the skin detrimentally and its degradation products are often carcinogenic and sulphur is environmentally unacceptable. Consequently other lubrication improvers under difficult conditions are searched for. Ester technology is used successfully for softer materials where high rates of metal working are needed, and where heat generation is not a major problem. (du Plessis, 2001) These can operate at higher temperatures as they have better resistance to thermal degradation than mineral oils. (Mortier & Orszulik, 1993) They are biodegradable and do not cause dermatitis and are therefore more environmentally acceptable. In many cases phosphor and sulphur do however still form part of the cutting fluid. (FVTC, 2000)

For the water miscible fluids water quality has a large effect on the coolant. Hard water (high mineral content) can cause stains and corrosion of machines and work pieces. Water can be deionized to remove the impurities and minerals. Water is the best fluid for cooling. It has the best ability to carry heat away. Water, however, is a very poor lubricant and causes corrosion.

Oil is excellent for lubrication but very poor for cooling, and it is also flammable. It is clear that, from a lubrication point of view water and oil have strengths but also some weaknesses. If water and oil are combined and an attempt is made to minimise the weaknesses the best properties of both may be balanced to obtain desirable end properties for the cutting fluid. Water-soluble fluids have been developed which have good lubrication, cooling ability, low-flammability and corrosion resistance. These fluids are usually mixed on site. It is crucial that the mixing directions and concentrations are followed very closely to get the maximum benefit from the coolant. (FVTC, 2000)

Emulsions

An emulsion is a dispersion of oil droplets in water. Soluble oils are mineral oils that contain emulsifiers. Emulsifiers are soaps or soap-like agents that allow the oil to mix with water and stay in suspension. Emulsions (soluble oils) when mixed with water produce a milky white product. Lean concentrations (more water, less oil) provide better cooling but less lubrication. Rich concentrations (less water, more oil) have better lubrication qualities but poorer cooling properties.

There are different types of soluble cutting fluids available including extreme pressure soluble oils. These are used for extreme machining conditions like broaching and gear hobbing for example. (FVTC, 2000)

Chemical Fluids

Chemical coolants are also miscible cutting fluids. Chemical cutting fluids are pre-concentrated emulsions that contain very little oil. Chemical fluids mix very easily with water to form an emulsion. The chemical components in the fluid are used to enhance the lubrication, bacterial control, and rust and corrosion characteristics. There are several types of chemical coolants available including coolants for extreme cutting conditions.

Inactive chemical cutting fluids are usually clear fluids with high corrosion inhibition, high cooling, and low lubrication qualities. Active chemical fluids include wetting agents. They have excellent rust inhibition and moderate lubrication and cooling properties.

Sulphur-, chlorine- and phosphorous- containing compounds are sometimes added to improve the extreme pressure characteristics. These are usually in an organic form, i.e.

the sulphur, chlorine or phosphorus is grafted onto a hydro-carbon backbone. (FVTC,2000)

Straight Cutting Oils

Straight cutting oils are not mixed with water. Cutting oils are generally mixtures of mineral oil and animal, vegetable or marine oils to improve the wetting and lubricating properties. Sulphur, chlorine, and phosphorous compounds are sometimes added to improve the lubrication qualities of the fluid for extreme pressure applications. There are two main types of straight oils: active and inactive.

Inactive Straight Cutting oils

Inactive oils contain sulphur that is very firmly attached to the oil. Mineral oils are an example of straight oils. Mineral oils provide excellent lubrication, but are not very good at heat dissipation (removing heat from the cutting tool and work piece). Mineral oils are particularly suited to non-ferrous materials such as aluminium, brass, and magnesium. Blends of mineral oils are also used in grinding operations to produce high surface finishes on ferrous and non-ferrous materials. (FVTC, 2000)

Active Straight Cutting Oils

Active oils contain sulphur that is not firmly attached to the oil, i.e. it is part of the oil molecule but is only weakly bonded to the hydro-carbon backbone. Thus the sulphur is easily released during the machining operation to react with the work piece. These oils have good lubrication and cooling properties. Special blends with higher sulphur content are available for heavy duty machining operations. They are recommended for tough low carbon and chrome-alloy steels. They are widely used in thread cutting. They are also good for grinding as they help prevent the grinding wheel from loading up. This increases the life of the grinding wheel. (FVTC, 2000)

