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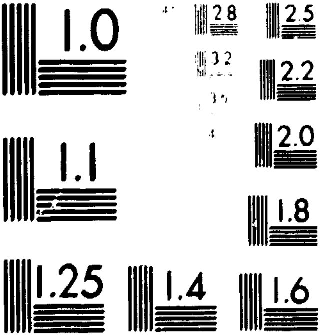

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Heat Treatment Techniques Applied in Manufacture of Tools and Dies Required for the Production of Engineering Spare Parts *

by

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1. BASIC CONCEPTS OF HEAT TREATMENT THEORY AND PRACTICE

In many situations the general aim of the heat treatment operation is to increase the hardness of the material. This, as will be demonstrated later, involves a quench hardening operation. The steel to be hardened is austenised at an appropriate temperature and then quenched at a sufficiently rapid rate to ensure the formation of martensite.

Steels are often supplied in a soft form, hardness <250 HV, in this condition they are easily machinable. The microstructure consists at this stage of ferrite (alpha-iron) and pearlite (alpha-iron and cementite eutectoid), figure 1(a), the relative amounts of these constituents may be calculated by the lever rule and the Fe-C phase diagram, figure 2. To harden such materials it is necessary to fully austenitise the material, in the case of low alloy engineering steels, Table 1, this is normally between 800^{o} and 900^{o}C. The material is then cooled rapidly to promote the change from austenite to martensite. Martensite is the microstructural constituent that is responsible for the strengthening effect within the steel.

The hardness of the martensite produced is related to the carbon content of the material as demonstrated in figure 3. During the quenching operation carbon in solution in the austenite does not have time to diffuse and, as a consequence, is retained in solid solution within the ferrite. The presence of these carbon atoms distorts the ferrite lattice, causing a strengthening effect. The greater the amount of carbon retained in solution the greater the distortion to the b.c.c. ferrite lattices and hence the greater the hardness.

It is true, therefore, to say that the hardness of a quenched material is directly related to its carbon content. However, under certain circumstances the martensitic structure may not be produced. This depends on the steel's ability to form martensite which is related to its overall composition.

1.1. Hardenability

The ability of a steel to harden by martensite formation on quenching is known as its hardenability. In general, the hardenability of a material is a function of its alloying element content. Consider two of the steels given in Table 1, i.e., En3 and H13, if bars of similar cross section are austenitised and then quenched in the same medium, the steel containing the highest alloying element content is hardened to a greater depth, figure 7(c). The use of more highly alloyed steels will be considered later.

1.2. Time-Temperature-Transformation Diagrams

TTT diagrams are very useful as an aid in predicting the micro-structures that will be produced in particular steels when different cooling rates are employed.

TTT diagrams are produced by isothermally transforming samples of the material at a series of different temperatures. The change in microstructure as a function of time is measured producing curves similar to those in figure 4(a). By producing a large number of curves the complete TTT diagram may be formed, figure 4(b).

These diagrams are used in the following manner: consider figure 5 for a 1%C steel (W1) Table 1. The shortest transformation time for this steel is $<1/_8$th second. With this material pearlite and bainite form simultaneously at about 550°C so there is only one continuous C-curve. In figure 5 the microstructures obtained are the result of austenitising the steel at 780°C for 10 mins and quenching into a salt bath at various temperatures. After holding for pre-determined times at various temperatures they are finally quenched into water.

1. Quenching in a liquid bath at 700°C; holding time 4 mins. During this interval the C has separated out, partly as pearlite lamellae and partly as spheroidised cementite. Hardness 225 HV.

2. Quenching to 575°C; holding time 4 secs. A very fine, closely spaced pearlite as well as some bainite has formed. Note that the amount of spheroidised cementite is much less than in the preceding case. Hardness 380 HV.

3. Quenching to 450°C; holding time 60 secs. The structure consists mainly of bainite. Hardness 410 HV.

4. Quenching to 20°C (room temperature). The matrix consists of roughly 93% martensite and 7% retained austenite. There is some 5% cementite as well which has not been included in the matrix figure. Hardness 850 HV.

With the exception of cobalt, all alloying elements delay the formation of ferrite and cementite, that is, they effectively displace the C-curves on the TTT diagram to the left. This means that the reduced cooling rates can be employed during a quench hardening operation. A further influence of the alloying elements is to split the C-curves into two regions.

1.3. Continuous Cooling Transformation Diagrams

Except in certain special quenching operations, such as austempering and martempering, cooling from the austenitising temperature occurs in a continuous manner. It is, therefore, more appropriate in many circumstances to use a CCT diagram instead of a TTT diagram. The C-curves in a CCT diagram are displaced down and to the right when compared with those on the TTT diagram.

These differences may be illustrated by considering the TTT and CCT diagrams for a eutectoid steel, figure 6. For a cooling curve, X, it takes 6 seconds to nucleate pearlite at 650^{0}C. However, at higher temperatures the time to the start of pearlite nucleation is longer, hence pearlite formation starts at point b on the curve, i.e., at longer times and at lower temperatures, similarly the pearlite finish is depressed and retarded to d.

In order to form a 100% martensitic structure it is clear that the cooling rate chosen must be such that the C-curves are not crossed. The slowest cooling rate that fulfils this condition is known as the critical cooling rate. If cooling is carried out at a rate faster than the critical cooling rate, diffusional transformation products are not formed, only martensite is produced.

1.4. End Quench Test/Jominy Test

Various tests may be performed to assess the hardenability of a steel, the Jominy test is the one most commonly used. In this test a round section bar 25 mm diameter and 100 mm in length is heated to the hardening temperature of the steel, figure 7(a) and held for 20 mins. One end of the specimen is then quenched by a jet of water (figure 7(b)). The rate of cooling thus progressively decreases up the length of the bar. When the bar has cooled two diametrically opposite flats are ground on the bar and hardness measurements are taken. A typical plot of the hardness versus the Jominy distance is shown in figure 7(c). The two curves in the figure correspond to a typical deep hardening steel and a typical shallow hardening steel.

As the cooling rates along the bar are well known the test provides data that enables the construction of CCT diagrams as indicated in figure 8. The microstructural constituents will change according to the distance from the quenched end of the bar.

The Jominy test data can be used in selecting the correct steel for a particular application. If a tool of large section size requires a certain through hardness to perform satisfactorily, consultation of Jominy test data can give an indication of the combination of steel and quenching rate required to achieve these properties. In the situation where the tool is large, it is generally better to use a high hardenability material and a less severe quench as this combination will reduce the susceptibility of the tool to crack. Selection of a steel with lower hardenability may also mean that on quenching, through hardening is not achieved.

2. CLASSIFICATION OF HEAT TREATMENT OPERATIONS

It is possible to divide all heat treatment operations into three broad categories:

Thermal Treatments

In this instance use is made of a suitable heating and cooling cycle to modify the properties of the material.

Thermochemical Treatments

These involve the addition of an alloying element such as carbon or nitrogen during a heating/cooling cycle, to alter the surface properties.

Thermomechanical Treatments

In this case a mechanical working operation is performed during the heat treatment cycle.

All these types of processes are capable of modifying the properties of the steel components under treatment. The selection of the correct treatment is influenced not only by the required final mechanical properties, but the overall economics of the manufacturing operation.

In this paper the emphasis has been placed on the thermal heat treatment operations as applied to tooling materials. However, mention of other treatment techniques has been made when considered appropriate.

2.1. Thermal Treatments

Heat treatment operations of this type may be sub-divided into:

(1) Annealing,
(2) Stress relieving,
(3) Normalising,
(4) Hardening,
(5) Tempering.

At this stage it is worth spending some time considering the characteristics of these treatments and the general reasons for their use.

2.1.1. Annealing treatments

An annealing treatment is used to reduce the hardness of the steel being processed or to produce a structure that facilitates the progress of subsequent manufacturing operations. The term annealing, when used by itself, normally implies full annealing, which involves a solution treatment in the austenite phase followed by slow cooling to produce a microstructure containing ferrite and carbide. Cooling is often carried out in situ in the furnace.

The exact nature of the conditions required are, of course, dependent on the type of steel under consideration and the properties required. Typical austenitising temperature ranges for a number of steels are listed in Table 1.

2.1.2. Spheroidising anneal

The spheroidising annealing temperatures are shown in figure 2 for a series of carbon steels where, for hypo-eutectoid steels (i.e., <0.8%C) annealing just below A_1 is suggested. However, in some cases annealing above A_1 followed by transformation below A_1 is to be recommended. During the treatment the pearlitic structure and the cementite lamellae form globules at their ends and split up into spheroids. Increasing the austenitising temperature speeds up the process: a typical spheroidised microstructure is shown in figure 9. However, if the annealing temperature exceeds A_1 temperature by more than $\sim 50^oC$ carbide will dissolve in the austenite and on cooling will separate out as lamellae cementite.

The softer structures are produced by processing as close to the A_1 temperature as possible. This may be summarised for plain carbon and low alloy steels as follows:

Austentise at a temperature not more than 50^oC above A_1 and transform at a temperature not more than 50^oC below A_1.

Although possessing the lowest hardness the structure may not be ideal for certain machining operations such as drilling, milling, planing or reaming. In these situations a slightly harder structure is better, this may be formed by increasing the annealing temperature to produce a lamellar carbide.

Hyper-eutectoid steels (>0.8%C) must be annealed above A_1 in order to spheroidise the grain boundary cementite. Steels with extensive grain boundary cementite networks can be problematic, in this instance a prior normalising treatment may be used to break up the networks.

For the majority of steels the annealing time is between 2 and 6 hours.

2.1.3. Recrystallisation annealing

During cold working processes, steel increases in hardness and hence becomes more difficult to work. Annealing steel above 600°C for times up to 1 hour causes recrystallisation to occur, this produces new stress free grains in place of the original deformed ones. This type of treatment is most commonly applied to 18/8 stainless steels, 13% manganese steels and to cold rolled low carbon sheet or strip steel.

2.1.4. Stress relieving annealing/stress relieving

Machining and working operations induce stresses within the surface of the components during manufacture. These can lead to increased hardnesses which make working the material more difficult. The presence of these stresses can induce distortion and, in extreme cases, even cracking on subsequent heat treatment. Stress relief may be achieved by heating the material for 1 to 2 hours. The temperature employed depends on the type of material, for low alloy and plain C-steels 550 to 650°C is required, while for hot work and high speed steels 600 to 700°C is necessary. Such treatments do not cause phase changes although in some circumstances grain growth may occur. Parts need to be slowly cooled, otherwise thermal stresses may be induced in the component.

When stress relieving hardened and tempered components a temperature some 20-30°C below the tempering temperature is normally used. Forgings should also be stress relieved if internal stresses are induced in the steel on account of rapid or uneven cooling, or if the forging has been subjected to severe straightening.

2.1.5. Normalising

This treatment involves austenitising the steel at its hardening temperature, holding it for up to 30 mins, then allowing it to cool in air. Normalising treatments are used to refine the grain size of a steel after it has become coarse grained during a forging or welding operation, c.f., figure 1(a) and 1(b).

These treatments are mainly applied to plain carbon and low alloy steels. The actual hardnesses produced depend on the steel dimensions and also the composition of the material. In even a larger diameter workpiece the cooling rates at the surface and the centre are similar therefore there will be similar structures produced over the whole cross-section.

2.1.6. Quench hardening treatments

The hardening operation consists of two stages; firstly heating to and holding at a suitable austenitising temperature for an adequate period of time; this is then followed by a quenching stage. Both the temperature and holding time selected, influence the amount of alloying elements present in solution in the steel. At higher temperatures and longer times more alloying elements go into solution, consequently, the hardenability is increased. Correct choice of these parameters is therefore essential if optimum hardening responses are to be achieved on quenching.

The choice of temperature also exerts an effect on the grain size within the material; if the structure becomes coarse grained during austenitising, the resulting loss in ductility may make it prone to cracking on quenching.

Hardening is then carried out by quenching in either brine solution, water, oil or by air cooling. The medium selected of course depends on the hardenability of the materials under treatment.

The volume changes occurring within the material through both the transformation sequence and thermal gradient affects give rise to distortion; this aspect will be covered in more detail later.

2.1.7. Tempering

After quench hardening and before the component reaches room temperature the tool is normally transferred to a tempering furnace. If the quenching stresses are not relieved immediately then cracking may well result. The tempering temperature selected is determined by the final hardness required on the component.

Care must also be taken in temperature selection in order to avoid temper embrittlement phenomena. In a number of situations the tempering operation may be carried out more than once, for instance high speed steels are often double or triple tempered to er [illegible] there is no untempered martensite remaining in the structu.

2.2. Special Treatments

In certain situations where excessive distortion and cracking are problems special treatments are employed to overcome the problems, figure 10.

2.2.1. Martempering

In this treatment steels are quenched with sufficient rapidity to ensure that transformation to pearlite or bainite does not occur. This is achieved by quenching into a salt bath at an appropriate temperature. The temperature is then held at a level above the martensite start temperature, Ms, to allow temperature equalisation between the surface and the core to occur. After a suitable time period the component is allowed to cool, tempering is then carried out as required once room temperature has been reached. This type of treatment reduces the effects of thermal stresses induced during quenching and hence reduces the danger of cracking, figures 10(b) and 11(a).

2.2.2. Austempering

Austempering treatments or bainite hardening treatments, use the isothermal transformation of austenite to bainite as the mechanism of hardening. Components are cooled from the austenitising temperature by quenching into a salt bath at a temperature below that at which the reaction to pearlite will occur and above the Ms temperature. The TTT and CCT diagrams provide useful information on these temperatures, figure 10(c).

The component is held at temperature in the furnace until the austenite has completely transformed to bainite, after which it is cooled to room temperature in still air. Such treatments are used to provide good impact properties and have found application on high speed steel tools which are used for interrupted cutting operations.

2.3. General Heat Treatment Information

In all of these treatments it is necessary to avoid surface decarburisation during the heat treatment. If this occurs then the properties of the tool are significantly altered and indeed it is likely that surface cracking will occur. To achieve this control over the surface carbon level it is necessary to carefully select the type of furnace to be used and also, if a gas furnace is chosen, the type of furnace atmosphere.

Although pre-heating, in most cases, is not essential before hardening treatments, it is good practise to pre-heat the part. A slow and uniform increase in temperature is preferable to ensure that the surface and the core both attain the correct austenitising temperature.

The supporting of parts in the furnace and also the manner in which the quenching is achieved are important, as both will influence the degree of distortion on the finished product. During the quench hardening operation care must be taken to ensure good circulation of the cooling medium.

3. HEAT TREATMENT FURNACES

As already mentioned, during heat treatment it is necessary to avoid carburising/decarburising of the surface layers as this may give misleading hardness results on subsequent quench hardening. In extreme cases, this can lead to cracking and can also lead to the choice of the wrong tempering temperature. It is also necessary to prevent severe oxidation as its removal represents another finishing operation which may well result in the piece being under-sized.

3.1. Salt Bath Furnaces

Salt bath furnaces, figure 11(b), contain a mixture of salts which are molten at the treatment temperature. Typical mixtures used at various temperature levels are given below:

45% NaCl + 55% KCl	675-900°C
20% NaCl + 80% BaCl	675-1060°C
100% $BaCl_2$	1025-1325°C

These compositions are only approximate as manufacturers of heat treatment salts do not specify precise compositions. Provided the salt bath is maintained in good condition the salt mixtures above provide a neutral medium for austenitising treatments. Good protection of the material is thus maintained during the time components are within the bath. Owing to the excellent heat transfer properties offered by the salt bath, heat up times are short and temperature uniformity is good.

Monitoring the composition of the bath at regular intervals is necessary to ensure the neutral conditions are maintained. During use, iron is removed from the components being treated, this is eventually oxidised, as the bath is in contact with the air, once formed the iron oxide can act as a decarburising agent. At this stage the salt bath must be regenerated. Regeneration is achieved by adding a few lumps of silicon brick; this combines with the iron forming a sludge which can be removed.

The presence of iron in the bath can be determined by immersing a graphite rod in it, this reduces any iron oxide present; with small beads of iron being formed on the graphite. A steel foil may be used to test the carburising/decarburising of the bath. If, after austenitising in the salt bath it is soft on quenching, the bath is decarburising, if it is more brittle then the bath is carburising. A suitable carbon concentration is necessary in the foil selected, i.e., it needs to be representative of the steel to be treated. Preheating the components is essential to remove moisture prior to placing in the bath. If this is not carried out the risk of an explosion is present.

3.2. Muffle Furnaces

Gas or oil fired muffle furnaces allow adjustment of the atmosphere to be carried out by controlling the air ingress and degree of combustion. By such control it is possible to largely maintain the carbon level of the material under treatment.

Electrically heated muffle furnaces, of a modern design, can also be generated with atmospheres; however, if these are not available packing in some neutral material is essential. Choice of this packing material depends on the carbon content of the steel under treatment. There is no universal material suitable for all types of steels.

Typical materials used for this purpose include paper, cast iron chips and stainless foil.

3.3. Quenching

With both of the types of furnaces above, quench facilities are not an integral part of the unit. Transfer from the furnace to the quench tank or quenching jig is necessary; this must be accomplished as quickly as possible, in order for full hardness to be achieved. With annealing, stress relieving and normalising treatments, quench facilities are obviously not required.

3.4. Sealed Quench Furnaces

These furnaces are more complex than those described; they are sealed against air penetration and contain an integral quench facility, figure 12. An atmosphere for the furnace is produced in an external gas generator; its composition can be adjusted to a suitable level for the material under treatment.

3.4.1.1. Exothermic gas

This is produced by the exothermic combustion (i.e., without the addition of heat) of gas and air; the combustion not going to completion. The gas produced contains significant amounts of CO_2 and H_2O, much of which must be removed, as these gases would cause significant decarburisation if left. The gas left consists mainly of N_2, H_2, CO with traces of CO_2 and H_2O.

3.4.1.2. Endothermic gas

This is produced by endothermic combustion (i.e., heat is required). Propane is mixed with air in controlled amounts and passed through a catalyst, and a carrier gas is produced. The gas produced has a low carbon potential $\sim$0.35%C. In order to increase the carbon potential, controlled additions of hydrocarbon are added to it within the furnace. Control of the carbon potential is achieved by employing dew point, infra red gas analysis or oxygen probe control systems. A carbon potential exactly equivalent to the carbon content of the material can thus be established. The gas generated consists typically of 30-40% N_2, 30-40% H_2, 18-20% CO, 0.5-1.5% CO, and 0.5% CH_4.

3.4.1.3. Inert gas

This is a gas that is unreactive to the steel, i.e., it contains no decarburising/carburising constituents. Gases such as nitrogen and argon fulfil this criterion. The cost of using this type of protection is greater than with the other two atmospheres. With the integral quench facility, cooling may be carried out under the protective atmosphere, thus reducing the risk of oxidation/decarburisation on exposure to air.

3.5. Vacuum Furnaces

A more sophisticated technique uses a vacuum furnace, figure
The components to be treated are placed in a cold furnace, which is then evacuated to a maximum pressure $\sim 10^{-2}$ torr. This may be achieved using rotary pumps, higher vacuums require the use of diffusion pumps. As air is removed from the furnace the risk of oxidation/decarburisation is eliminated. After the charge has been heated up it is cooled in an inert atmosphere such as argon or nitrogen under reduced pressure. However, more recent developments have introduced an integral oil quench facility and also the ability to fast gas quench under several bars of pressure. This allows vacuum furnaces to be used to harden materials of lower hardenability not previously considered suitable for vacuum hardening. A comparison of the advantages of vacuum heat treatment relative to atmosphere and salt bath furnaces is presented in Table 2.

3.6. General Comments

Furnaces should be able to provide protective atmospheres to prevent surface reactions occurring. They should be capable of providing slow uniform heat-ups and allow accurate control of the temperature.

