Scale on Wire Rod and its Removal by Mechanical Means

S Garber

G. M. Sturgeon

THE rod from which plain carbon steel wire is produced is normally supplied in the original rolled condition with its scale attached. As a preliminary to the successful drawing of the rod down to wire, it is essential to remove this scale. The traditional method of removal has been to pickle the rod coils by submerging them in solutions of dilute acid. In recent years one has seen developments introduced to achieve mechanical scale removal.

To replace acid cleaning as a means of scale removal by a mechanical method is not a new idea, and although recent developments have taken place in this field, there is still room for further improvements, especially in the removal of scale by deformation. Some of the earliest references in the U.S.A. to mechanical descaling date back to 1893, but the method was not developed to any extent until the 1914–1918 war when wire manufacturers became very interested due to the shortage of acid in many countries and the increase in production brought about by the war. In the period between the two world wars, very little progress was made and it was not until 1941 that Andre Line[1] working in conjunction with Societe Metallurgique De-Gorcy in France, introduced the De-Gorcy System. The introduction was received with considerable interest because again it was at a time when acid was in short supply and the industry was in full production. This initial development stimulated activity in many countries and further work followed in Germany, Italy and the U.S.A. Since the war developments have been made mainly in the U.S.A. and Germany and now in Britain using shot blasting as a means of wire cleaning. The interest since the war in this method and its increased use in many countries has, in some cases, been accelerated by the strict imposition of laws regarding industrial effluent discharges into public sewers and rivers, and the possible economic advantages[2,3,4].

As an example of the rapid growth of the use of mechanical descaling, one can quote the production figures cited by Eisenhuth[5] in connection with the wire industry of West Germany. Approximately 20,000–25,000 tons of wire per month are produced using the mechanical method of descaling. This is approximately 16–18% of the total produced in that country. In the same paper, Eisenhuth has also listed the difficulties that firms had with this process. Poor lubrication and excessive die wear plus unsatisfactory surface quality comprised the bulk of this list.

The chemical and mechanical properties of the scale have been the subject of some investigations and rod producers have been concerned over the conditions under which the scale is produced. In practice, efficient removal of the scale is not always achieved. This occurs both in the acid and the mechanical processes. Scales are encountered which require longer times in the bath for their complete removal and in the case of the mechanical method, the amount of residual scale left on the rod can vary from coil to coil or even along the length of the same coil. Even if there is no apparent change in the amount of residual scale, the life of the dies can fluctuate to a marked degree.

With a view to extending the use of mechanical descaling of wire rod, the existing mechanical methods of removal and the associated problems were reviewed. Special attention has been paid to some of the more obscure but promising techniques and the economics of the latest developments have been considered in relation to conventional cleaning and other mechanical methods of scale removal. The end product is the deciding factor for the choice of the most suitable cleaning method but it is shown that the mechanical cleaning can be considerably extended by employing the latest developments.

PART I

MECHANICAL REMOVAL OF SCALE

Methods of mechanical descaling

The two main methods of mechanical descaling are deformation of the rod by flexing, twisting or stretching and by direct treatment of the surface, of which shot blasting is the most common. The first of these two methods does not remove all the scale and it is necessary to supplement it with some further secondary treatment.

Scale removal by bulk deformation

Primary scale removal : The conventional method of coarse scale removal is to deform the wire by bending it over pulleys. The method favoured by

---

Dr. S. Garber, B. Eng. (Met.), Ph.D and Mr. G. M. Sturgeon, Grad. I, Mech. E. The British Iron and Steel Research Association, Sheffield, U. K.