Gases and vapours

Cutting oils and water miscible types of cutting fluids are the most widely used. Compressed air, inert gases like carbon dioxide, Freon, and Nitrogen are sometimes used. A vortex tube may be used to apply gaseous lubricants or coolants (ARTX, 2002). Using this tube, it is possible to apply the gases at a very low temperature and under medium pressure thereby facilitating a higher gas density and cooling and lubrication capability. Cutting using sub-zero cold gas is known as cryogenic cutting. The gas stream also helps to blow away chips from the cutting area. (FVTC, 2000)

The further advantage of a gaseous or vapour phase cutting fluid is that the constituents are of a far finer nature than liquids or solids, and due to the way of application, namely jet application, have far greater kinetic energy, and therefore have a greater penetrative capability. Molecular exchange is much slower when flood lubrication is used. Any adhered film is static and can be penetrated by the cutting fluid when jet type application is used. This promotes convective cooling and adds capacity for evaporative cooling.

(Varadarajan, Philip and Ramamoorthy, 2001) As far as vapour phase cutting fluids are concerned carbon tetra chloride (although forbidden to use as a cutting fluid) is very volatile and vaporises easily under ambient temperature conditions. Gas phase molecules do not adhere to each other as much as the molecules of liquids and are thus far more free to move.

Paste and Solid Lubricants

Waxes, pastes, soaps, graphite and molybdenum disulphide are examples falling into this category. These are generally applied directly to the work piece or tool or in some cases impregnated directly into the tool, for example the grinding wheel of a grinder. One example of a paste lubricant is lard. Many experienced journeymen recommend lard for tapping.

Lubricants for metal cutting may be presented schematically as in figure 4.1 .

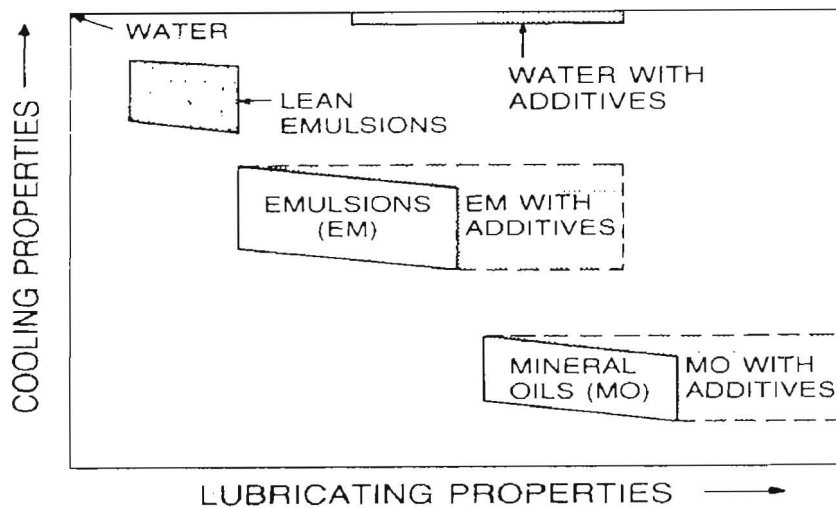


Figure 4.1 Lubricating and cooling properties of metalworking fluids.

(Mortier & Orszulik, 1993)

Coolants

The use of coolants becomes particularly essential when machining high melting point metals and alloys. Their use is most important when cutting with steel tools, but they are also used when cutting with carbide tools. (Trent, 1977).

In section 3.2 the two main sources of heat in the cutting operation were discussed – on the primary shear plane and in the flow-zone on the tool/work interface. The work done in this region is converted into heat, while the work done by sliding friction only makes a minor contribution to heating under most cutting conditions. Coolants cannot prevent the heat being generated, as they do not have direct access to the zones which are the heat sources.