4. MANUFACTURE OF TOOLS

4.1. Design Aspects

In the manufacture of tooling, designers need to be aware of the effects of the heat treatment operation required to produce the necessary mechanical properties in the finished article. Consequently, when designing the tool he must pay particular attention to material selection and the subsequent heat treatment operation.

No matter how good the material selection/heat treatment operation, problems can arise through bad design features. In general, it is necessary for the tool designer to avoid sharp corners and drastic changes in selection. On large dies and in complex tooling set ups, it is far better to use a number of segments rather than make the whole article out of one piece.

In figure 13 a complex segmented mould to make an auto-body panel is shown. The manufacture of such tooling can only be achieved in this manner. As an illustration of the design features that may cause problems a number of situations are considered in figure 14. When these rules are not observed the results can be as shown in figure 26.

The importance of these design aspects can be emphasised by considering fatigue failure in general engineering components. Fully 90% of all the fatigue failures that occur are attributable to design and production defects; only the remaining 10% occur through material defects, material specification or heat treatment.

4.2. Material Selection

The selection of the appropriate material will, of course, be dependent on the processes to be carried out. This may be dictated in a mould or die casting operation by the bursting pressure, by the effects of the material being processed, i.e., wearing of the die, or by high temperature strength requirements etc.

As an example, there would be little point in selecting a cold work tool steel for the manufacture of an aluminium extrusion die, as the tensile strength of these materials drops considerably at the temperatures employed during the operation. Of course, when considering material selection the additional cost of a more sophisticated material must be weighed against the expected lifetime of the component and the manufacturing costs. It is economic sense to produce a tool out of a more expensive material if this leads to increased lifetime, as the material costs are generally much less than the cost of producing a new tool.

An important point is to make sure the material is what you think it is before commencing the manufacturing operation.

4.3 Heat Treatment

Most of the work on the tool is carried out before the heat treatment operation is carried out. Tools at this stage may be worth thousands of dollars, therefore the choice and effectiveness of the heat treatment is critical.

In the following sections typical heat treatment conditions will be outlined for the various materials. The types of problems that may be encountered will be explained along with their solution. Typical case histories will be used to illustrate the effects that can be obtained.

Before considering these examples it is appropriate to look in more detail at the types of steels available and more specifically their heat treatment.

5. CLASSIFICATION OF TOOL STEELS

The existence of large numbers of tool steel types makes a classification difficult. However, by considering the type of heat treatment required and the subsequent working operation to be performed, it is possible to define a number of specific categories:

(1) Water hardening tool steels,
(2) Shock resisting tool steels,
(3) Oil hardening tool steels,
(4) Cold work tool steels,
(5) Hot work tool steels,
(6) High speed steels.

Typical examples of steels falling into these categories are given in Tables 3, 4, 5, 6 and 7.

5.1. Water Hardening Tool Steels

This type of tool steel is essentially a plain carbon steel with only small amounts of other alloying elements being present. A typical example is given in Table 1., the AISI W series. The relatively low hardenability of these materials means that they can be used in situations where a tough core is required in addition to a hardened surface.

Because of the low alloy content these materials are relatively cheap. This type of material is generally supplied in the annealed condition, and is frequently used for punches, figure 15.

5.1.1. Stress relieving

After fabrication of the tool, it may be beneficial to perform a stress relieving treatment prior to hardening. This is especially true for tools with complex geometry or after severe cold working. A temperature between $650^{\circ}C$ and $720^{\circ}C$ would be required for this treatment.

5.1.2. Quench hardening

The steel should be austenitised in the range $760^{\circ}C$ to $840^{\circ}C$ and held for between 10 and 30 mins, depending on the size of the tool. Quenching is then carried out in water or a brine solution consisting of 10% NaCl. With very small tools an oil quench could suffice.

5.1.3. Tempering

Tools should be tempered directly after hardening, preferably before they reach the ambient temperature, if this is not done cracking may occur. Tempering may be carried out in the range $150^{\circ}C$ to $300^{\circ}C$ in a salt bath for up to an hour.

The data sheet in figure 16 shows typical properties for the W1 materials listed in Table

5.2. Shock Resisting Tool Steels

Steels in the AISI S series are known as shock resisting tool steels. Typical compositions are given in Table 1. This type of material has been designed for operations in situations where high impact loading occurs. Its principal uses lie in the manufacture of chisels, hammers, punches, etc., where impact loading is prominent.

5.2.1. Annealing

Owing to their relatively high silicon contents these steels are susceptible to graphitisation. It is therefore imperative that annealing temperatures are not exceeded, while soak time should be kept short. Protective atmospheres or vacuum furnace techniques should be used in order to prevent decarburisation.

5.2.2. Stress relieving

It is not normal practise to stress relieve this grade of material. If stress is induced in the component through machining it can be relieved by taking the tool up to 650°C and then allowing it to cool to 500°C in the furnace followed by oil quenching down to room temperature in air.

5.2.3. Quench hardening

Austenitising is carried out at temperatures between 815°C and 950°C. Preheating may be advantageous in situations where the tool is large in order to reduce distortion. Protective atmospheres are required with this type of material, a reducing atmosphere is best at temperatures >870°C while an oxidising atmosphere is preferred at lower temperatures. Soak time should be kept to a minimum, especially with the high silicon grades, S2, S4 and S5; to prevent graphitisation these should be quenched as soon as the austenitising temperature is reached. The lower hardenability grades S2 and S4 require water quenching although on small sections oil quenching may be sufficient. Most of the other steels in the group are hardened by oil quenching with the exception of S6 which, in small section sizes, will harden in air. Tempering is undertaken in the range 150-250°C as can be seen from the data in Table 1.

5.3. Oil Hardening Steels

Steels in the AISI O series fall into this category. They contain greater quantities of alloying elements than the W series steels while maintaining essential , the same carbon level. This, of course, increases the hardenability of the material and permits hardening on oil quenching. The material is inexpensive and among the most popular used in tool manufacture; typical applications include blanking and forming dies, gauges and punches in cold working operations.

In selecting the particular grade of material to be used it is essential to control the amount of alloy additions as these can have a significant effect on the performance of this material.

5.3.1. Normalising

This type of treatment is sometimes employed on these materials if they have been subjected to treatments at temperatures greatly in excess of the austentising temperature. Prolonged soaking at the treatment temperature is undesirable; this can be minimised by prehating.

5.3.2. Annealing

If severe cold working has been necessary in the production of the tool it is advisable to carry out an annealing operation. Annealing temperatures will be specified by the material manufacturer for each specific steel. Annealing treatments are also employed before rehardening a previously hardened tool, as these minimise the risk of cracking.

5.3.3. Stress relieving

When precision components such as gauges are being manufactured and the tolerances are small, stress relieving operations are required. Thorough soaking at temperatures in the range 550°C to 650°C is advisable. Dimensions should be checked and corrected after this operation.

5.3.4. Quench hardening

Tool steels of this type are austenitised in the range 790°C to 880°C. Preheating, although not essential, can reduce distortion to a minimum on hardening. Slow and uniform heating is required if distortion is to be minimised. The low hardening temperatures <800°C aid in this respect.

Steels are hardened by quenching in oil at 50°C. Long articles should be quenched vertically to avoid warpage. After quenching tempering should be carried out immediately. Temperatures in the range 180°C to 200°C being optimum. Sub-zero quenching at ∿-75°C to transform the retained austenite found in the microstructure can be used to improve dimensional stability; a further tempering operation should then be performed (see figure 17).

Materials in this series are also suitable for martempering treatments, components can be quenched into a salt bath about 50°C above the Ms temperature, before air cooling to room temperature. Sufficient time of course is allowed in the salt bath to produce a uniform temperature.

In heavy sections the O series of steels do not through harden, as can be seen from figure 18. This has the advantage of having a hard case on a tough core, which improves shock resistance.

5.4. Cold Work Tool Steels

These steels are used in tooling applications that require high wear resistance. The high hardenability of these materials means that low hardening temperatures can be employed, while quenching in air is often sufficient for hardening. As mentioned earlier, the strength of these steels falls off at high temperatures, ∿350° to 400°C.

Both the AISI A series and the AISI D series steels fall into this category. The A series steels are used in situations where toughness in addition to wear resistance is required, while D series steels have higher wear resistance with lower toughness. A typical application of AISI A2 steel for a plastic mould tool is illustrated in figure 19.

5.4.1. Annealing

These treatments are used prior to rehardening tools to prevent cracking. Slow uniform heating, up to the manufacturer's recommended annealing temperature, in a protective atmosphere is required.

5.4.2. Stress relieving

After rough machining and prior to finish machining, tools should be stress relieved to minimise subsequent distortion on hardening.

5.4.3. Quench hardening

Tools of these types should be preheated prior to austenitising, again this helps to minimise distortion on hardening. The time at the austenitising temperature , A series 800^{o}C to 900^{o}C, D series 925^{o}C to 1025^{o}C, is important as it controls the dissolution of the carbide particles and, consequently, the hardenability of the material. Quenching is carried out in either oil, air or under vacuum, the choice of quenching medium is, of course, dictated by the steel type and the specific property requirements. The high hardenability of the material means that retained austenite will be present in the structure after quenching. This should be removed by a sub-zero quenching treatment. This may be carried out as a continuous operation after austenitising, or after a stress relieving treatment at 150 to 160^{o}C performed once the component has attained room temperature. Double or triple tempering at an appropriate temperature is required to ensure that no untempered martensite is present in the structure. Full heat treatment data for these steels is presented in Table 6 and 7.

5.5. Hot Work Tool Steels

This type of steel is used in the forming of metals at elevated temperatures. These steels, therefore, require high temperature strength, toughness and wear resistance. They find applications in forging, extrusion and stamping operations where the tools may be at elevated temperatures for considerable periods of time. Steels for this type of service are of three types: chromium, tungsten and molybdenum hot work steels. Chromium grades are the most widely used, while the tungsten and molybdenum types have advantages in greater resistance to thermal shock and heat checking. Heat checking of the surface is discussed later.

These steels may be satisfactorily used at temperatures up to 540°C. Full heat treatment data are presented in Tables 3 and 4.

5.5.1. Annealing

Once again, slow uniform heating is required to prevent cracking. Annealing is carried out generally in the temperature range 815°C to 900°C under a protective atmosphere. Cooling should be slow, ~20°C/hr to 400°C, then fairly fast to room temperature.

5.5.2. Stress relieving

This should be carried out after rough machining prior to finish machining. Treatments are carried out in the range 650°C to 730°C under a protective atmosphere.

5.5.3. Quench hardening

Preheating is essential with these grades of material as this minimises the soaking time at the austenitising temperature. A preheating temperature of 875°C is generally recommended, slow uniform heating up to this temperature is required, soaking for 1 hour per inch of cross section is adequate once 815°C is attained.

Austenitising temperatures lie in the range 1010°C to 1070°C at these temperatures dissolution of carbides occurs rapidly. Grain growth occurs on prolonged soaking, reducing ductility and hence increasing the risk of cracking on hardening. Protective atmospheres should be used as this will produce a soft surface on quenching and increase the likelihood of fatigue failure.

Cooling in air is adequate for these materials as they possess extremely high hardenability, large cross sections may be through hardened. To reduce scaling an interrupted quench may be used, i.e., quenching into a salt bath at 600°C to allow temperature equalisation prior to air cooling down to room temperature; sub-zero quenching can then be carried out to remove any residual austenite.

After quenching, the tool should be tempered immediately in order to avoid any risk of cracking. The tempering temperature should be selected to give the appropriate hardness. Multiple tempering ensures that no brittle martensite remains in the structure. Martempering treatments are often carried out on these steels, see figure 11(a).

A useful effect occurs in these materials when tempered at ∿500°C, precipitation of carbides M_6C and MC occurs which produce a a secondary hardening mechanism, as is shown in figure 20.

5.6. High Speed Steels

Two types of high speed steels are in general use today, (Table 5): these are the tungsten alloyed AISI T series, and the molybdenum alloyed AISI M series. The latter series were developed from the T series by replacing tungsten with molybdenum. High speed steels are used where high temperature strength and wear resistance are of extreme importance. Typical uses include drills, millers, and other cutting tool applications where operating temperatures may reach >600°C.

5.6.1. Annealing

The lowest hardness of a high speed steel can only be achieved after a full annealing treatment. Annealing is carried out at temperatures ∿875°C. It is essential that high speed steels are annealed prior to rehardening, if not, the resultant increase in grain size decreases ductility and can lead to cracking on quenching.

5.6.2. Stress relieving

High speed steels are difficult materials to machine, fabricating tools can, therefore, be expected to induce a lot of stress into the component. To relieve this stress, an anneal at a temperature in the range 680°C to 700°C should be carried out.

5.6.3. Quench hardening

As with other groups of tool steels, slow heating is necessary; a typical heating cycle involves preheating to a temperature ∿500°C. This should be followed by slow heating through the α/γ phase transition around 830°C. The austenitising temperatures required for these materials are high being very close to the region of melting for these steels. These temperatures, 1170-1230°C M series, 1250-1290°C T series, are required to ensure sufficient solution of carbides, and hence a high carbon content within the austenite. Time at temperature should be minimised to avoid grain coarsening. Over-heating can cause 'burning', i.e., grain boundary melting and the formation of a brittle grain boundary eutectic carbide phase. Quenching is then carried out at a rate sufficient to allow martensite formation. The retained martensite in the structure is transformed to martensite by sub-zero quenching and multiple tempering treatments. As in the case of hot work tool steels, high speed steels exhibit a secondary hardening characteristic on tempering between 540°C and 650°C through precipitation of carbides. A typical hardening cycle is shown in figure 21.

High speed steels can be hardened by both martempering and austempering techniques.

5.7. General Comments on Tool Steel Heat Treatment

When hardening tool steels, the main requirements are:

(a) preheating to help minimise distortion,

(b) slowly heating to the correct hardening temperature,

(c) protective atmospheres must be used to avoid surface decarburisation,

(d) short soak times at the hardening temperature to avoid grain coarsening and burning,

(e) choice of the correct quench medium/cycle,

(f) immediate tempering after quenching in order to avoid cracking,

(g) sub-zero treatment and/or multiple tempering treatments to temper any brittle martensite,

(h) care must also be taken with jigging and supporting the tools in the furnace and during quenching.

6. TYPICAL APPLICATIONS FOR SOME COMMONLY USED TOOL STEELS

In this section attention will be focussed on some typical uses for some of the types of steels already mentioned.

6.1. Punching Tool

The tool shown in figure 22 is made from AISI 01 steel, for blanking out parts for an office machine. The material is suitable for use in the manufacture of forming tools, cutting tools and plastic moulding tools. It possesses good dimensional stability after hardening, high surface hardness and good machinability. In the above instance, the material has been hardened and tempered to a hardness in the region 54-56 Rc. The size of the tool, some 15 mm, allows a considerable number of regrinds, thus ensuring a long tool lifetime.

6.2. Extrusion Die

The high temperatures involved with aluminium extrusion place very severe conditions on extrusion dies. In this application the requirements are for resistance to thermal shock, high temperature strength, toughness and ductility. Hot work tool steels, such as AISI H13, possess these characteristics. Additionally, these steels are easily machinable, can be highly polish and through hardened.

Figure 23 shows an aluminium extrusion die capable of producing complex shapes. A typical heat treatment involves hardening and tempering the material to 44-52 Rockwell C. The ability of this material to maintain its strength at high temperatures is illustrated in figure 24.

6.3. Cutting Blades

Cutting substances, such as paper, which are particularly abrasive can cause severe wear on tools. Figure 25 shows a cutting blade from a cash dispensing machine; the blade is used to cut the statement produced by the machine as cash is dispensed. The operation clearly can be classed as a cold working operation. Materials in the D series possess extremely good abrasive wear characteristics and are, therefore, most suitable for this application. The tools are hardened and tempered to give a hardness of 60 Rc. They are then given a light grind to produce a keen cutting edge.

6.4. Cutting Tools

In this application, high material removal rates produce high temperatures within the tool. An additional feature will be the impact loading on the drill, especially at the start of cutting. High speed steels, such as M2, are generally used in these applications. They possess good hot strength and high toughness.

It is possible, using a suitable hardening and tempering treatment, to produce hardnesses of 66 Rc; these hardnesses may be further enhanced by the use of a surface heat treatment or coating operation.

7. PROBLEMS ENCOUNTERED DURING TOOL PRODUCTION

To illustrate some of the problems that may be encountered during the manufacture of a die a series of case histories will be discussed.

7.1. Failures Due to Bad Design

It is worth emphasising the importance of good tool design at this stage. In designing a tool it is necessary to avoid drastic changes in section size, sharp corners or fillets, closely spaced holes, deep machining marks or identification marks, etc. All these features act as localised stress raisers which, on subsequent heat treatment, may provide the initiation site for a crack. A typical example of a component incorporating a number of these features is shown in figure 26. This type of component can be classed as a "hardener's" nightmare.

7.2. Failures During Heat Treatment

7.2.1. Pre-heating

If heavy working has been carried out on a component during the manufacturing sequence, rapid heat-up to the austenitising temperature can lead to cracking. The combination of residual stress and thermal stresses can be sufficient to nucleate a crack. To overcome this type of failure, very slow heating is required to ensure temperature uniformity, with a suitable holding time at some specified pre-heat temperature.

7.2.2. Austenitising

This is, of course, determined by the type of steel being used as has been shown earlier. The main variables are the temperature, the time at temperature, the atmosphere and the method of supporting the components.

Too high a treatment temperature can lead to increased solution of alloying elements in the material. This affects the hardenability of the material which may then cause problems on cooling to room temperature. In certain cases, such as those involving high speed steel, 'burning' can occur; this is a localised melting phenomenon that occurs in regions of heavy segregation. If a high speed steel is burnt it means that melting has occurred at grain boundaries with the formation of a brittle eutectic phase on cooling.
There is, as a consequence, a loss in toughness of the hardened product, and an increased risk of cracking in service.

The combined effects of too high a temperature and too long a holding period can lead to grain growth, this has the effect of reducing the ductility of the material and hence makes it more susceptible to cracking on cooling.

7.2.3. Atmosphere composition

The requirement is for the atmosphere/processing medium to be neutral/inert to the material being processed. In some instances, when control is poor, carburising or decarburising may occur. The presence of a carburised case can lead to cracking on quenching, problems with retained austenite and heat checking. Similarly, decarburisation of the surface can produce extensive cracking as shown in a high speed steel die, figure 27(a), after quenching. A cross-section through the die revealed extensive decarburisation, figure 27(b). Carbon loss from the surface causes an increase in the Ms temperature, hence the material at the surface transforms before the region below the surface. This results in a tensile stress in the surface which will cause cracking if of a sufficient magnitude.

7.2.4. Distortion

At high temperatures the yield stress of the material is much reduced, consequently, the material is much less able to support its own weight. It is, therefore, necessary to ensure that the component being treated is well supported. Consider a long shaft as an example; if this is laid horizontally within the furnace without proper support it may 'sag' in the centre. However, if it is supported vertically, no such distortion would occur. Another source of distortion at high temperatures arises from stress relieving effects. To minimise this effect a stress relieving operation should be employed after rough machining prior to finish machining. This reduces the extent of the residual stress induced in the component.

The major part of the distortion occurs as a result of the quenching operation, but contributions from various sources are possible as is indicated in figure 28.

7.2.5. Quenching

The quenching operation induces thermal gradients within the component which can lead to the generation of high stresses. With air cooling grades the stresses are relatively small in comparison with those induced by quenching in oil. As the severity of quench is increased the stresses formed in the component increase in magnitude. Consequently, it can be expected that the water, and oil hardening tool steels are more susceptible to cracking than the air hardening grades.

A further source of internal stress arising from the quenching operation is that due to the phase transformations.

The change from austenite to martensite is accompanied by an increase in volume of some 4%. Stress is produced in the component by the phase transformation sequence, as there are temperature differentials within the material the start of martensitic transformation will vary according to the position within the tool.