many manufacturers in Britain is to bend the rod round to pulleys in planes at right angles to one another, as in the descaling machines shown in Figs. 1 and 2. Eisenhuth[6] and others[7] have studied the problem of scale removal with various degrees of cold work and have carried out tensile tests to determine the optimum condition. The scale on rod starts to crack with an elongation from 3 to 5% ; with 8 to 9% the majority has fallen off, but not until 12% elongation has been reached are the rods free of scale without brushing. The required pulley diameter can easily be calculated and Eisenhuth quotes the formula :

$$\text{Max. Elongation\%} = \frac{(x+2d)-(x+d)}{x+d} \times 100$$

where x=diameter of roll
d=wire diameter

This can, of course, be simplified to :

$$\text{Max. elongation\%} = \frac{rw}{R_{\text{p}}+r_{\text{w}}} \times 100$$

where r_{w}=wire radius
R_{p}=pulley radius

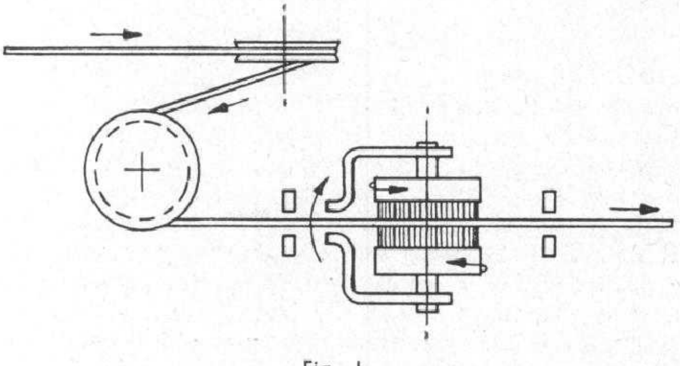


Fig. 1.
De Gorcy descaling system.

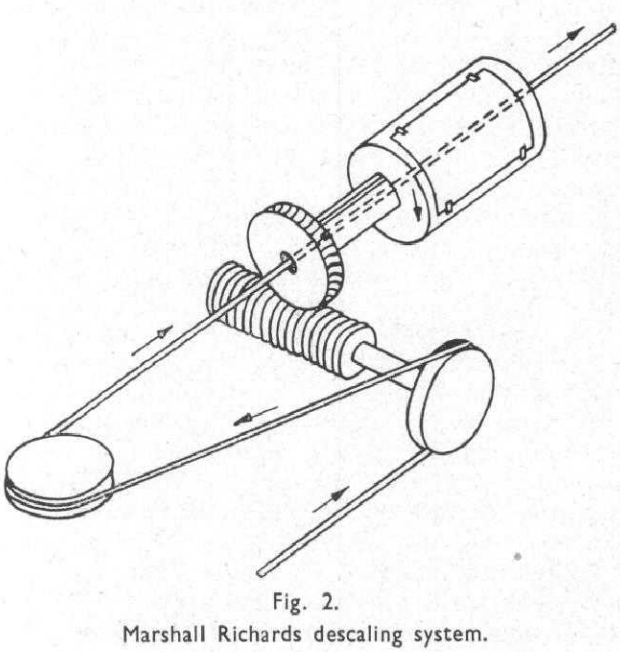


Fig. 2.
Marshall Richards descaling system.

In practice, however, it has not been found possible to strain the material to the optimum value of 12% by bending over to pulleys as a 5 SWG rod would have to pass over pulleys of approximate 1½" diameter. This would cause frequent weld breakages and would damage the structure of the material, thus affecting the drawability of the wire. A compromise has been reached whereby the material is strained to a maximum of 8%.

The above-mentioned system of pulleys becomes difficult to work with when a heavy gauge rod is being descaled and in fact, the use of this system is limited by the ability of the operator to thread up the machine. Several descaling manufacturers have adopted a system of rollers, whereby the rod is laid in between rolls and the rolls are adjusted mechanically to obtain the required deformation. Various authors[8,9] have reported their findings on this system and a method[10] for calculating the optimum deformation is as follows :

$$\mu = \frac{\sphericalangle\, d\, \pi}{1{\cdot}8\, R}\ \%$$

where

$\sphericalangle$ = angle of contact with each roller expressed in degrees.
d = thickness of wire in mm.
R = radius of curvature in mm.
μ = the difference between the outer and inner peripheral lines of the wire expressed as a percentage of the bending radius.

The maximum value of μ recommended is 45% but it would be very difficult to calculate this value under industrial conditions.