Cutting fluids used in more severe operations must have very good anti-weld and lubricating properties to protect the cutting tool and to ensure proper surface finish and accuracy. (Mortier & Orszulik, 1993). More severe operations are those where the cutting

fluid cannot be in direct contact with the tool at the cutting point as for example during a band sawing operation or any other operation where the work-piece restricts access to the cutting point, hence turning is a less severe operation. More severe operations demand more active cutting fluids and usually also a decrease in cutting speed. This means that additives, particularly of the extreme pressure type, must be used under severe operational conditions. Cutting fluids contain a wide variety of speciality chemical additives designed to improve lubricity, surface activity, stability and anti-weld properties. (Mortier & Orszulik, 1993)

The Chemistry of cutting fluids : a partial overview

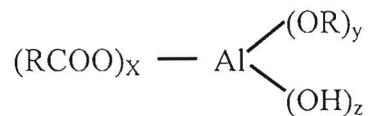
When the metal is cut a clean nascent surface at atmospheric pressure results that is very reactive and quickly adsorbs either by chemisorption (strong) or physisorption (weak) any substances (liquids or gases) in sufficiently close proximity to itself. Chemisorption is the adsorption onto a surface where a chemical bond such as a covalent or ionic bond forms, whereas physisorption involves lesser forces of adhesion like van der Waals forces from polar interactions between atoms. Depending on the cutting process used, the time available for chemical equilibrium to establish itself on the new metal surface varies, and this could influence the performance of the cutting fluid used. Monitoring certain cutting process parameters that will need to be determined from the experimental results should indicate cutting fluid life, i.e. how long it takes when cutting for the cutting fluid to stop aiding the cutting process.

It does seem feasible that the cutting fluid that is applied to the tool tip just before cutting can last for a short time as a protective film as its bond energy from chemisorption is typically 40 to 800 kJ/mol (Nix, 2002) and the bond energies of aluminium are typically in the region of 0.015kJ/mol to 57 kJ/mol. (Xuegang et al, 2002) The metal soaps that would originate are layers that would have a lower tendency to weld than metal. Catalysis can and often does happen, and there may be a need for the initial cutting fluid to have a specific molecular arrangement for catalysis to occur in the metal at the interface of the tool and the shear-zone. Thus it may be possible for similar cutting fluids to exhibit different results during cutting.

As limited volume lubrication uses only very little cutting fluid it is necessary that the cutting fluids must have enhanced reactivity. According to Rowe and Murphy (Rowe & Murphy, 1974), such enhanced surface activity may be represented as follows:
Enhanced reactivity = Exoelectron + Elevated temperature + High pressure.

To provide lubricants with sufficient load carrying capacity and friction characteristics for cold rolling of aluminium, additives are added to the low viscosity mineral base oils. These additives are mainly fatty alcohols, fatty acids and fatty esters. Fatty alcohols ensure better performance of the lubricant because they do not affect the annealing properties of the aluminium.

Tribochemical reactions of these additives with aluminium are very interesting. Organometallic products result from reaction of the fatty additives with fresh unoxidised metal surfaces that formed during plastic deformation. These surfaces are very reactive and are called nascent surfaces. Fatty acid soaps are well known. It is clear that esters, ethers and alcohols react with fresh aluminium surfaces. (Montgomery R.S., 1965). It has been suggested that polymeric soap formation results from reaction with esters and fatty acids, and alkoxide formation from alcohols and ethers. Fatty alcohols can lead to a similar reaction of soap formation but to a lesser extent than fatty acids. In this case, it was assumed that part of the alcohol was changed in to an acid which can react to give an ester and a blend of hybrid soaps of the general formula



where $x = 1, 2$ or 3 and $x + y + z = 3$.

The negative-ion lubrication mechanism proposed by Kajdas, (Kajdas, 1987) explains the formation of aluminium alkoxides i.e. the $\text{Al}(\text{OR})_y$ part of the hybrid soap from alcohols. The mechanism is based on the low-energy electron emission process from the aluminium surface. The action of the emitted electrons on alcohol molecules produces negative and radical-negative ions, including $\text{R-CH}_2\text{-CH}_2\text{-O}^-$ ions which provide alkoxides by reacting with the positively charged sites on the plastically deformed aluminium surface. (Mortier & Orszulik, 1993)