Stresses arising from these sources can produce cracking on cooling to room temperature.

7.2.6. Tempering

The tempering operation serves two purposes; firstly, it acts as a stress relieving operation, i.e., it allows relaxation of the quenching/transformation stresses and, secondly, the brittle martensitic phase starts to decompose, producing a tougher more ductile and hence, a less crack sensitive matrix.

7.3. Failures in Service

7.3.1. Grinding

Before being put into service it may be necessary to correct unavoidable distortion by a grinding operaticn. In a grinding operation, intense localised heating may be developed which can cause scorching cracks or heat checks in tools. Careful grinding is therefore very important; particular care should be taken to avoid:

(a) scorching - removing the metal too rapidly,

(b) grinding - with a 'dull' wheel,

(c) grinding - with too fine a grit size,

(d) ineffective cooling.

A network of fine cracks can be created in the surface of the tool if the grinding operation has not been correctly carried out.

7.3.2. Fatigue

In many instances tooling is used in situations where cyclic stressing is present. The creation of small cracks at localised stress concentrations, or through some deficiency in the heat treatment, such as very slight decarburisation, may significantly affect tool life.

7.3.3. Heat checking

This occurs in tooling used for hot work applications, e.g., after a period of use an aluminium die casting die may develop a surface crack network. Again this failure is associated with a fatigue mechanism. Thermal stresses are created by the operating conditions, i.e., the outer surface may be in contact with the hot metal under work, while the interior is relatively cool. As conditions cycle, fatigue cracks are initiated within the surface. Once formed, these cracks propagate and individual grains within the material separate out, the resulting voids act as stress raisers and hence sites for further crack nucleation. This effect cannot be avoided in hot work steels, but can be minimised by ensuring optimum hot strength, resistance to oxidation, and high fatigue strength.

In many instances, therefore, hot work tool steels benefit from an additional surface hardening treatment, as discussed later.

7.3.4. Wear

Two types of wear may occur, abrasive wear and adhesive wear. The former is associated with abrasive particles scoring the die surface causing metal removal, and ultimately affecting size, shape and surface finish.

Abrasive wear is often preceded by an adhesive wear mechanism which involves the localised welding together of the two contacting surfaces. These minute welds are formed and broken, in some instances small particles of metal may be pulled out of the mating surfaces; once this occurs abrasive wear can take place. Again a further surface treatment such as nitriding may improve the wear characteristics.

8. SURFACE HEAT TREATMENTS

Further improvements in the performance of steel cooling is sometimes required in arduous applications. A number of surface hardening/coating techniques are available; the use of these treatments can considerably improve the lifetime of tools.

The following treatments fall into this category:

(1) Steam treatments,

(2) Ferritic nitrocarburising treatments,

(3) Ferritic nitriding treatments,

(4) CVD coating techniques.

Each of these treatments will be discussed in turn, and the advantages and improvements demonstrated.

8.1. Steam Treatments

This type of treatment, which is also known as blueing, has been used for a considerable period of time. It involves carrying out the tempering operation in an atmosphere containing steam. At temperatures around 500°C a thin layer of iron oxide Fe_3O_4 is produced. This layer can improve the performance of high speed cutters such as drills, reamers, taps and millers. The improved lifetime is believed to be associated with the ability of the porous layer to retain an oil film. Welding of the tool to the workpiece is thus prevented and the resultant damage reduced. High speed steel tooling is often treated in this manner.

8.2. Ferritic Nitrocarburising Treatments

Nitrocarburising treatments can be performed in a salt bath containing cyanide salts or in an atmosphere containing both nitriding and carburising constituents.

At a treatment temperature in the range 550 to 570°C nitrogen and carbon are transferred to the surface of the workpiece with which they react. A non-metallic ε-carbonitride layer, figure 29, is formed on the surface. Treatment times are of the order of a few hours duration. Nitrogen has sufficient mobility to diffuse into the substrate where it is able to combine with nitride forming elements such as chromium, aluminium, titanium, molybdenum, vanadium, etc. Nitride formation occurs, this strengthens the surface of the material. Figure 30, demonstrates a typical hardness profile after treatment. Compressive residual stresses are formed within the surface which improve the fatigue performance of the component.

Typical applications are an H13 hot work tooling, such as crankshafts and cam rod forging dies, and aluminium extrusion dies. In this latter application the ε-carbonitride layer helps prevent galling and pick up of aluminium during working.

8.3. Nitriding

Plasma nitriding is the latest in a line of surface nitriding methods. This vacuum heat treatment process can operate in the temperature range 400°C to 570°C and can, therefore, be applied in a greater number of instances than the nitrocarburising treatments mentioned above.

The treatment employs a glow discharge, figure 31, to bring about the transfer of nitrogen to the workpiece. In order to suppress the formation of surface nitride layers, treatment times are limited to a maximum of 2 hours for high speed steel. The conditions selected depend on the material, the application and also the prior heat treatment conditions. Processing at temperatures of the order of 50°C below the tool's tempering are essential to avoid softening.

High hardnesses may be produced; these may be in excess of 1400 HV on high speed steels. A similar hardening mechanism to that mentioned above occurs; consequently, this treatment also enhances the fatigue performance.

8.4. Coating Treatments

Coating treatments such as those carried out using a chemical vapour deposition (CVD) technique, can drastically improve the product lifetime. In this type of treatment gaseous constituents are reacted in a vessel at high temperatures, ∿900-1000°C. A typical reaction is illustrated below:

$$TiCl_4 + 2H_2 + \tfrac{1}{2}N_2 \rightarrow TiN + 4HCl$$

the titanium nitride is deposited on to the material. This coating is very thin, 5 to 10 μm, but has very high hardness, ∿2500 to 3000 HV, and possesses good lubricity characteristics. However, the disadvantage of the treatment is that it softens the tool, therefore a rehardening operation is required. In order to maintain the wear resistant layer this treatment must be carried out under vacuum. Rehardening does, however, induce distortion, therefore this treatment can only be applied if the tolerances are greater than ±0.025 mm.

6.4.1. Case History

The effectiveness of these treatments has been illustrated with cold forming tooling, made from M2 (ASP 23) high speed steel. The punch tool shown in figure 32 is used to manufacture drive axle coupling for a number of automobiles. In this severe application the dies are subject to adhesive wear and stress cycling.

In the hardened and tempered condition these dies produce hundreds of components, before failure occurs. Table 8. shows the effects of surface treatments. It can be seen that a titanium nitride coating improves the performance of the forming tool by a factor of 100.

The expense of the additional surface heat treatment is more than justified by the improvements obtained.

READING LIST - GENERAL TEXTS

ASM Metals Handbook: 8th Edition, Volumes 1-10, American Society for Metals, Metals Park, Ohio.

R. Wilson: Metallurgy and Heat Treatment of Tool Steels, McGraw Hill Book Company (UK) Ltd., 1975.

K.E. Thelning: Steel and Its Heat Treatment, Bofors Handbook, Butterworths, England, 1975.

L.H. Van Vlack, Elements of Materials Science, Addison-Wesley Publishing Co. Inc., 1959.

R.E. Reed-Hill: D. Van Nostrand Company Inc., Princetown, New Jersey, U.S.A., 1964.

D.C.A. Wilkins: Heat Treatment and Quality Control of Metals, The Scientific Publishing Company, 40 Dalton Street, Manchester M4 4JP.

B.N. Chapman and J.C. Anderson: Science and Technology of Surface Coating, Academic Press, London and New York, 1974.

Carrs Fine Tool Steels Catalogue: R.W. Carr & Co. Ltd., Pluto Works, Sheffield S6 1LL.

Uddeholm Tool Steels Catalogue: Uddeholm Ltd., Crown Works, Rubery, Birmingham B45 9AG

Climax Molybdenum: Three Keys to Satisfaction, Climax Molybdenum Co., 1 Greenwich Plaza, Greenwich, Conn., U.S.A.

E.C. Rollason: Metallurgy for Engineers, Publisher: E. Arnold (Publishers) Ltd., London, 1954.

G.A. Roberts, J.C. Hanaker and A.R. Johnson: Tool Steels, American Society for Metals, Metals Park, Ohio, U.S.A.

C.A. Siebert, D.V. Doare and D.H. Breen: The Hardenability of Steels, American Society for Metals, Metals Park, Ohio, U.S.A.

L.H. Seabright: The Selection and Hardening of Tool Steels, McGraw-Hill Book Company, 1958.

E.C. Barr and H.W. Paxton: Alloying Elements in Steel, American Society for Metals, Metals Park, Ohio, U.S.A., 1966.

R.M. Brick, R.B. Gordon and A. Phillips: Structure and Properties of Alloys, McGraw-Hill Book Company, 1965.

D.A. Porter and K.F. Easterling: Phase Transformations in Metals and Alloys, Van Nostrand-Reinhold Company, 1981.

Source Book on Heat Treating, Volume 1, Materials and Processes, American Society for Metals, 1975; American Society for Metals, Metals Park, Ohio, U.S.A.

Source Book on Heat Treating: Volume II, Production and Engineering Practises, American Society for Metals 1975; American Society for Metals, Metals Park, Ohio, U.S.A.

M. Atkins: Atlas of Continuous Cooling Transformation Diagrams for Engineering Steels, British Steel Corporation, P.O. Box 35, Bridge St., Sheffield, England.

SPECIALISED READING

T.D. Atterbury:	Tool and Die Heat Treatment - A User's Assessment of Available Equipment, Heat Treatment of Metals, 1975.3, p. 87-92.
J.W. Sullivan:	Preventing Failures in Cold Forming Tests - Heat Treatment and Design, Metals Engineering Quarterly, February 1973, p. 128-138.
C.A. Montreal:	Heat Treatment of Tools Steels, Heat Treatment of Metals, 1974.4, p. 142-145.
B.S. Levert:	Plastic Mold Steels, Climax Molybdenum Publication, Climax Molybdenum Company, 1 Greenwich Plaza, Greenwich, Conn., U.S.A.
G.E. Wieland and E.M. Rudzki:	Effects of Furnace Design and Operating Parameters on the Decarburisation of Steel, Metal Progress, February 1979, p. 40-46.
R. Hewell:	High Speed Steels - A World Survey, Metal Bulletin Monthly, December 1971.
The Iron and Steel Institute:	Materials for Metal Cutting, Published by The Iron and Steel Institute, London, 1970.
The Metals Society:	Proceedings of Conference 'Tools and Dies for Industry', 28-29 September 1976, The Metals Society, London.
The National Physical Laboratory and The Metals Society:	Proceedings of Conference 'Towards Improved Performance of Tool Materials', Tipton, 1981 published by The Metals Society, London, 1981.
A. Kulmburg and A. Schindler:	New Developments in the Processing and Heat Treatment of High Speed Steels, Heat Treatment of Metals, 1977.2, p. 33-38.
J.T. Berry:	High Performance, High Hardness, High Speed Steels, Climax Molybdenum Company, 1 Greenwich Plaza, Greenwich, Conn., U.S.A.
O.C.F. Lunn:	High Quality Heat-Treatment of Tool Steels, Metallurgia, April 1983.
T. Bell:	Plasma Heat Treatment of Tooling for the Plastics Industry, Plastics and Rubber Processing, December 1976.
A.M. Staines and T. Bell:	Plasma Nitriding of High Alloy Steels, Heat Treatment - Methods and Media, Institution of Metallurgists, June 1979.

T. Bell: The Surface Heat Treatment of Steel to Combat Wear, Metallurgia, Vol. 49, No. 3, 1982, p. 103-111.

T. Bell: Ferritic Nitrocarburising, Heat Treatment of Metals, 1975, 2, p. 39-49.

B. Edenhofer: Physical and Metallurgical Aspects of Ionitriding, Klockner Ionon Gmbh, Cologne, W. Germany; Heat Treatment of Metals, 1974.1, p. 23-28 and 1974.2, p. 59-67.

T. Bell: Survey of the Heat Treatment of Engineering Components, January 1972, The Metals Society, London.

T. Bell: Sub-atmospheric Pressure or Vacuum Heat Treatment Processing, The Metals Society - Metals Technology, May 1974.

Metal Forming: Fuel and Metallurgical Journals Ltd., London, 1968, 35, (12), p. 348-351.

TABLE 1.

Designation		Average Composition										Austenitising Temperature
BS 970	En	C %	Si %	Mn %	P ≤%	S ≤%	Cr %	Mo %	Ni %	V %	W %	°C
070M20	3A	0.2		0.7	0.05	0.05						880 - 910
080A35	8A	0.36	<0.4	0.8	0.05	0.05						830 - 870
708M40	19A	0.4	0.23	0.85	0.04	0.05	1.05	0.2				850 - 880
817M40	24	0.4	0.23	0.57	0.04	0.05	1.2	0.27	1.5			820 - 860
655M13	36A	0.13	0.23	0.47	0.04	0.05	0.85		3.3			760 - 820
722M24	40B	0.24	0.23	0.85	0.025	0.025	3.25	0.55				870 - 910
BS 4659 BH13		0.37	1.0	<0.4			5.0	1.5		1.0		850 - 1030
BO1		0.9	<0.4	1.23			0.5			<0.25	0.5	760 - 850
BS1		0.5	0.85	0.5			1.5			0.2	2.25	790 - 920
BS5		0.55	1.8	0.7				0.40		0.2		800 - 950
BW1		0.9	<0.3	<0.35			<0.15	<0.1	<0.2			760 - 830

Table 2 Comparison of reported advantages of vacuum heat-treatment furnaces with protective gas atmosphere furnaces and salt baths

Vacuum furnaces (all types)	Protective gas atmosphere furnaces	Salt baths
Very pure environment easily maintained	Lower capital cost than vacuum	Lower capital cost
Consistent performance	Reducing atmosphere used for oxide removal	Simplicity
Failure to maintain required environment seen immediately	..	Ease of operation
Ease of operation	..	Very rapid and uniform heating
Speed of maintenance	..	
Automatic purging of trapped volumes	..	..
Removal of volatiles and adsorbed gas	..	..
Possible improvements in surface finish	..	..
Uniform heating of charge and reduced distortion	..	..
Rapid heating	..	..
No explosion hazards	..	..
No standby power required for cold retort types of furnace	..	..
Suitable for operating temperatures up to 3 000 °C	..	..
Flexibility of operation	..	..
Minimal purge period	..	..

Table 3 Hardening and tempering parameters for H series chromium-based tool steels

AISI designation	Composition, % C	W	Mo	Cr	V	Others	Preheat temp., °C	Hardening temp., °C	Vacuum,* torr	Quench	Tempering temp., °C	Final HRC
H10	0·4	..	2·5	3·25	0·4	..	820	1 000–1 040	10^{-1}–10^{-2}	Inert gas	530–650	40–56
H11	0·35	..	1·5	5·0	0·4	..	820	990–1 030	10^{-1}–10^{-2}	Inert gas	530–640	40–52
H12	0·35	1·5	1·5	5·0	0·4	..	820	990–1 050	10^{-1}–10^{-2}	Inert gas	530–640	40–52
H13	0·35	..	1·5	5·0	1·0	..	820	990–1 050	10^{-1}–10^{-2}	Inert gas	530–640	40–52
H14	0·4	5·0	..	5·0	..	..	820	1 010–1 060	10^{-1}–10^{-2}	Inert gas	530–640	40–52
H16	0·55	7·0	..	7·0	..	..	820	1 120–1 180	2×10^{-1} to 1×10^{-1}	Inert gas/oil	530–640	40–54
H19	0·4	4·25	..	4·25	2·0	4·25 Co	820	1 090–1 200	2×10^{-1} to 1×10^{-1}	Inert gas/oil	530–640	40–54

*vacuum required to give a bright clean finish

Table 4 Hardening and tempering parameters for H series tungsten- and molybdenum-based tool steels

AISI designation	Composition, % C	W	Mo	Cr	V	Others	Preheat temp., °C	Hardening temp., °C	Vacuum,* torr	Quench	Tempering temp., °C	Final HRC
Tungsten-based steels												
H20	0·35	9·0	..	2·0	..	..	820	1 100–1 200	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	42–52
H21	0·35	9·0	..	3·5	..	..	820	1 100–1 200	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	42–52
H22	0·35	11·0	..	2·0	..	..	820	1 100–1 200	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	42–52
H23	0·3	12·0	..	12·0	..	..	820	1 200–1 260	2×10^{-1} to 10^{-1}	Oil	Temper to precipitation harden	
H24	0·45	15·0	..	3·0	..	..	820	1 100–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	42–54
H25	0·25	15·0	..	4·0	..	..	820	1 150–1 260	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	42–54
H26	0·5	18.0	..	4·0	1·0	..	820	1 180–1 260	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	50–60
Molybdenum-based steels												
H41	0·65	1·50	8·0	4·0	1·0	..	820	1 080–1 190	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	50–62
H42	0·6	6·0	5·0	4·0	2·0	..	820	1 120–1 220	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	50–60
H43	0·5	..	8·0	4·0	2·0	..	820	1 090–1 190	2×10^{-1} to 10^{-1}	Inert gas/oil	530–650	48–58

*vacuum required to give a bright clean finish

Table 5 Hardening and tempering parameters for T and M series high-speed steels

AISI designation	Composition, % C	W	Mo	Cr	V	Others	Preheat temp., °C	Hardening temp., °C	Vacuum,* torr	Quench	Tempering temp., °C	Final HRC
Tungsten-based HSS												
T1	0·7	18·0	..	4·0	1·0	..	850	1 260–1 300	2×10^{-1} to 10^{-1}	Inert gas/oil	530–630	56–66
T2	0·8	18·0	..	4·0	2·0	..	850	1 260–1 300	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T4	0·75	18·0	..	4·0	1·0	5·0 Co	850	1 260–1 300	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T5	0·8	18·0	..	4·0	2·0	8·0 Co	850	1 260–1 300	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T6	0·80	20·0	..	4·5	1·5	12·0 Co	850	1 260–1 290	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T7	0·75	14·0	..	4·0	2·0	..	850	1 260–1 300	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T8	0·75	14·0	..	4·0	2·0	5·0 Co	850	1 250–1 280	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T9	1·2	18·0	..	4·0	4·0	..	850	1 250–1 280	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
T15	1·5	12·0	..	4·0	5·0	5·0 Co	850	1 000–1 200	2×10^{-1} to 10^{-1}	Inert gas/oil	550–630	58–66
Molybdenum-based HSS												
M1	0·8	1·5	8·0	4·0	1·0	..	820–850	1 180–1 210	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–66
M2	0·85	6·0	5·0	4·0	2·0	..	820–850	1 190–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–66
M3	1·05	6·0	5·0	4·0	2·40	..	820–850	1 200–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–66
M4	1·3	5·5	4·5	4·0	4·0	..	820–850	1 200–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–67
M6	0·8	4·0	5·0	4·0	1·5	12·0 Co	820–850	1 180–1 220	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–67
M10	0·9	..	8·0	4·0	2·0	..	820–850	1 180–1 220	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–67
M15	1·5	6·5	8·5	4·0	5·0	5·0 Co	820–850	1 190–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–67
M33	0·9	1·5	9·5	4·0	1·15	9·0 Co	820–850	1 200–1 230	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–68
M42	1·1	1·5	9·5	3·75	1·15	8·0 Co	820–850	1 190–1 210	2×10^{-1} to 10^{-1}	Inert gas/oil	550–640	56–68

*vacuum required to give a bright clean finish

Table 6 Hardening and tempering parameters for A series tool steels

AISI designation	Composition, % C	W	Mo	Cr	V	Others	Preheat temp., °C	Hardening temp., °C	Vacuum,* torr	Quench	Tempering temp., °C	Final HRC
A2	1·0	..	1·0	5·0	..	..	750–800	910–980	10^{-1}–10^{-2}	Inert gas	150–600	50–64
A4	1·0	..	1·0	1·0	..	2·0 Mn	670	820–870	10^{-1}–10^{-3}	Inert gas	150–500	50–64
A5	1·0	..	1·0	1·0	..	3·0 Mn	600	790–840	10^{-1}–10^{-3}	Inert gas	150–500	50–64
A6	0·7	..	1·0	1·0	..	2·0 Mn	650	830–870	10^{-1}–10^{-3}	Inert gas	150–500	50–64
A7	2·25	..	1·0	5·25	4·75	..	800–830	950–980	10^{-1}–10^{-2}	Inert gas	150–500	50–64
A8	0·5	1·25	1·25	5·0	..	..	800	980–1 010	10^{-1}–10^{-3}	Inert gas	150–550	50–62
A10	1·35	..	1·5	..	..	1·8 Mn 1·8 Ni	650	790–820	10^{-1}–10^{-3}	Inert gas	150–500	50–62

*vacuum required to give a bright clean finish

Table 7 Hardening and tempering parameters for D series tool steels

AISI designation	Composition, % C	W	Mo	Cr	V	Others	Preheat temp., °C	Hardening temp., °C	Vacuum,* torr	Quench	Tempering temp., °C	Final HRC
D1	1·0	..	1·0	12·0	..	..	815	970–1 010	10^{-1}–10^{-2}	Inert gas	150–590	52–64
D2	1·5	..	1·0	12·0	..	..	815	980–1 020	10^{-1}–10^{-2}	Inert gas	150–590	52–64
D3	2·25	..	..	12·0	..	..	815	930–980	10^{-1}–10^{-2}	Oil	205–450	52–61
D4	2·25	..	1·0	12·0	..	..	815	930–980	10^{-1}–10^{-2}	Inert gas	150–500	52–64
D5	1·5	..	1·0	12·0	..	3·0 Co	815	980–1 020	10^{-1}–10^{-2}	Inert gas	150–590	52–64
D7	2·35	..	1·0	12·0	4·0	..	815	1 000–1 060	10^{-1}–10^{-2}	Inert gas	150–590	52–64

*vacuum required to give a bright clean finish

TABLE 6.