A method that has been patented in Germany[11] may prove superior to either of the above-mentioned systems, but it has not, as yet, been widely adopted. This method consists of bending a wire round a pulley mounted in a frame, which rotates about the axis of the wire, as shown in Fig. 3. By this means, the wire is subjected to bending and torsion, but by the construction of the apparatus, the wire is twisted the same amount in opposite directions as it enters and leaves the pulley so that the material is not twisted as it enters the die. This technique of stressing the material appears promising from the viewpoint of loosening the scale and should be given further attention. The bending stresses should break off scale in crevices and pin holes and other surface irregularities, because the majority of the defects which assist in keying the scale to the parent metal are imparted to the rod by the roll surface so that they are longitudinal in direction and will open up in torsion.

A further method[12] developed in Germany is to deform the coils elliptically either in the rod or wire mill during transport. The coils enter a tapered, motor-driven channel and as they rotate and travel along, they are deformed elliptically and by adjusting the degree of taper of the channel, the amount of flexing of the coil can be varied

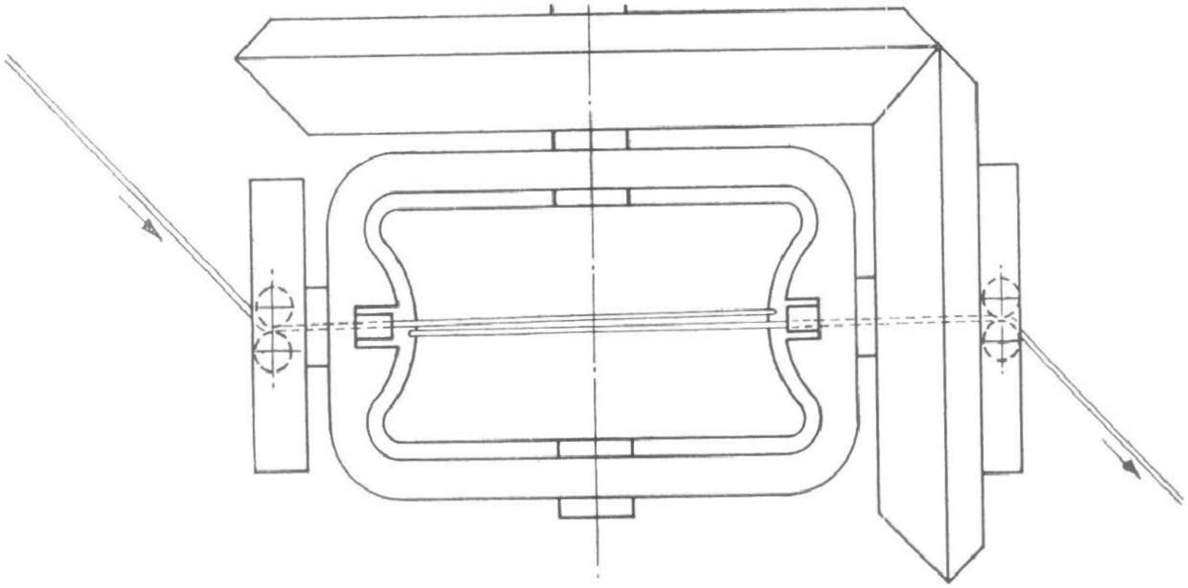


Fig. 3.
Method of descaling by torsion and bending.

and thus the bending stresses in the rod can be increased to the desired value.

Secondary scale removal: There are many methods, used by various manufacturers to remove the scale dust and adherent layers of scale remaining on the rod after descaling with pulley systems. The Line-Gorcy machine employs rotary brushes which also rotate about the axis of the wire. It has been shown by Sanderson[3] and Marsden[13] that a brush life of 200 tons of cleaned rod can be obtained but the speed of the rod through the descaler is critical and at speeds over 200–300 f.p.m. the brush wear increases rapidly. The most suitable wire for brushes appears to be hard drawn Swedish steel, 33–39 SWG[14]. A further critical factor in brush design, however, is the clearance between opposing brushes and between each brush and rod; from experiments carried out in Germany, an interference of 0·020″ between rod and brush is recommended. There are also many types of brushes such as motor-driven brushes where a number of small tassels are attached by chain to a pulley on the motor shaft and the brushing action is assisted by centrifugal force. Another ingenious brushing device[15] allows air from a turbine which drives the brushes to pass out through the bristles and so keep them free from scale, and to assist in blowing away the fine dust on the rod. A practical difficulty with any brushing system is to brush hard enough to remove the scale, yet not hard enough to produce a brushing effect, which would affect lubrication in drawing.