The cutting fluids stabilise the nascent metal surfaces by means of reacting with them. The metal salts that form serve as a low shear strength film that reduces friction and provides improved anti-weld properties, i.e. the resulting surface has better anti-weld properties than the unreacted freshly formed nascent metal surface. The result is a shorter welded-zone or contact length and there is therefore less shear, a lower cutting force and a reduced cutting temperature. When metal is cut in a vacuum a longer contact length is observed than when it is cut in air. (Trent, 1977) When air is present the oxygen reacts with the nascent metal surface instead of the tool and this reduces the contact length. The oxide layer on the tool does not form at the hottest region on the tool but a little further away in the cooler region, because the oxygen in the air reacts preferably with the nascent metal surface and is thereby removed from the cutting edge region of the tool. Similar to the oxide layer producing a shorter contact length the cutting fluids also react with the nascent metal surface produced in metal cutting to bring about a reduced contact length, i.e. the size of the welded zone is reduced.

In a paper by Kajdas (Kajdas, 1996) it is stated that metal surfaces that are coated with oxides, hydroxides and adsorbed organic contaminants are not sufficiently chemically active. The mechanical action at solid surfaces tends to promote reactivity of the surfaces by exposing nascent high reactivity surfaces that can promote chemical reactions that are entirely different to those reactions that would be observed for static systems. Friction at the nascent surfaces initiates and accelerates chemical reactions that would otherwise only occur at higher temperatures or not initiate at all.

Experiments done in a vacuum chamber of restricted volume, where 27 elemental metals were rubbed on each other, and mass spectrometry was used to show the nature of the gases being adsorbed showed the following: (Kajdas, 1996)

- 1) Oxygen and water molecules were adsorbed on the metal surfaces, and hydrogen molecules were desorbed from the metal surfaces during sliding. Far more adsorption of oxygen was observed during mild wear than during severe wear.
- 2) Oxygen adsorption on the metal surfaces during the wear process was governed by the position of the metallic element in the periodic table
- 3) A high gas consumption rate was observed in rare earth metals and in the transition metals, which tend to wear in a mild manner during rubbing.
- 4) A higher gas consumption rate for Fe/Fe rubbing in the mild wear mode than in the severe wear mode.

The chemical nature of nascent metal surfaces is one of the most important active sources for tribochemical reactions. From experiments performed in a restricted volume chamber under vacuum where nascent surfaces were produced by scratching the metal surface the following was found (Mori, S., 1995).

- 1) Enhanced activity on the nascent metal surfaces. The gold surface for example became so active that organic compounds chemisorbed on it.
- 2) Aromatic compounds decomposed catalytically on nascent transition metal surfaces even at room temperature.
- 3) The chemical nature of the nascent surfaces for the simple metals was different from that of the transition metals
- 4) According to the chemisorption activity of organic compounds, the chemical activities of nascent metal surfaces were dependent on their electronic surfaces.

The tribochemical activity of fresh metal surfaces is very complex and is still not well understood. (Kajdas, 1996).

Application of cutting fluids

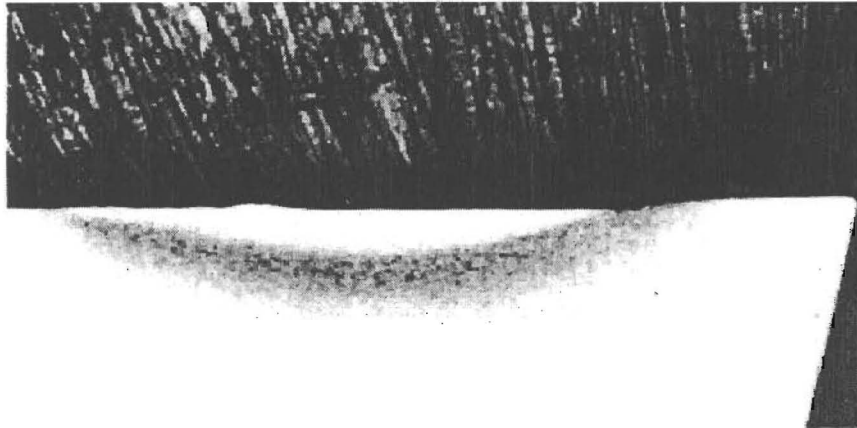
Many machine tools are fitted with a system for handling the cutting fluids. For near-dry machining a spray or mist type applicator is used. The position on the tool and work-piece where the lubricant/coolant is applied plays a significant role in the temperatures and the temperature distribution that will result during metal cutting. (See figures 4.2 to 4.4 (Trent, 1977 and also figure 2.3)