Influence of Surface Treatment on Tool Performance

Untreated H & T	700
Nitrocarburised	4,000
Plasna Nitrided	30,000
CVD Coated and Rehardened	70,000

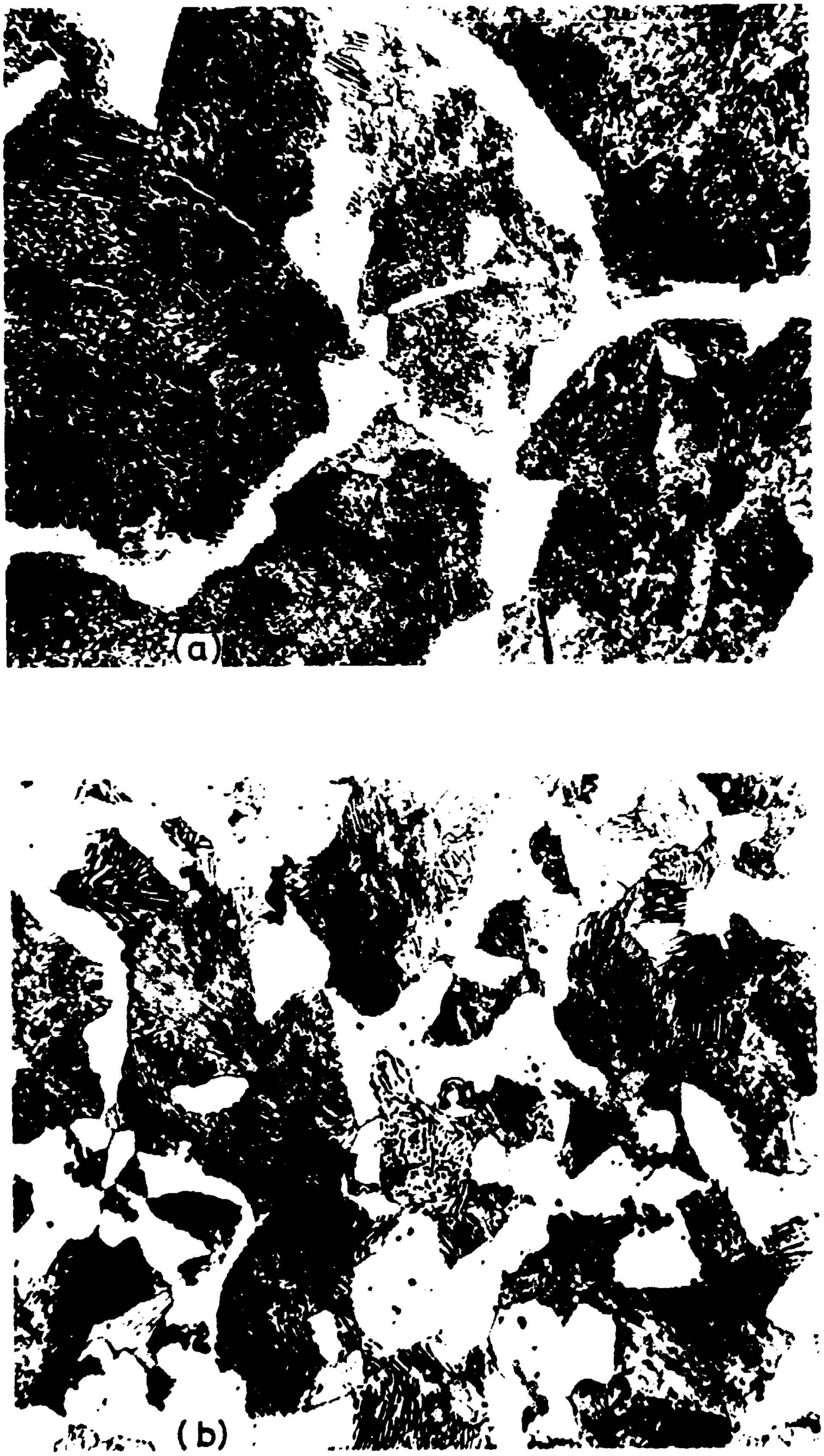


Figure 1 Influence of normalizing anneal on grain size. Carbon steel 0·50% C (a) As rolled or forged. Grain size 3 ASTM; (b) Normalized. Grain size 6 ASTM. Both 500×

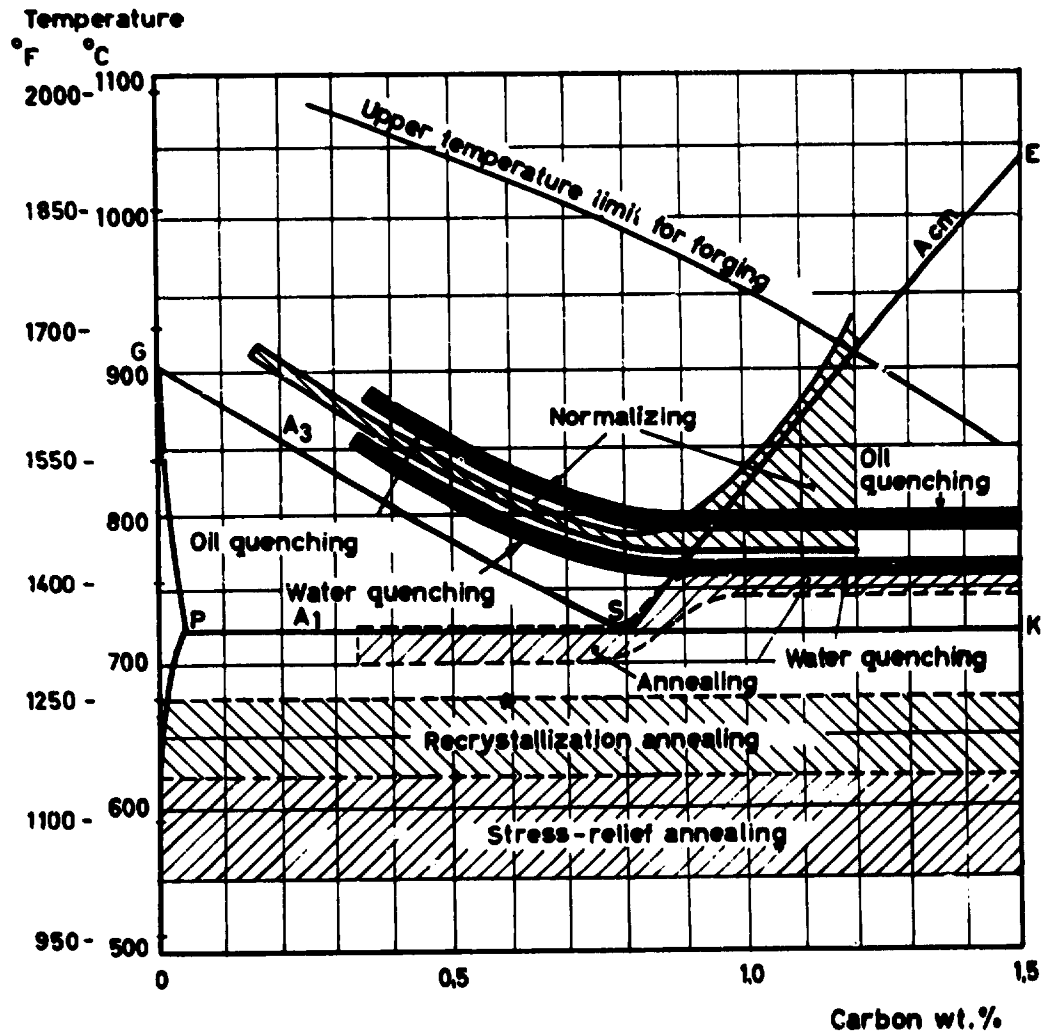


Figure 2 Iron–carbon equilibrium diagram showing temperature regions for various heat-treatment operations

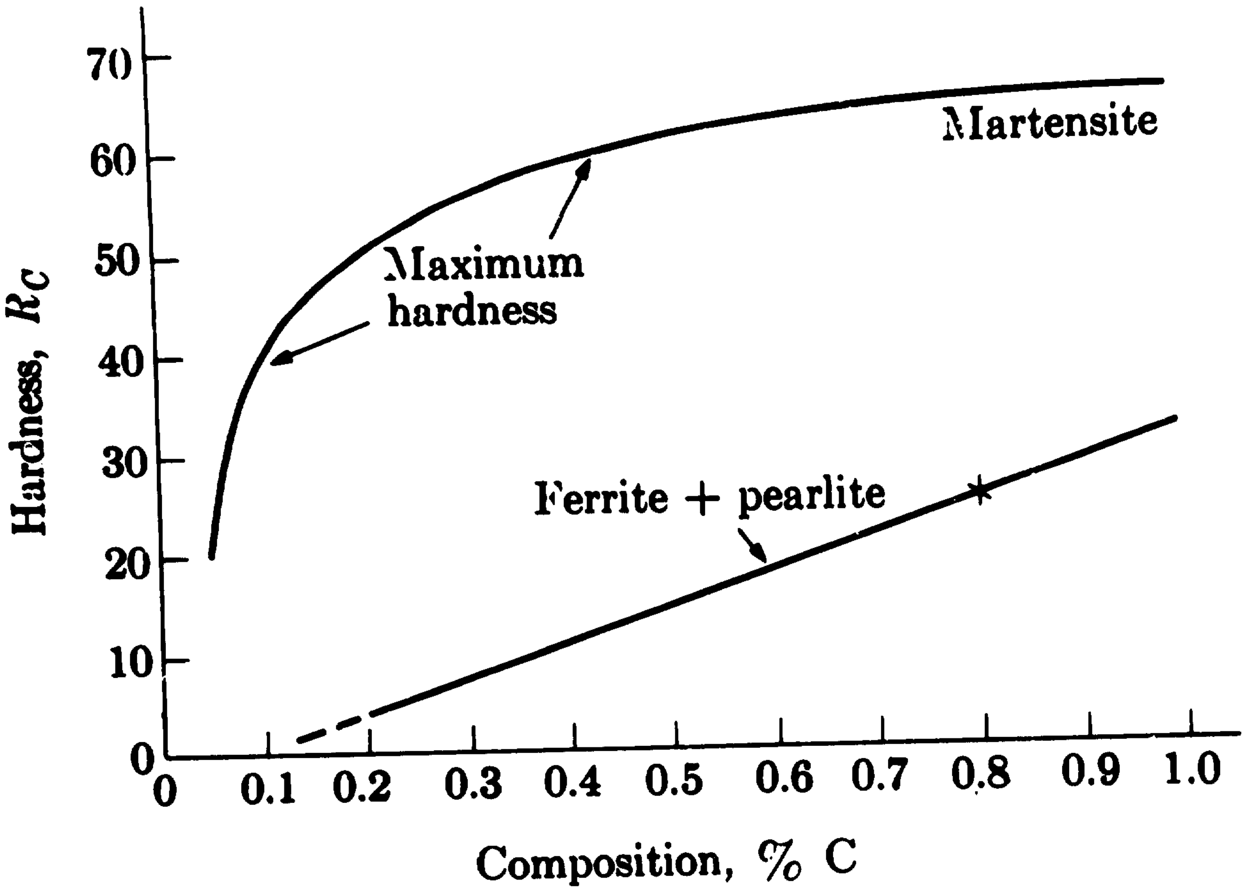


FIG. 3 Maximum hardness *vs.* carbon content. Maximum hardnesses arising from martensite compared with the hardnesses developed by pearlitic microstructures. To produce maximum hardness, the reaction $\gamma \rightarrow \alpha + C$ must be avoided during quenching.

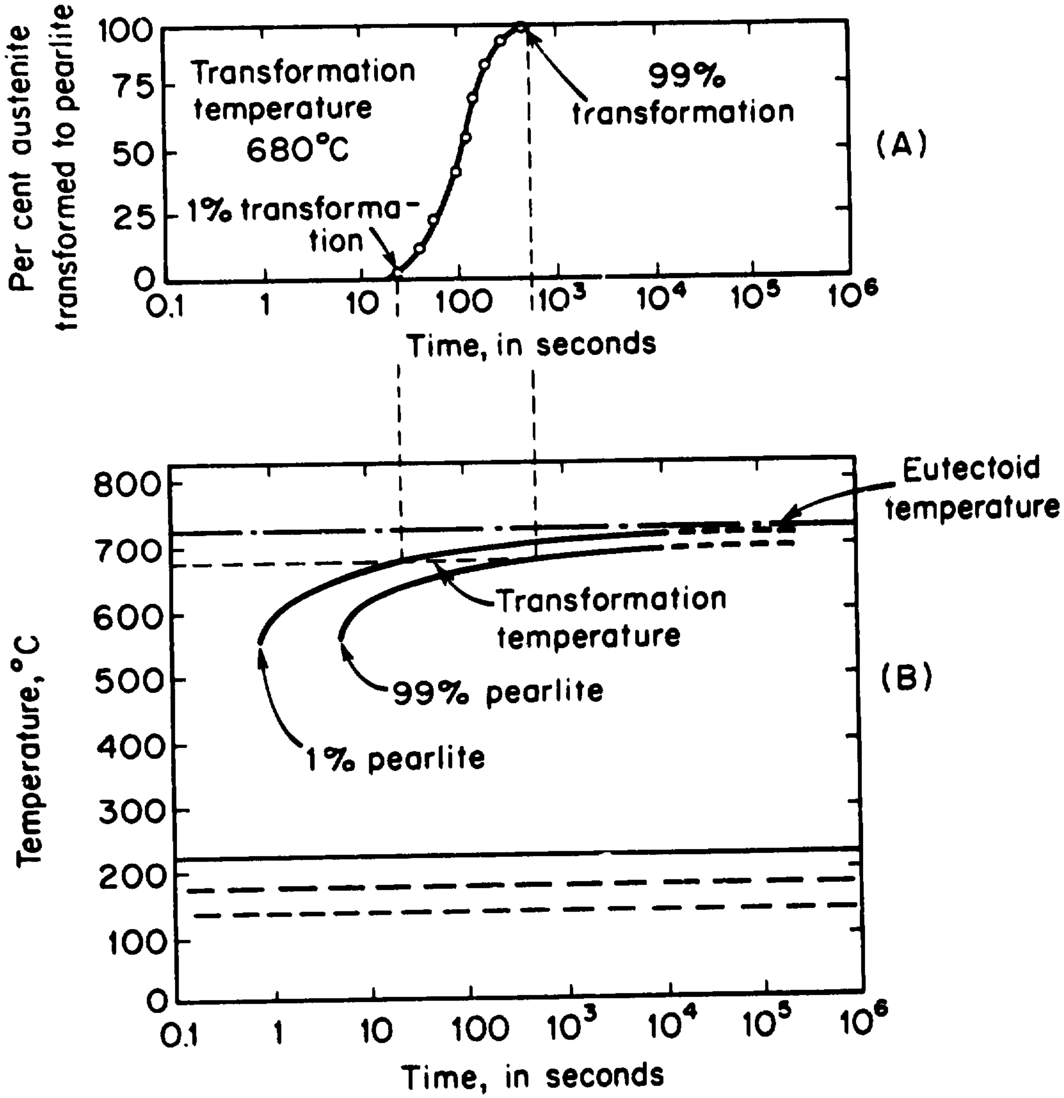


FIG. 4 (A) Reaction curve (schematic) for isothermal formation of pearlite. (B) Time-temperature-transformation diagram obtained from reaction curves.