Tumbling articles on their own or with abrasive material is an old established cleaning method, which has been adopted for the descaling of wire. Limestone, granite and quartz chippings have been used in rotating barrels immediately after passing the rod over scale breaking pulleys. One of the main drawbacks is that the rod tends to carry the chippings to the exit end of the barrel and this can cause the rod to seize in the outlet guide causing breakage, or if seizure does not occur, chippings frequently mark the rod which can cause breakages during drawing. By the careful use of correctly designed baffle plates it is possible to overcome this trouble and in fact this system is used on the Marshall Richards descaling machine shown in Fig. 2.

Many types of stationary and vibrated boxes are employed in this cleaning stage containing such materials as steel grit, shot, steel wool, wood wool and waste. These boxes, however, are very prone to channelling and may soon become contaminated with scale and the parts in contact with the rod worn smooth. A German machine[8] employs a vertical container for this cleaning which is filled with steel grit or other similar material and relies on gravity to keep the particles in contact with the rod. The dust is allowed to fall out of the container through a grill at the bottom. This method would appear to be superior to other types of cleaning boxes and has one advantage in that it can be tilted into the horizontal position and opened up longitudinally for threading up. Various electromagnetic devices have also been patented for the removal of scale, but, of course, this will not attract any particles of scale which are non-magnetic. However, if the non-magnetic oxide is mixed with iron particles or other magnetic oxides it may be removed by attraction, but on the other hand, vibrations of the wire longitudinally or magnetostriction effects will shake scale off the wire whether it is magnetic or not.

A general description of several of the more common descaling machines[16] commercially available is given in Appendix I.

Scale removal by shot blasting: Due to the inefficient operation of the secondary cleaning process, many types of wires cannot be drawn from a descaled rod, especially those wire which are sold on appearance since a mechanically descaled wire generally has a darker colour than chemically cleaned material. In the U.S.A. and Germany, the technique of removing scale from rods by shot blasting has been developed and several installations described by Sorace[17] and Dill[18] are now is production. The development of this type of plant has been reported[17,18,19,20,21]and it appears that in the early stages cast iron shot was used which shattered in the wheelabrator plant causing a high shot consumption per hour. Also, Doty[22] found that if the scale or a mixture of shot and scale was used as the abrasive in the shot blasting unit, sharp notches were formed and small fragments of scale were embodied in the surface of the rod. Further developments in machine design and the use of heat treatment steel shot together with methods of scale separation have improved the process considerably.

At the moment, however, it would be difficult to install this type of plant in existing works as it would be impossible to find the necessary floor space in the average wire mill. Further developments of this type of shot blasting or air or liquid borne types may enable costs and space requirements to be reduced. The surface finish obtained by this process is superior to that of rod descaled by flexing, and the Americans claim that it is at least as good as a pickled surface.

Problems associated with mechanical descaling

A major factor affecting the performance of any descaling machine is the type and formation of the scale on the rod. This factor is dealt with fully in Part II of this paper but Fig. 12 illustrates the intrusion of magnetite towards the parent metal. The hardness of this constituent is approximately 420–500 D.P.H. as against 270–350 D.P.H. for wustite. It can well be imagined that after descaling, a certain percentage of the harder oxide will be in the residual scale and also keyed into surface defects, and this could cause excessive die wear and accelerate grooving of the capstan. This factor could explain the anomaly reported by Eisenhuth[5] who found that the greatest die wear was not necessarily caused by the mechanically descaled rods having the largest amounts of residual scale.

Effect of surface finish of rods: The surface finish of the rod must play an important role in mechanical descaling as it will affect the keying of the scale to the parent metal. Three samples of industrial rod are shown in Fig. 16 after they have been mechanically descaled in tension and finally cathodically descaled. Even at a low magnification of ×6 it is apparent that the rod shown in Fig. 16c will tend to retain residual scale more easily than either of the other two samples.