Most of the heat generated on the shear plane is carried away in the chip, only very little is conducted into the work-piece which is voluminous in relation to the chip and thus the temperature rise is much lower in the work-piece. The work-piece is usually kept cool for purposes of dimensional accuracy. In relation to the tool in the cutting process all surfaces are stationary; only the tool itself is moving and in constant contact or proximity of the zones in which heat is generated. It is the tool that is damaged by the high temperatures and therefore, cooling is most effective through the tool in most cases. The

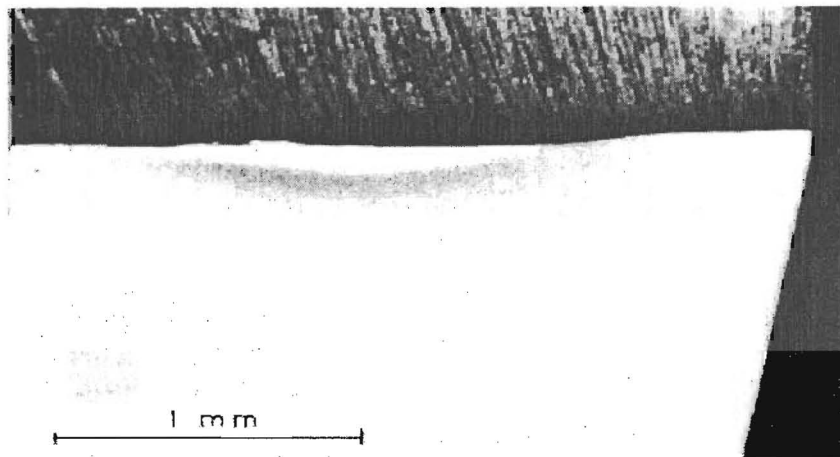


tool is cooled most effectively by directing the coolant to the accessible surfaces of the tool which are at the highest temperatures, as these are the surfaces from which the heat is most rapidly removed, and the parts of the tool most likely to suffer damage. It is helpful to know the temperature distribution in the tool for a rational approach to coolant application.

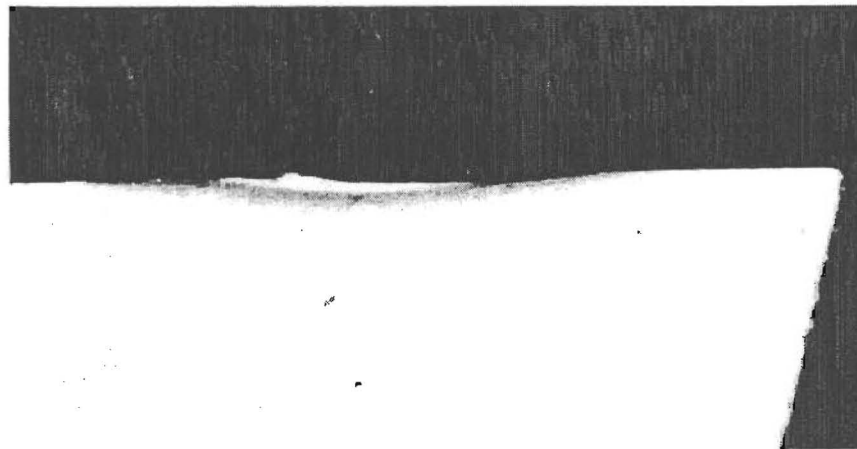
In figures 4.2 to 4.4 (Trent, 1977,) the HSS tool that was used to cut iron at 183 m/min. was etched to show temperature distribution is shown for a few cases where a) no coolant was applied, b) the tool was flooded with coolant over the rake face and c) lastly for a jet of coolant that was directed at the end clearance face.