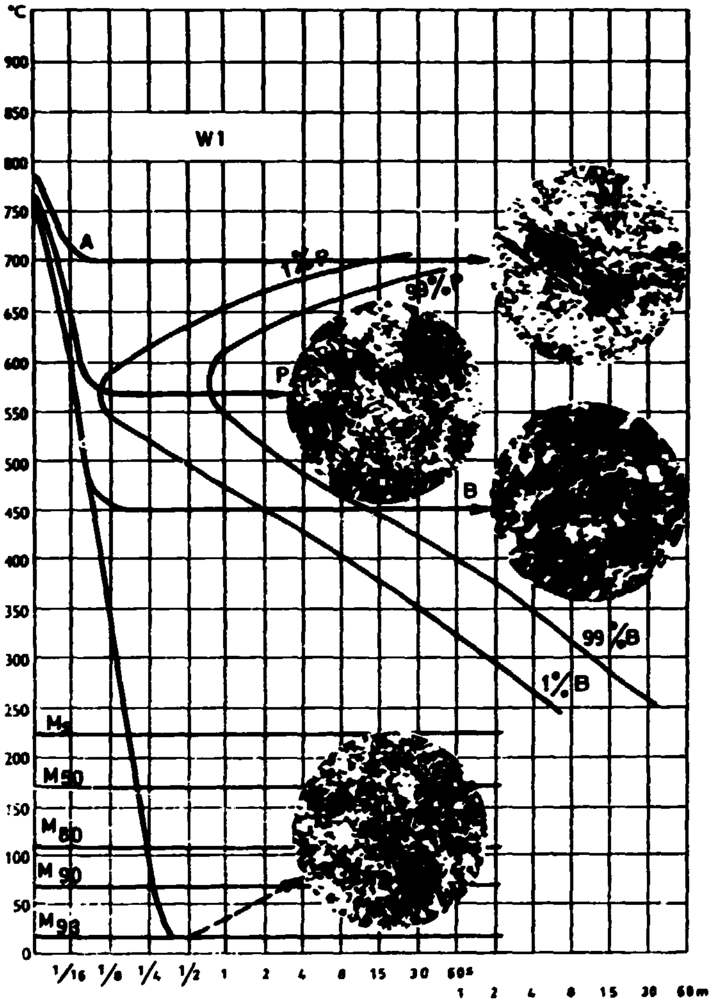


Figure **5** *TTT diagram for isothermal transformation of steel W1 (1% C steel). A = Austenite. B = bainite. M_s = start of martensite transformation. M_{50} = 50% M. P = pearlite*

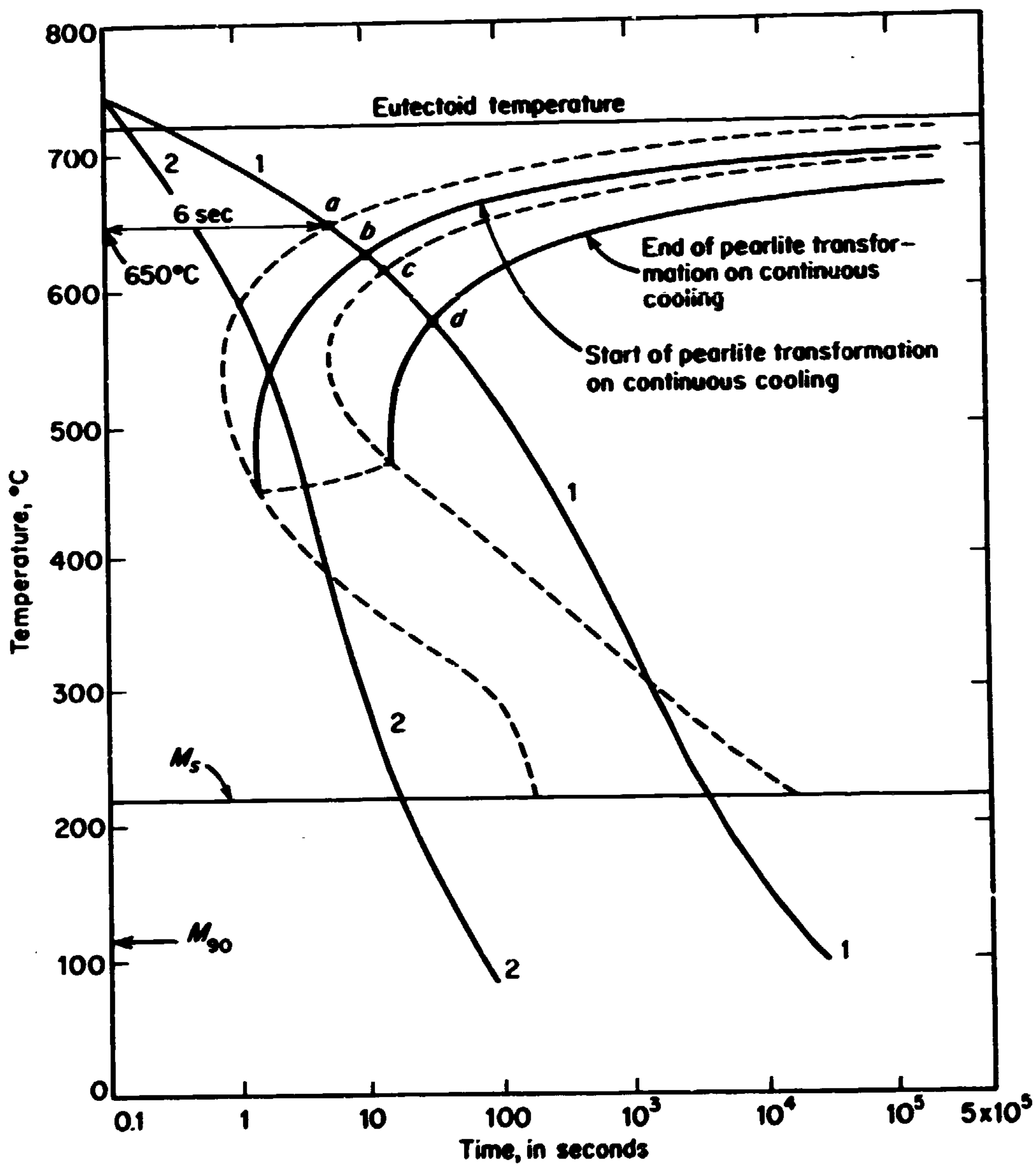


FIG. 6 The relationship of the continuous cooling diagram to the isothermal diagram for an eutectoid steel (schematic)

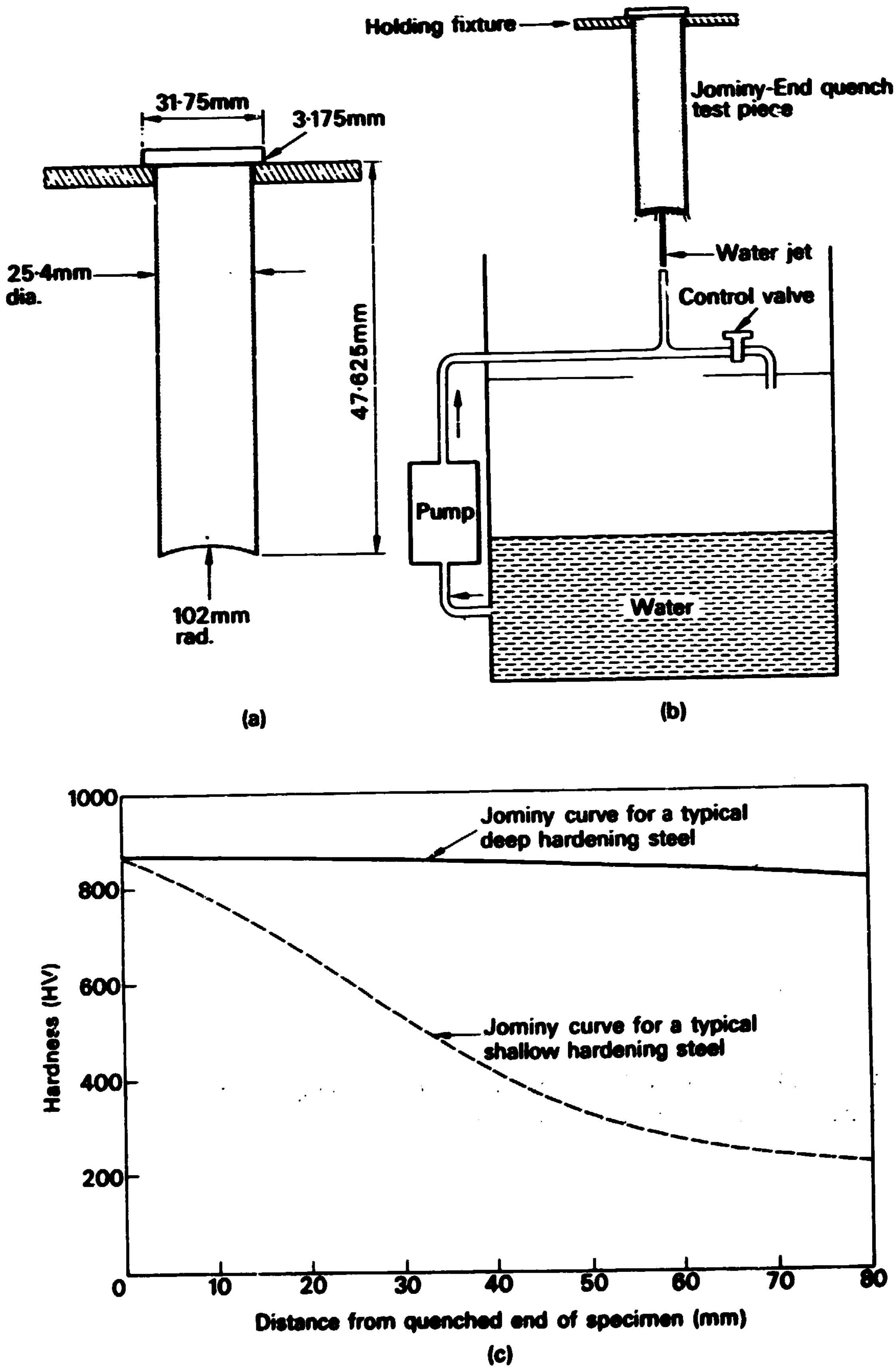


Fig. 7 Diagrammatic representation of the Jominy-end quench test.

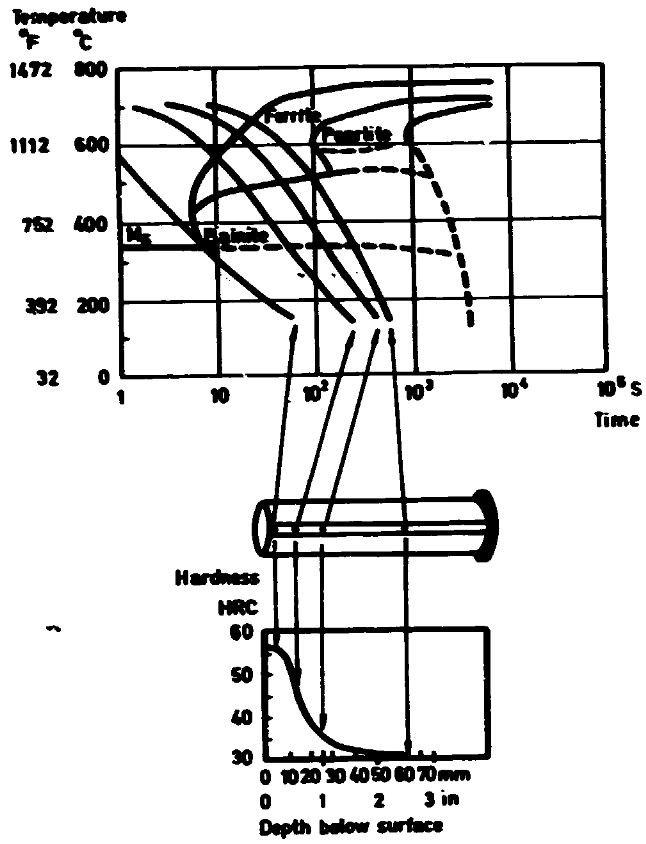


Figure 8 Continuous-cooling transformation (CCT) diagram with some cooling curves for corresponding Jominy distances. The lower diagram shows the hardness values along a Jominy test specimen

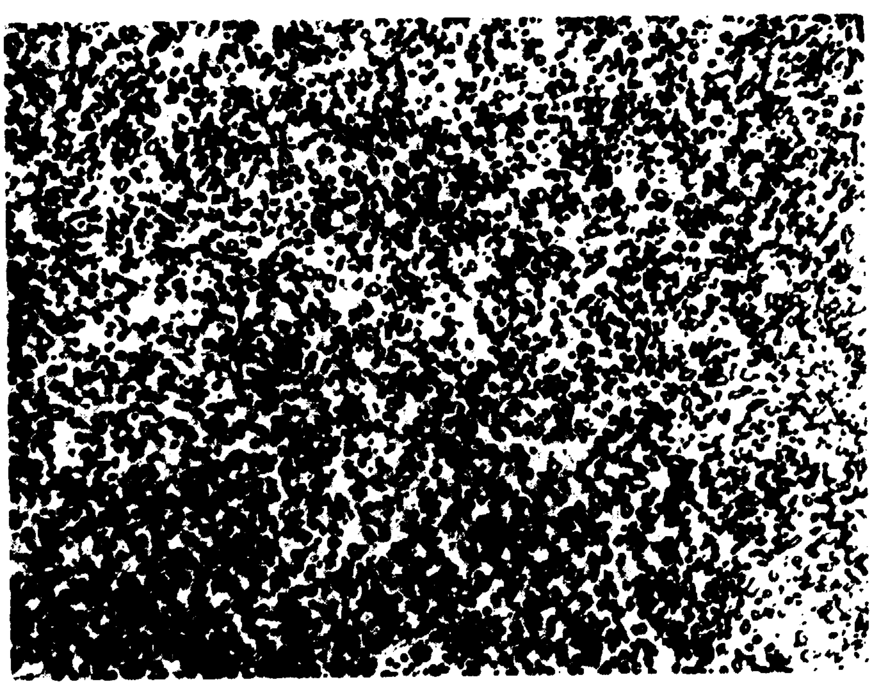
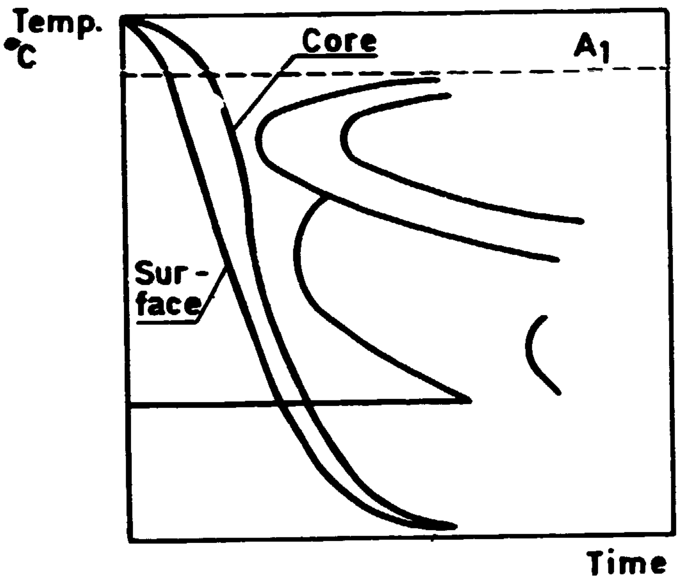
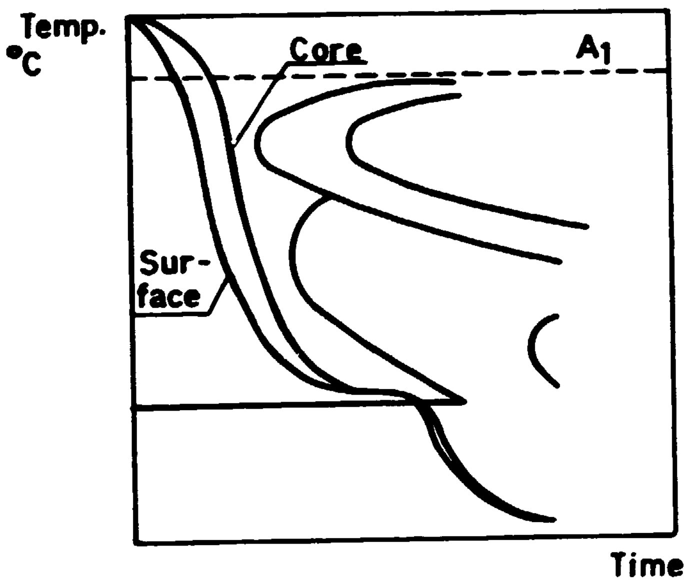


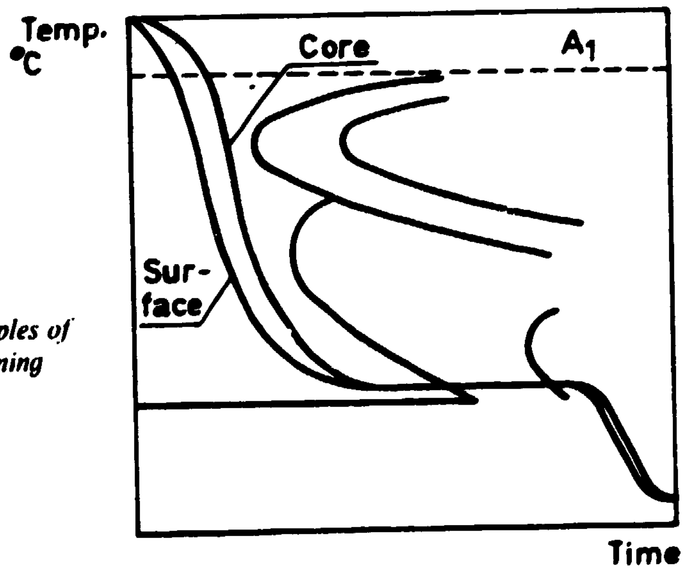
Figure 9 Typical annealed structure showing completely spheroidized carbides



Direct quenching to martensite



Martempering

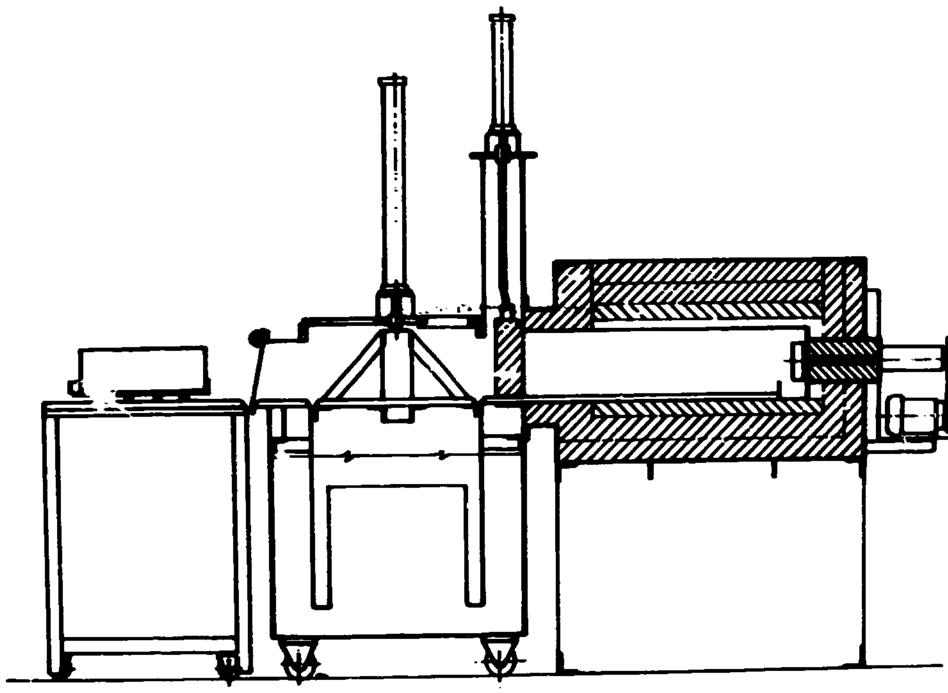


Austempering

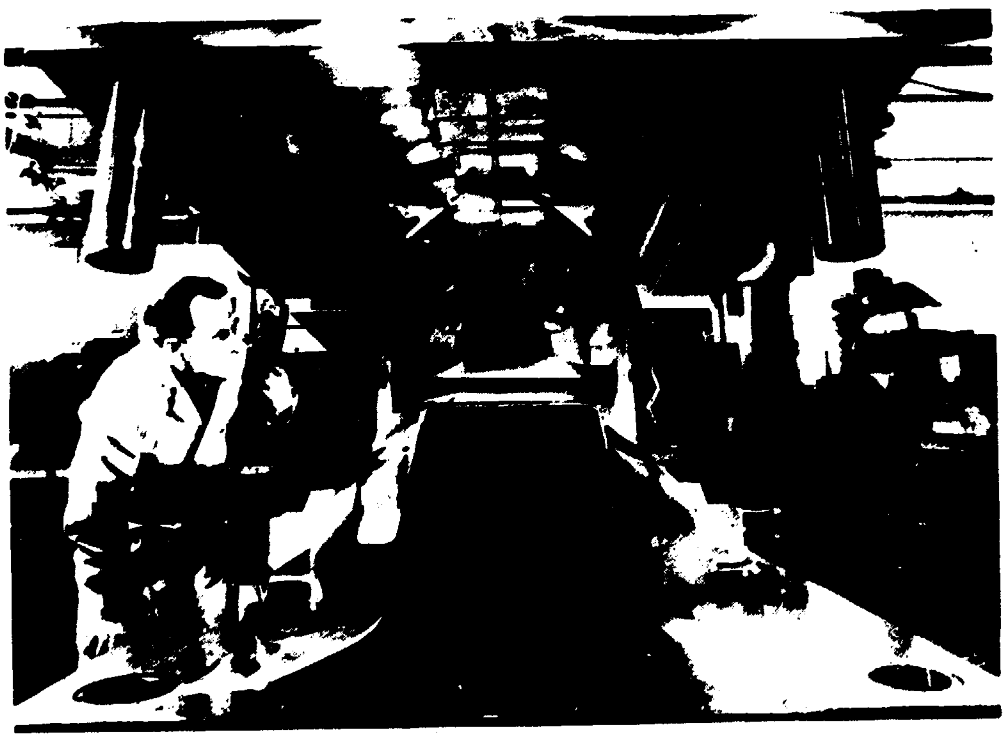
Figure **10** *Diagrams showing principles of different methods of cooling for hardening*

Figure 11a Martempering of die-casting die for aluminium. Die made from steel H 13 (Bofors ROP 19)

Fig. 11 b
'Cassel' salt bath furnaces, with pots 6 ft. (2 metres) deep, using 'Rapideep'-H for carburising and C.S. 700 for heat-treatment of fluted rollers.