Unfortunately, both the above-mentioned factors are generally outside the control of the wire manufacturer and until such time as rod rollers can consistently produce rod with a smooth surface, he can only rely on the development of descaling machines to cope with these conditions.

Heat treatment scale: It is now common practice to use protective atmospheres in annealing furnaces and this is being extended to include patenting furnaces. Generally, heat treatment scale is very thin and is formed at relatively low temperatures and this type of scale is known to be very difficult to remove by flexing mechanically. Air patented rods have been mechanically descaled, however, and it was noticed that the higher the heat treatment temperature, the easier was the descaling. Very often rods and wires in patenting furnaces are tied together and even those that are welded are very often not suitable for mechanical descaling in line with the heat treatment furnace because the power required for mechanical descaling is usually not available on patenting rigs. However, the patented material is frequently passed over a series of large pulleys on the winding frame, thus cracking the scale and so assisting the acid cleaning process. On the other hand, shot blasting cleaning methods appear to be very suitable for this type of application and in fact a plant is now operating in the U.S.A.[17, 18, 19, 20].

Storage of rod: Many workers have reported that it is advisable to bake the rods or store them in the wire mill to allow them to dry out and reach the ambient temperature prior to descaling. This will also assist in flipping, although Marsden[13] has designed an overhead take-off type swift because of the tendency for laps to stick together. Rods should not be weathered as was customary in certain mills when acid cleaning, as it is very difficult to remove traces of rust in this process. The advantages and disadvantages have been fully reported in the proceedings of a symposium[2] in the U.S.A.

Drawing lubrication: Conventional lubricants appear to be unsuitable for the drawing of wire from mechanically descaled rod. Hard metal and lime base soaps are slightly better, but means have to be devised to assist the carriage of soap to the die if good die life is to be obtained. Serrated or plain-rollers[3] in contact with the wire in the soap box have been used to try and improve lubrication by compacting the soap into the wire. Marsden[13] has used extremely long first hole soap boxes, with devices which afford a rotary displacement to the rod in the soap box and so minimise channelling. The BISRA nozzle[23] has proved to be very effective on industrial trials drawing mechanically descaled rod and with one of these units in the first hole only, die life on the whole machine has been increased by a factor of 6. The nozzle, Fig. 4, is simple to operate and full details for construction and operation have been reported[24]. The particle size of the soap also has an important effect on lubrication. With a hard soap with lime filler added during manufacture, improvements in lubrication have been noted when only soap particles of 10/40 mesh were used. Whatever type of soap is used in drawing, care must be taken to ensure that the contamination of the soap in the first box is reduced to a minimum and it may even prove to be advantageous to change the soap from time to time. Under industrial conditions, it has been observed that 2·0 to 4% contamination of the soap in the first box can occur after drawing only a few tons of rod.

With conventional dies, it is recommended[5] that the first hole drafting should be reduced to a maximum of approximately 27% although this has not been found necessary with BISRA nozzles. The optimum die angle of 14° suggested by Eisenhuth for mechanically descaled wire agrees very well with the optimum die angle suggested by Wistreich[25] for cleaned and limed material.

In general, the other dies should have included entrance angles of 14° or smaller so that any soap coating obtained on the first die is preserved as much as possible in subsequent passes.