(a)

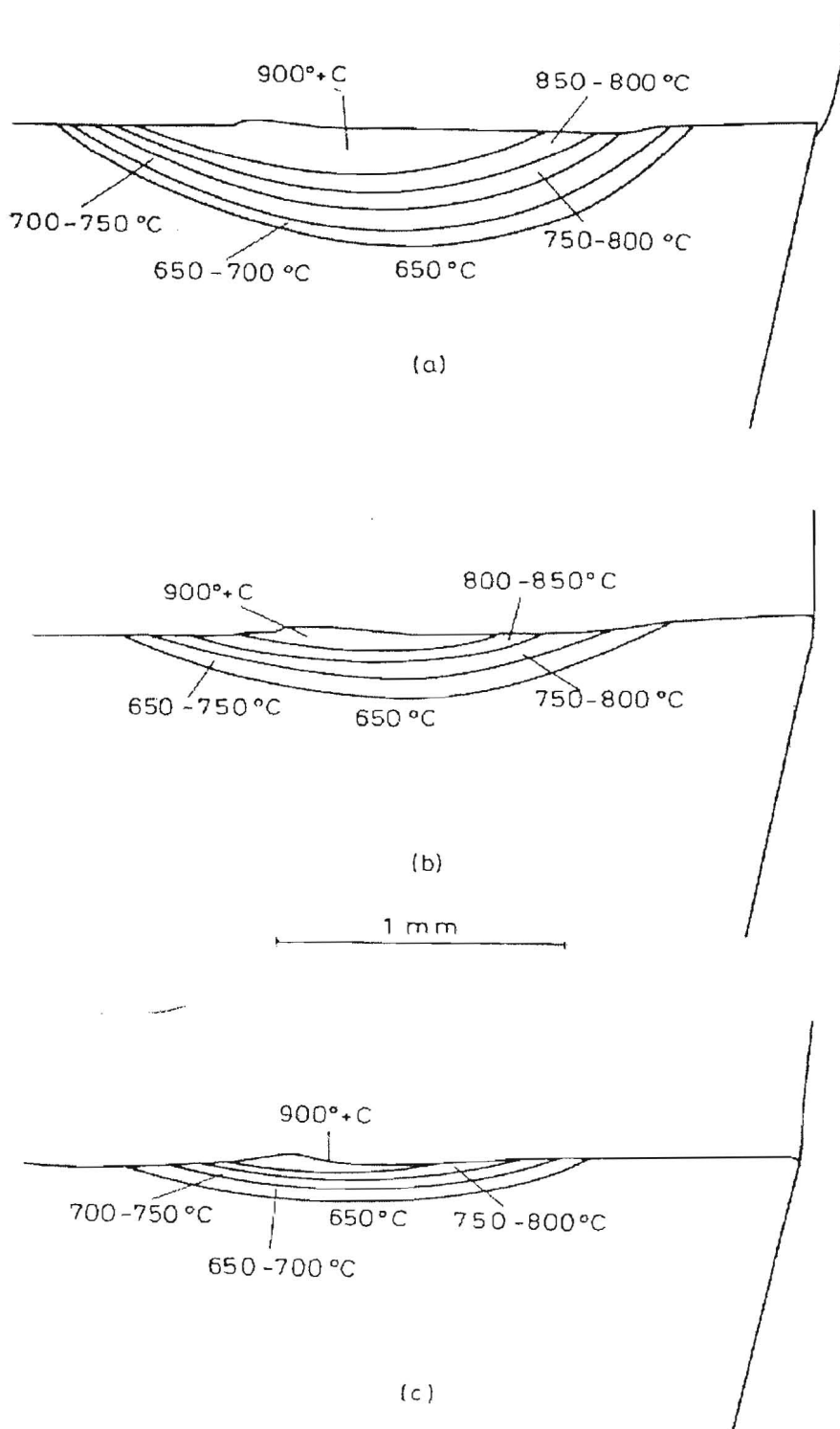


(b)



(c)

Figure 4.2 (a) Section through HSS tool after cutting iron in air at 310m/min., etched to show temperature distribution. (b) As (a) for tool flooded with coolant over rake face. (c) As (a) with jet of coolant directed at end clearance face. Trent, 1977



Figures 4.3 (a), (b) and (c) Temperature contours derived from Figures 4.2 (a), (b) and (c) respectively. (Trent, 1977)

The method of temperature contour derivation is by micro-hardness determinations and by metal crystal structure evaluation as was explained for structural changes in HSS tools.