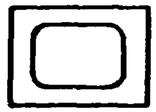
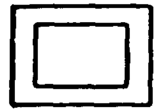
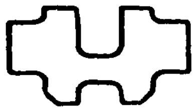
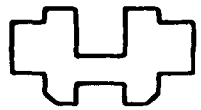
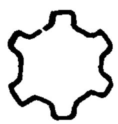
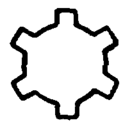
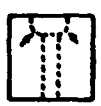
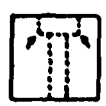


Schematic: toolroom sealed quench furnace Fig 12



A complex, segmented mold used to make an auto body panel

Fig 13

CORNERS	DO	DO NOT
INTERNAL CORNERS	 Use fillets and radii	 use sharp corners
MACHINE PARTS	 Use fillets and radii	 use sharp corners
INTERNAL OR EXTERNAL SPLINES OR KEYWAYS	 Use fillets and radii	 use sharp corners
EMBOSSING DIES	 Use rounded corners or edges	 use sharp corners or edges
RECESSED SCREW OR BOLT HOLES	 Use fillets and radii	 use sharp corners

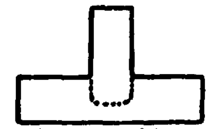
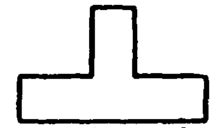
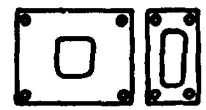
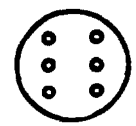
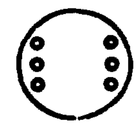
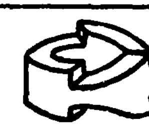
SECTION BALANCE	DO	DO NOT
PROJECTIONS	 Use inserts if sharp angles are necessary	 use integral projections
HEAVY AND LIGHT SECTIONS	 Separate heavy from light sections	 design heavy and light sections as single unit
LAYOUT DESIGN	 Ma̧intain uniform sections	 crowd openings into small! clusters
BLANKING DIE BALANCE	 Balance section by adding openings	 use unbalanced section
NOTCH EFFECT	 Space cutting edges for most uniform strength	 put 'stress raisers' in a common line

FIG 14

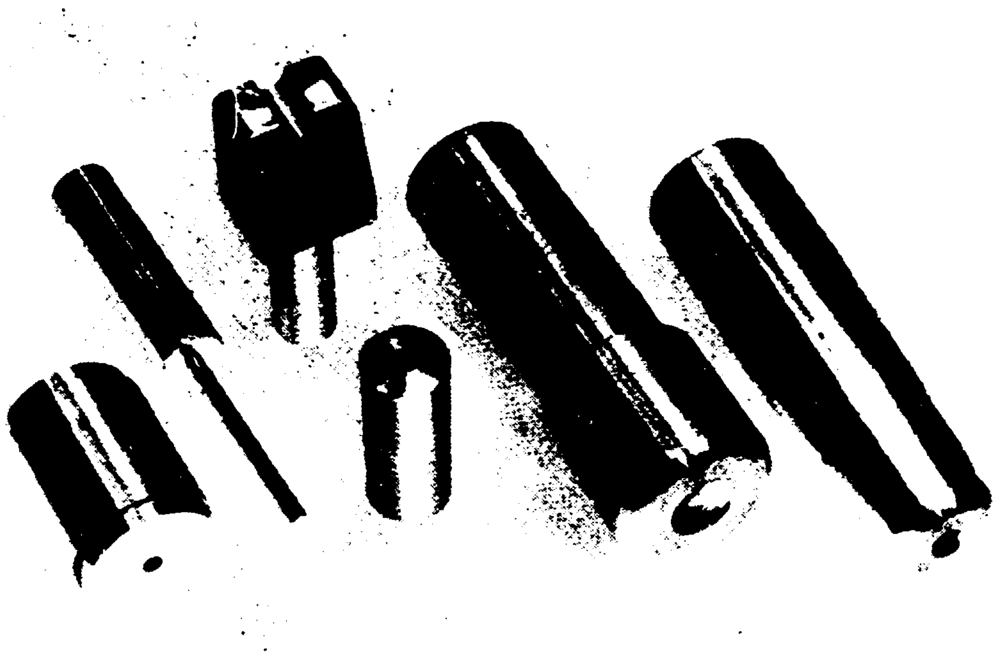
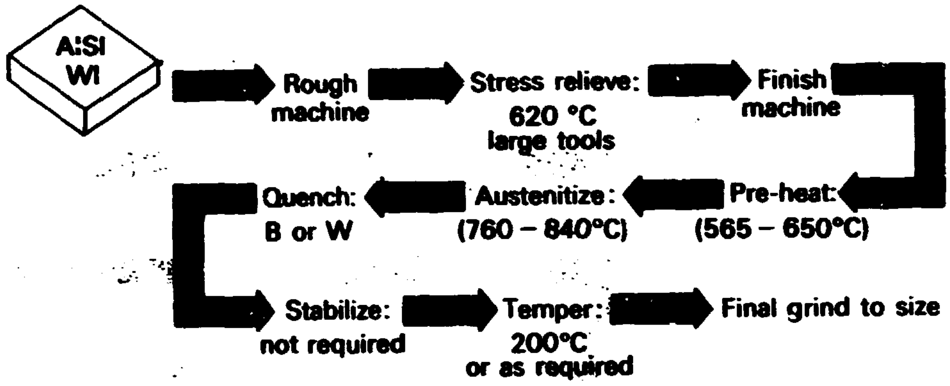
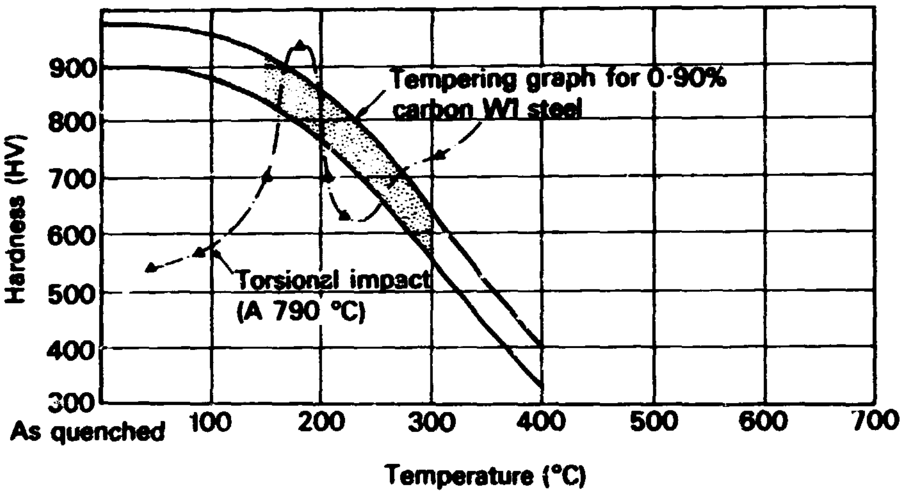


Figure 15 Punches made from steel W 1 (Bofors B 20 V)

Heat-treatment data.





Comments
Tempering graph shows approximate upper and lower limits of hardness to be expected after heat treatment. Snaded portion gives optimum tempering renge. Hardness may vary with bulk of tool, analysis, hardening time and temperature.

Source of data	
Tempering	British Steel Corp., Special Steels Divn., England
Torsional impact	Carpenter Steel Co., USA.
Isothermal diagram	Atlas Isothermal Diags., Iron and Steel Inst., England.

Isothermal diagram

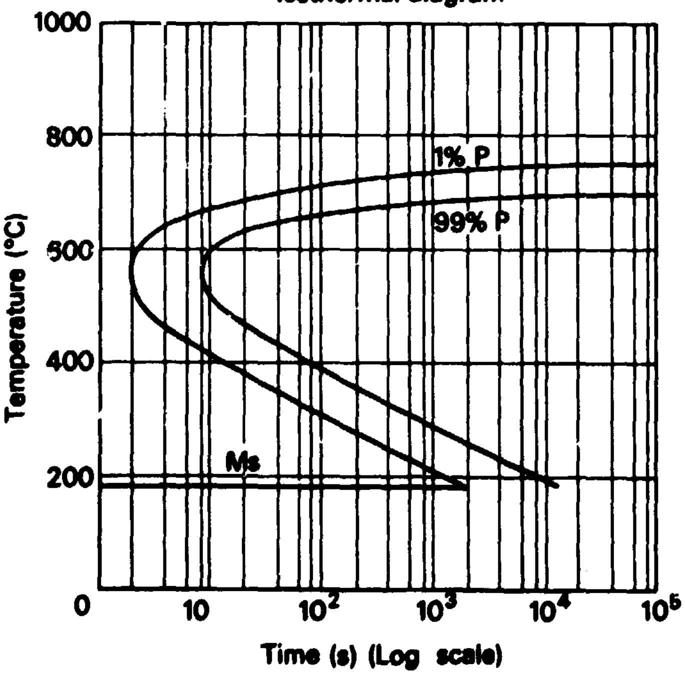
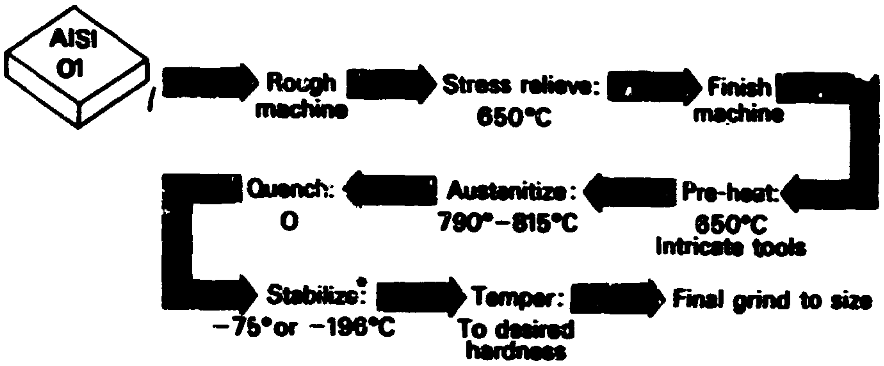
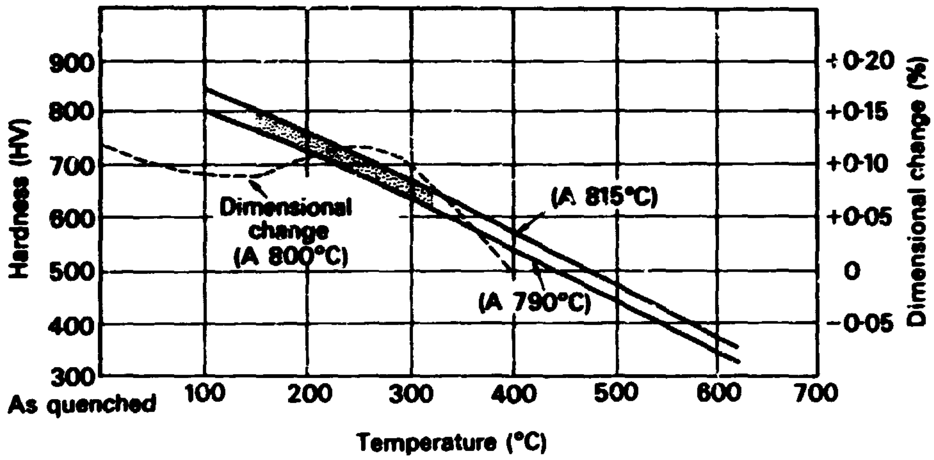


FIG 16

Heat-treatment data.





Comments
This steel is one of the most commonly used low alloy cold work tool steels. It is essentially a carbon–manganese steel with relatively high dimensional stability during heat treatment. Used for all types of small, precision tooling. As shown by isothermal diagram it is relatively shallow hardening. Tempering graph shows approximate upper and lower limits of hardness to be expected after tempering. Shaded portion gives optimum tempering range.
Source of data
Uddeholm Steels, Sweden

* Note stabilize
For maximum stability on gauges, etc., also recommend stress relief at 150°C prior to treatment.

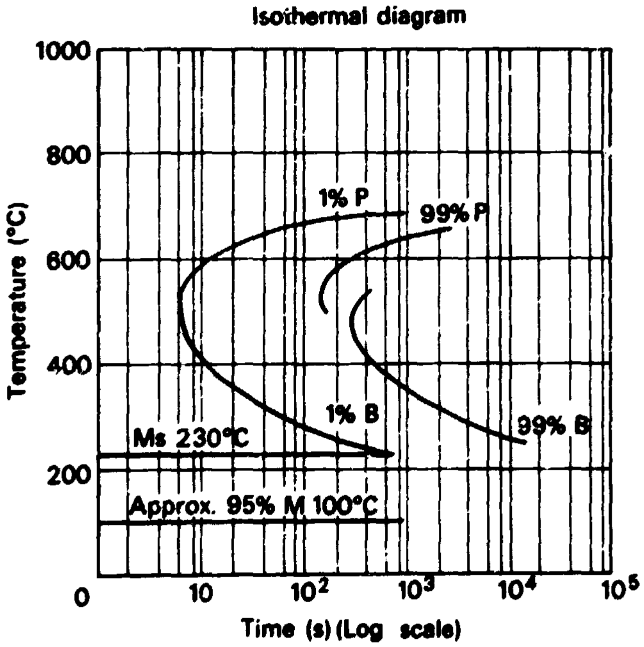


FIG 17

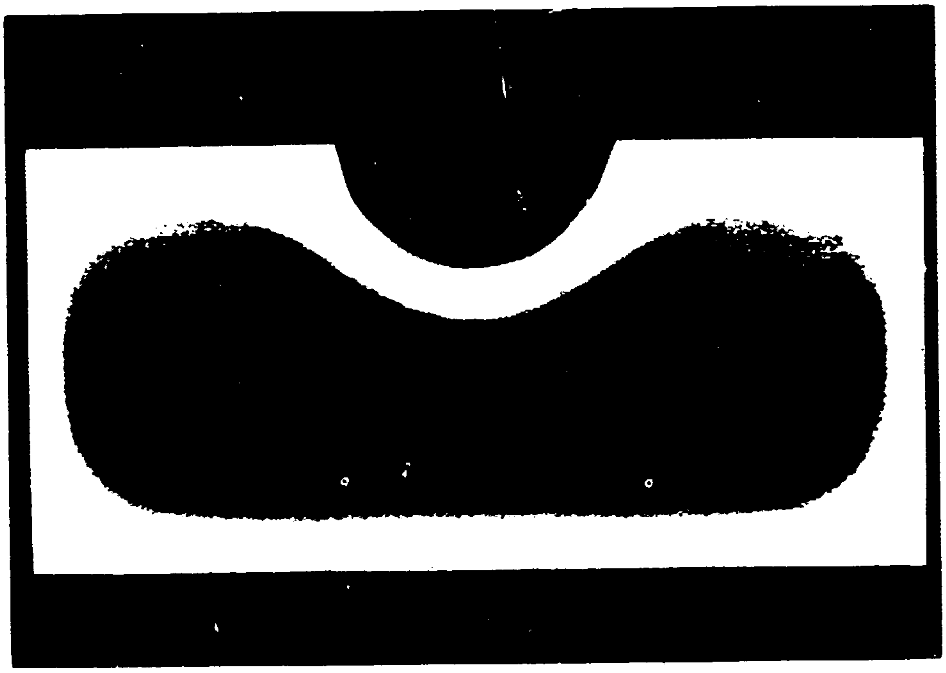


Figure 18 Transverse section through a Pilger roll made from SIS 2092 (Bofors SR 1855). Size 50 × 120 mm

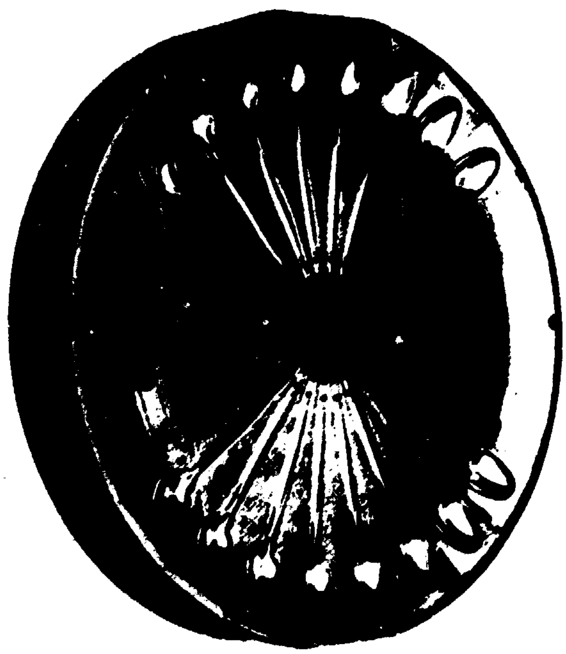
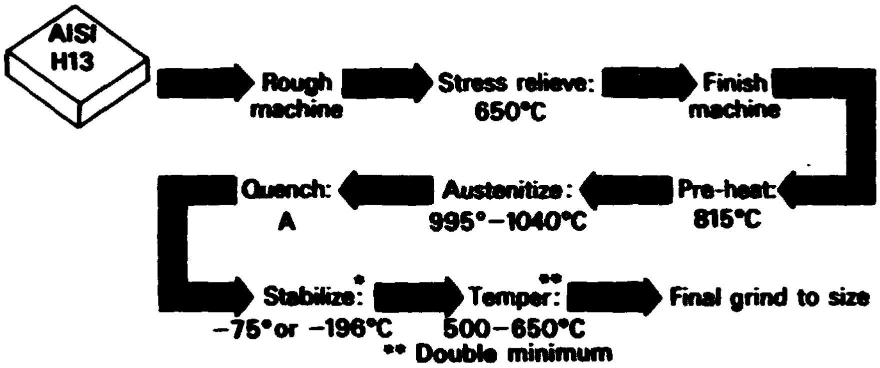
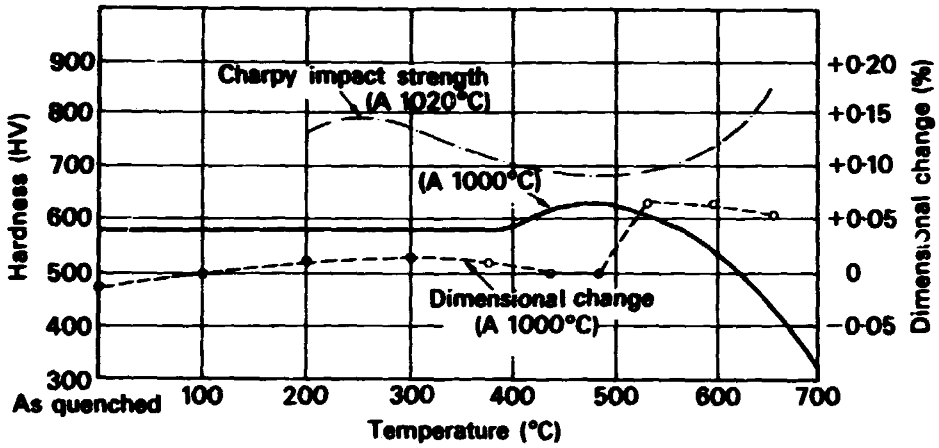


Fig. 19 Multi-cavity plastic mould tool in AISI A2 steel (Courtesy of Stora Steel Ltd, Sweden.)

Heat-treatment data.





Comments
Deep hardening—can be used for tools of all sizes including large blocks. It has excellent resistance to thermal shock and is considered the standard material for a wide range of hot working tools.

Source of data Tempering and isothermal	Jessop-Saville, England
Dimensional change	A.S.M. Tool Steels Roberts, Hamaker and Johnson
Impact strength (arbitrary figures only)	Uddeholm Steels, Sweden

*Note stabilize
Recommend stress relief at 150°C prior to treatment.

Isothermal diagram

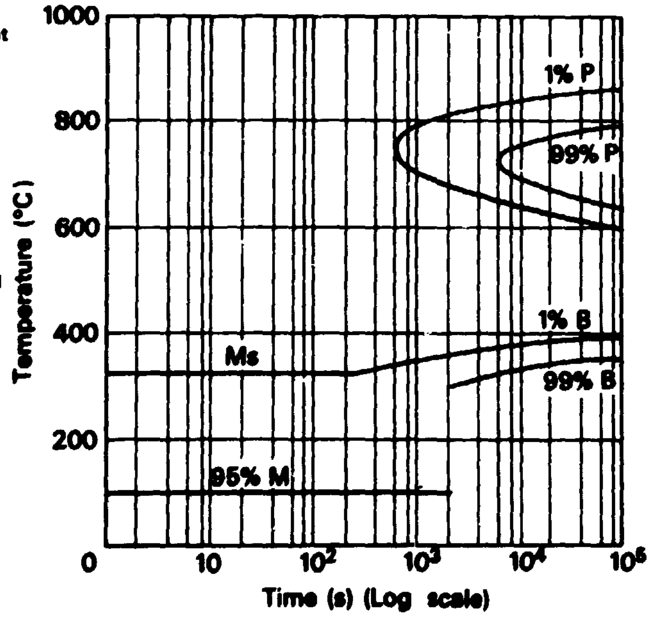
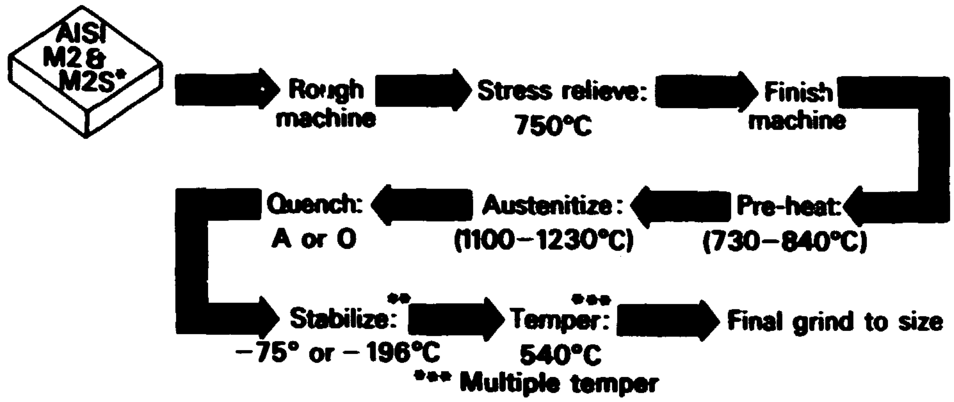
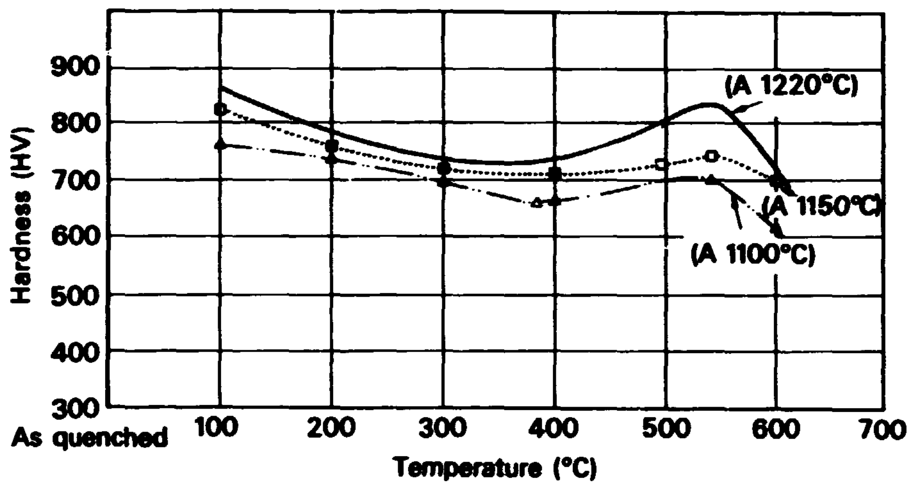


FIG 20

Heat-treatment data.





Comments
This is an 'all-round' grade of the most common type of tool steel. It has excellent toughness, red hardness and resistance to wear. It will be noted from tempering graph that the highest austenitizing temperature produces the maximum response to secondary hardening, this being due to maximum solution of alloy carbides.

Source of data
Stora Steels, Sweden

*Supplied re-sulphurized as a free machining grade (M2S).

** Note stabilize
Recommend stress relief at 150°C prior to treatment.

Isothermal diagram

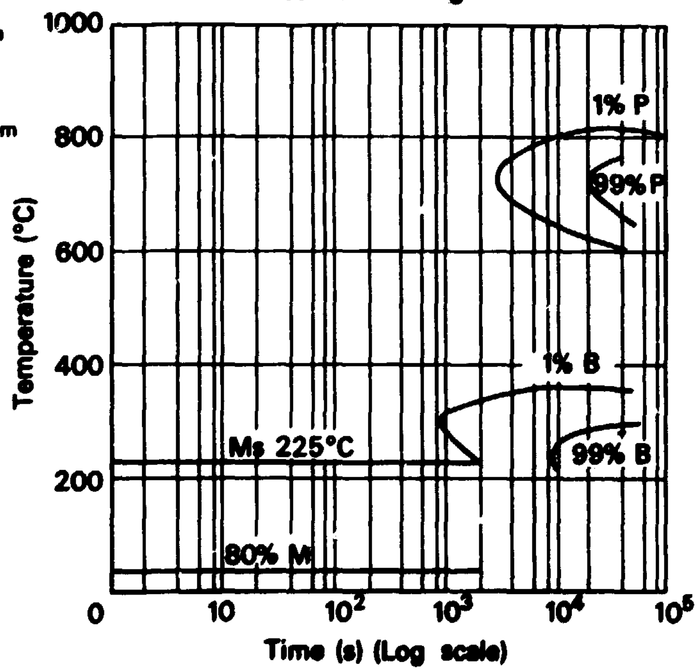


FIG 21

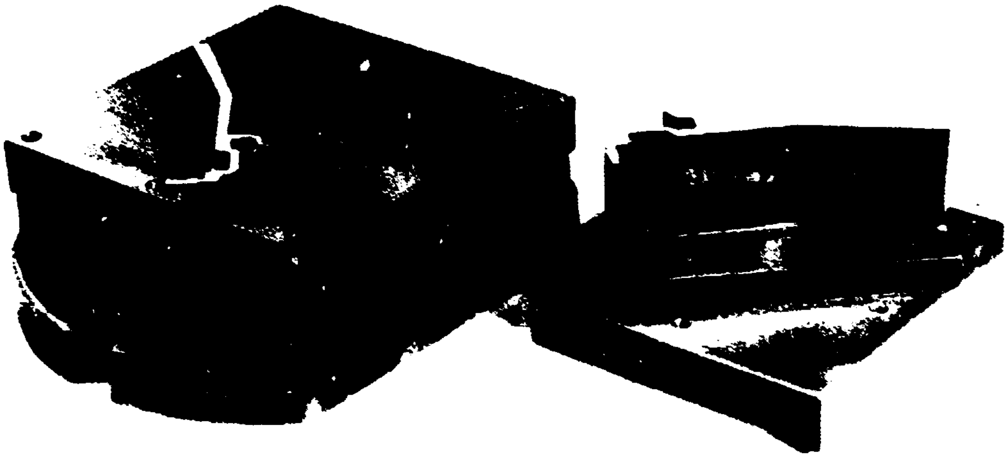


Fig 22
In this tool UHB Arne is used to blank out a part for a Swedish-made office machine. The deep punch enables up to 15 mm (19/32 in.) to be re-ground, ensuring an exceptionally long tool-life.

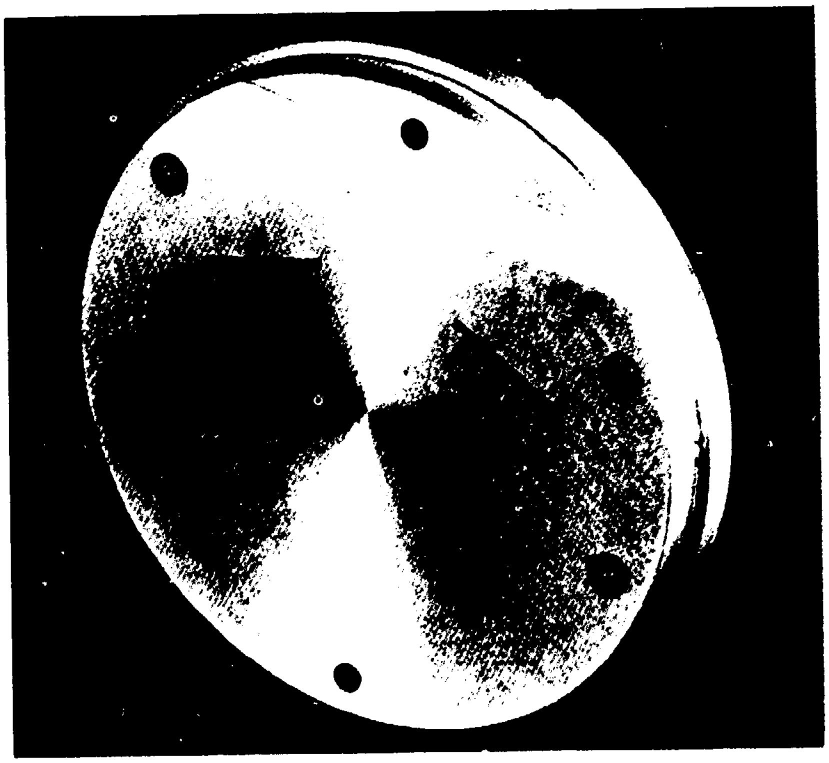


Fig 23 Extrusion die for aluminium profiles.

Tensile strength at elevated temperatures

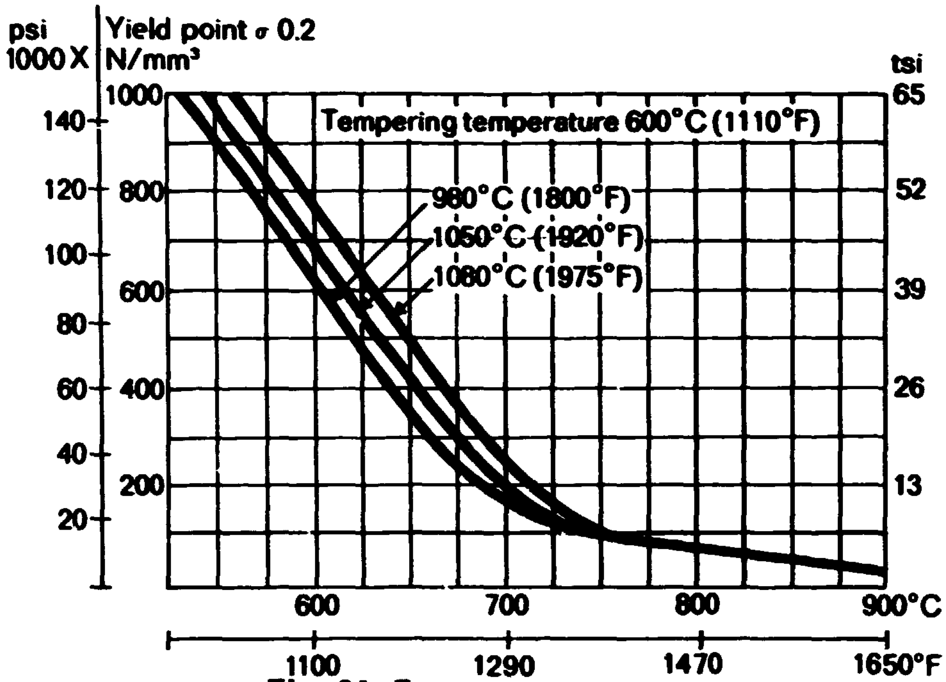


Fig 24 Testing temperature

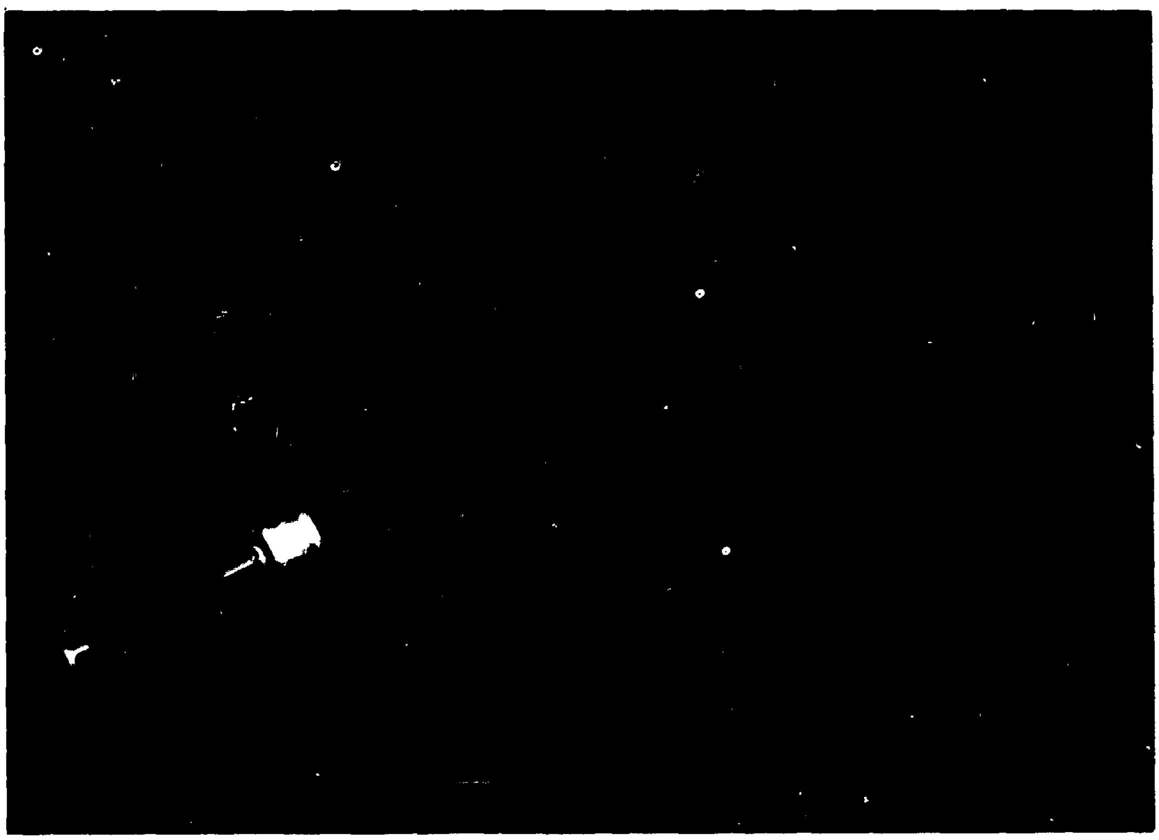


Fig 25

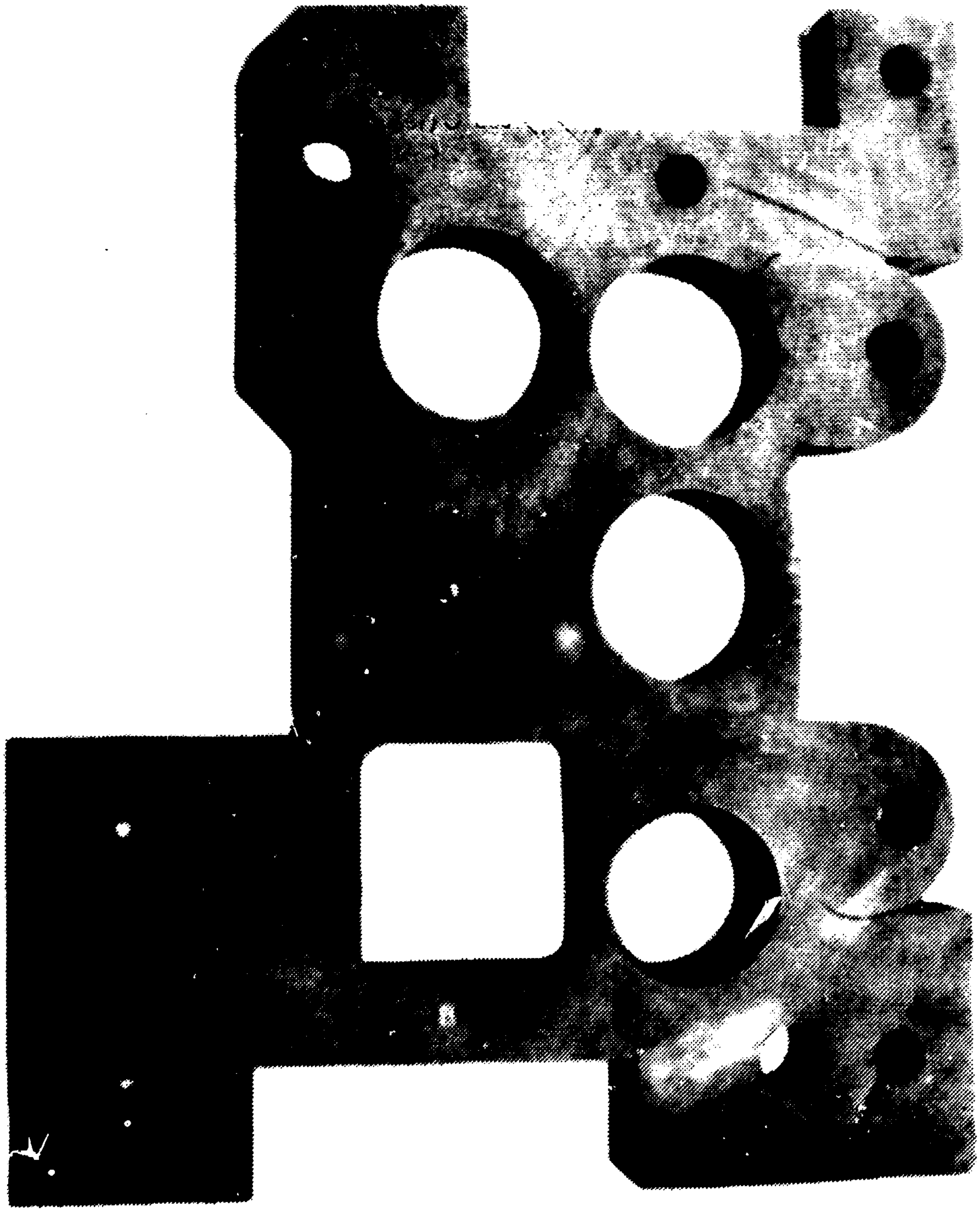


Fig.26 "Hardener's Nightmare" — design highly susceptible to distortion and cracking.