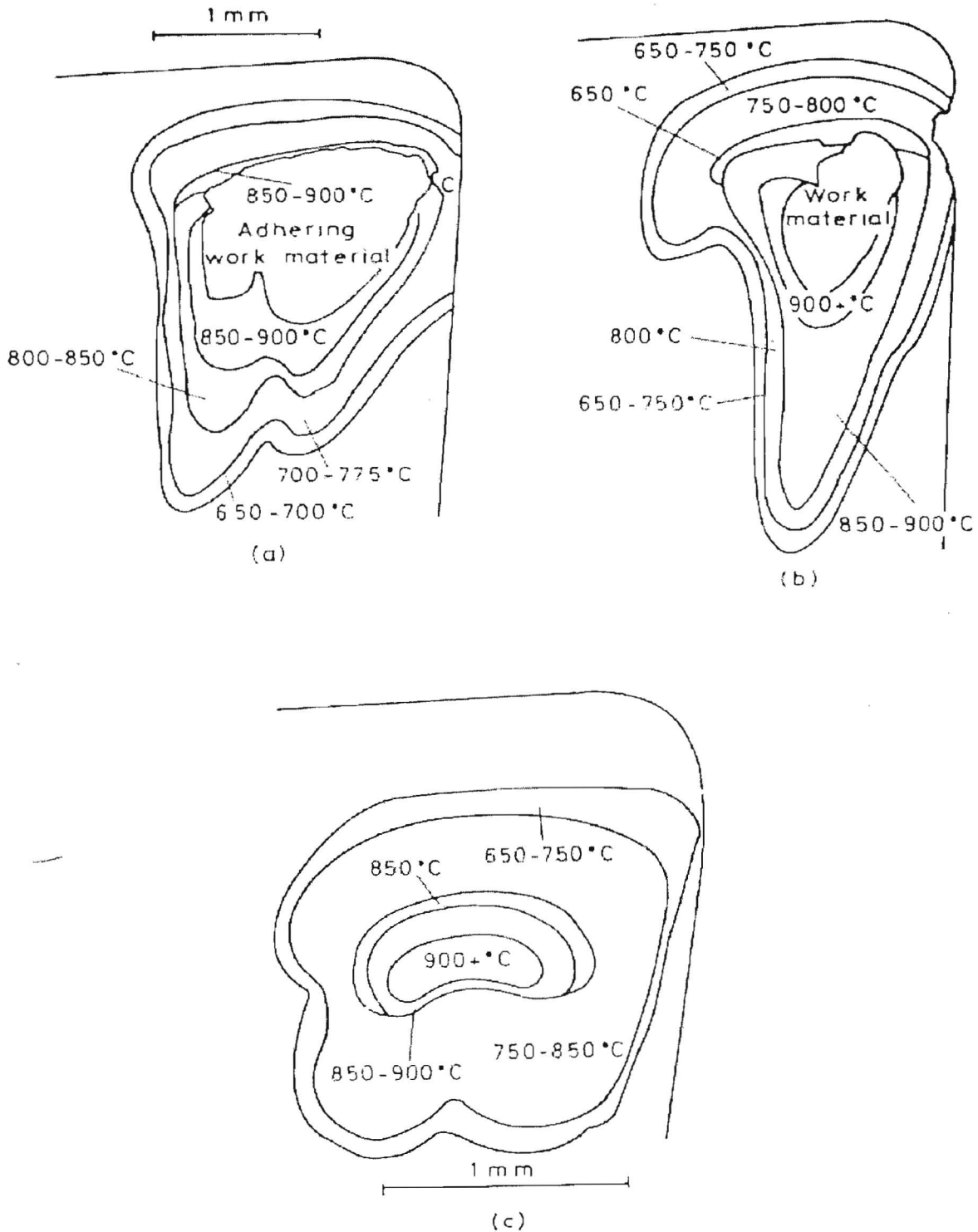


Figure 4.4 (a), (b) and (c) are rake face views of the temperature contours for figures 4.2 (a), (b) and (c) respectively of the same HSS tool used to cut iron in air (Trent,1977)

It is evident that the temperature gradients in the tool are very steep. They cover a range of about 300 °C in the space of 1 mm.