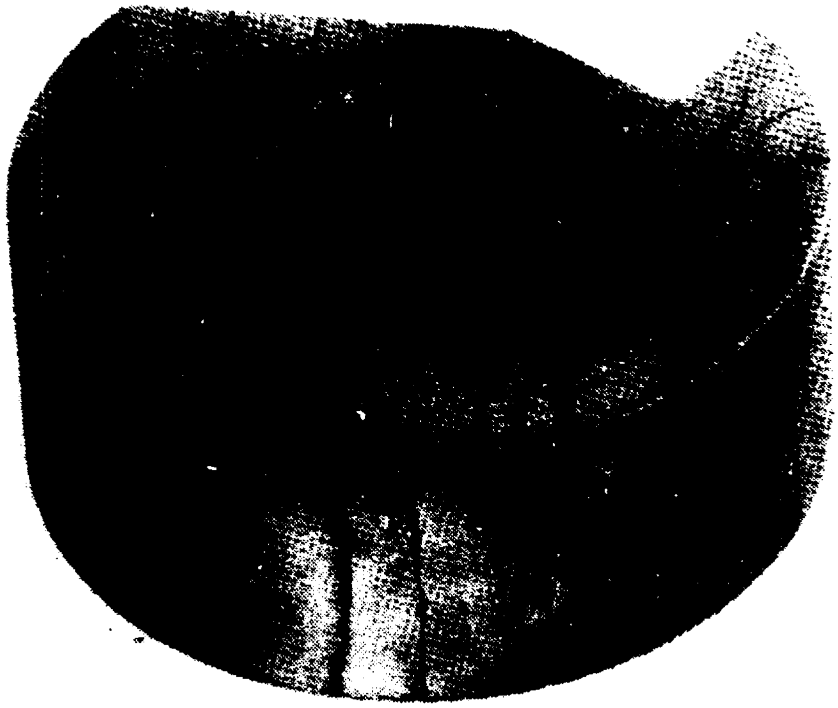


Fig.21a Decarburised high-speed steel tool after quenching, showing gross quench cracking[2]

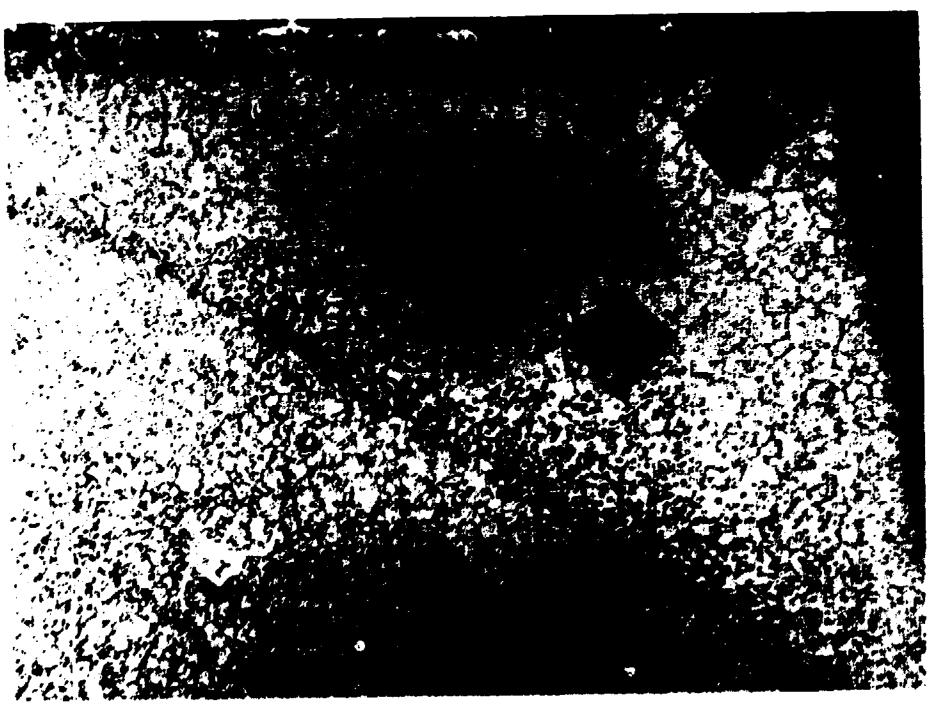


Fig.21b A decarburised tool after vacuum hardening, indicating the very marked structural change. X 160. Etchant: 4% Nital[3].

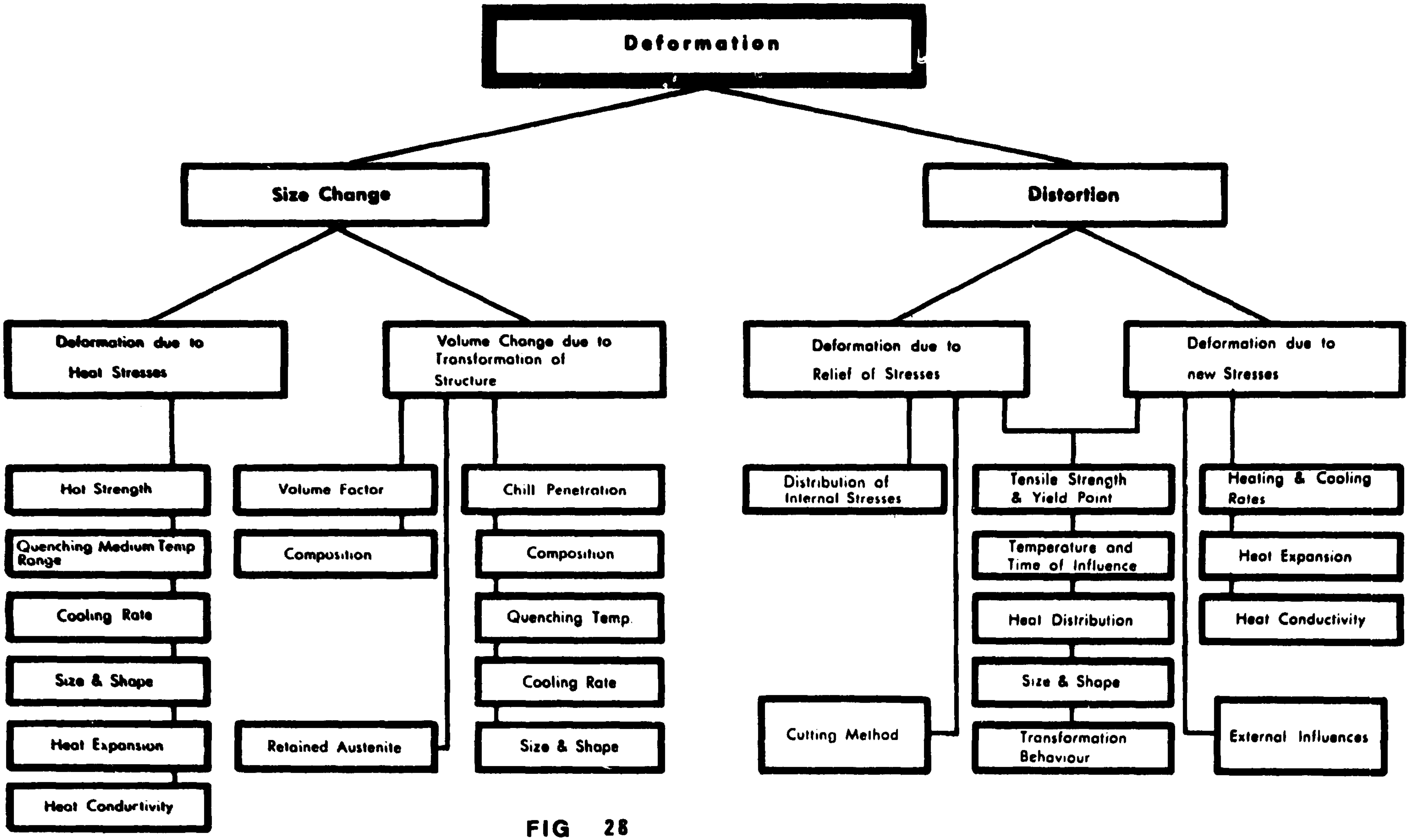

Deformation
Size Change
Distortion
Deformation due to Heat Stresses
Volume Change due to Transformation of Structure
Deformation due to Relief of Stresses
Deformation due to new Stresses
Hot Strength
Quenching Medium Temp Range
Cooling Rate
Size & Shape
Heat Expansion
Heat Conductivity
Volume Factor
Composition
Retained Austenite
Chill Penetration
Composition
Quenching Temp.
Cooling Rate
Size & Shape
Distribution of Internal Stresses
Cutting Method
Tensile Strength & Yield Point
Temperature and Time of Influence
Heat Distribution
Size & Shape
Transformation Behaviour
Heating & Cooling Rates
Heat Expansion
Heat Conductivity
External Influences

FIG 28

74

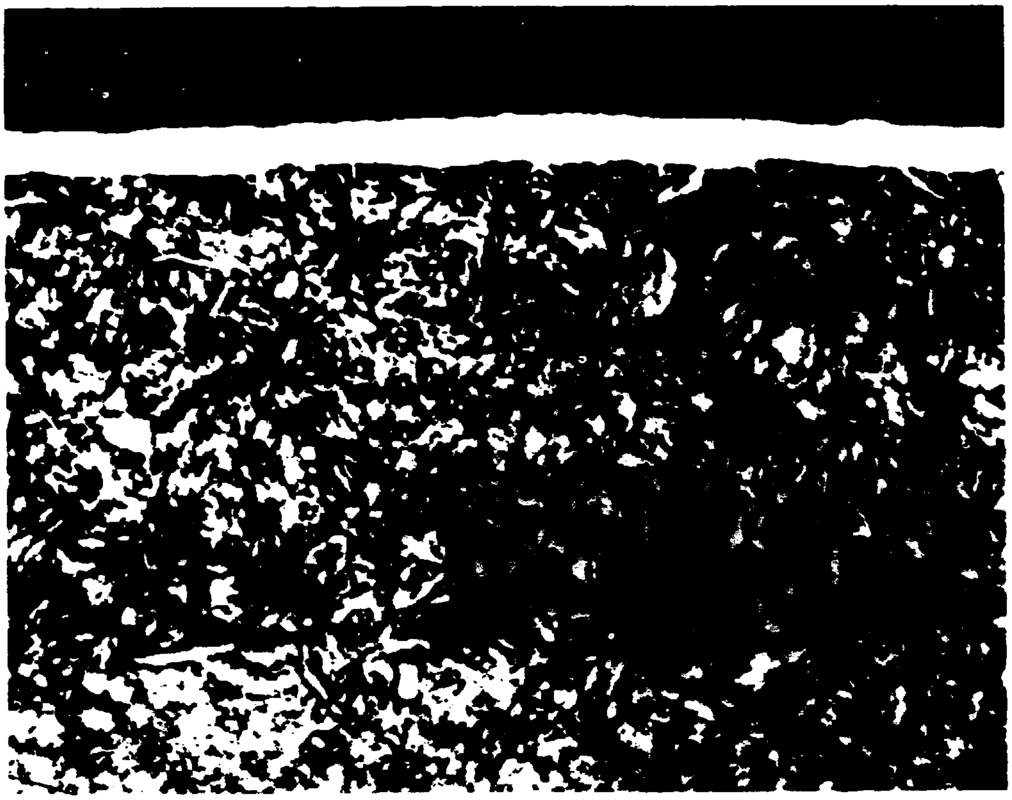


Fig 29

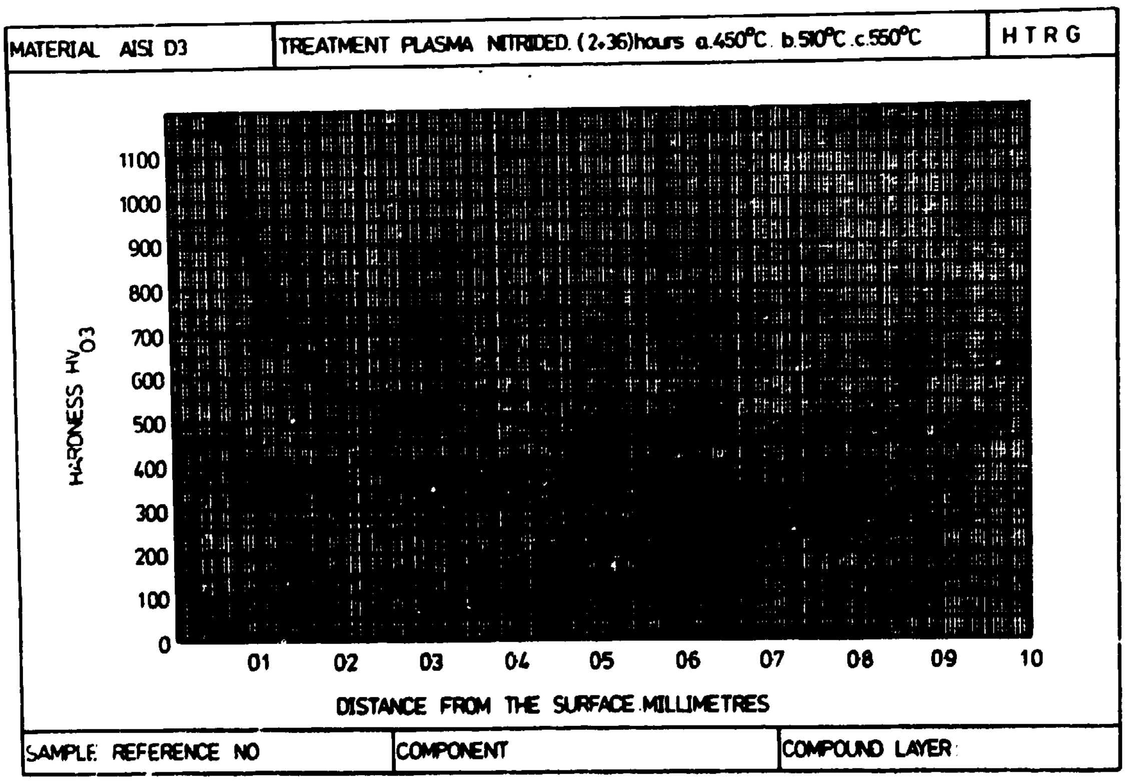

MATERIAL AISI D3
TREATMENT PLASMA NITRIDED. (2+36)hours a.450°C. b.510°C. c.550°C
H T R G
HARDNESS HV03
1100
1000
900
800
700
600
500
400
300
200
100
0
01
02
03
04
05
06
07
08
09
10
DISTANCE FROM THE SURFACE MILLIMETRES
SAMPLE REFERENCE NO
COMPONENT
COMPOUND LAYER:

Fig 30

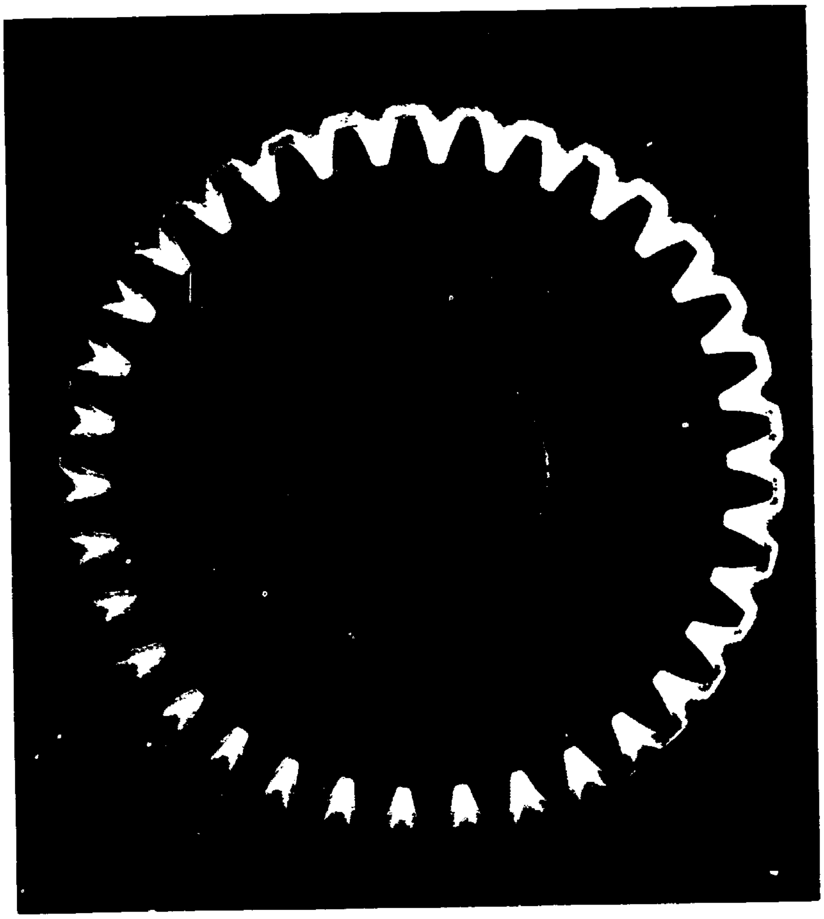


Fig 31

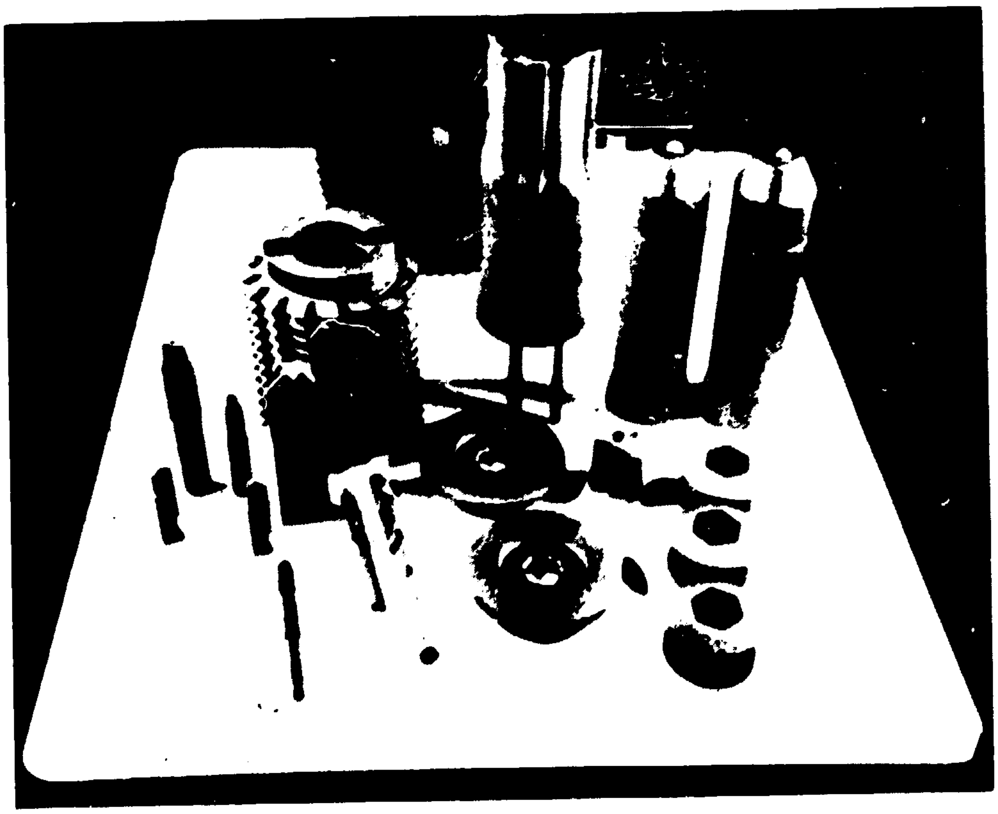


Fig 32