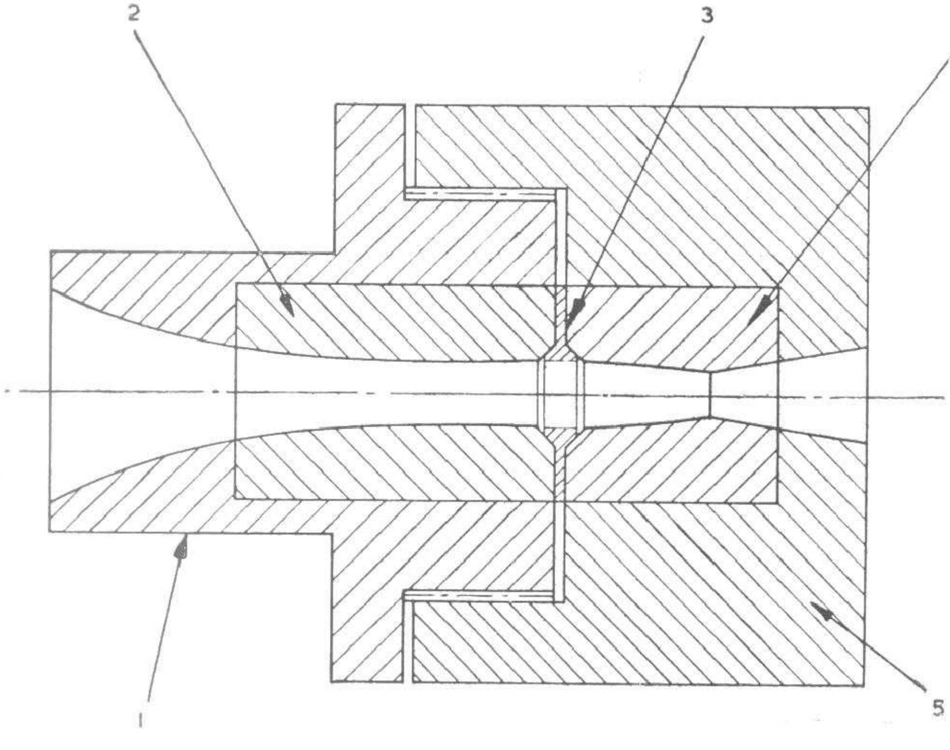
Drawing speeds: Sanderson and Marsden, quoted above, have used descaling speeds of 200–300 f.p.m., and in the German works trials reported by Eisenhuth, the descaling speeds were from 185–300 f.p.m. As the descaling machines become more efficient it is not difficult to envisage increased speeds becoming common practice. In fact, descaled material may even be handled in the same manner as conventionally cleaned material is today.

Wire properties

Sanderson[3] and others have reported differences in the mechanical properties of wire from rod cleaned by mechanical descaling and wire from rod cleaned by acid. The following results were obtained on a 0·3% carbon steel and it will be seen that after five passes, the differences in U.T.S. between the two methods of cleaning disappeared.

Pass No.	1	2	3	4	5
R of A % ...	35·7	60	73·8	80	85
U.T.S. tons/sq.in. acid cleaned ...	48	59	64	70	82
U.T.S. tons/sq.in. mechanically ...	58	64	68	72	82

The effects on lower carbon steels and mild steels are less noticeable and generally speaking disappear after the second or third pass with mild steel. Higher carbon steels are more complicated and allowances have to be made in drafting schedules for the amount of cold work imparted to the rod by the descaling rolls. In the U.S.A., however, with the new type of shot blast cleaning[18] it may be



1. Pressure nozzle.
2. Tungsten carbide insert.
3. Pressure sealing washer.
4. Tungsten carbide die.
5. Die case.

Fig. 4.

General arrangement of the BISRA nozzile-die unit.

possible to produce nearly all types of wire and bar with this plant without materially affecting their properties. The only foreseeable difficulty with this process will be the handling of shaped material but no doubt means will be found to overcome this difficulty.

Economic considerations

Mechanical descaling is to a certain extent being forced on to the industry by the tightening of local authorities' regulations concerning effluent discharge. In some areas the use of pickling necessitates the provision of expensive plant for neutralisation of waste acid, but even neglecting these considerations, mechanical descaling may still compare favourably in cost with pickling.

In general, the running costs of descaling machines are very low compared with conventional cleaning. The power-driven machines have a very low power consumption when compared with the actual drawing machine, and the extra load on the drawing machines caused by the De-Gorcy or Marshall Richards type descalers is also low. Sanderson[3] has estimated that the initial outlay in purchasing and erecting a De-Gorcy type machine can be recovered after it has produced aproximately 200 tons. In other words, taking a machine output of 20 tons per week, the above mentioned costs are recovered in less than three months. Maintenance costs may be high compared with the initial costs of the machine but are very small when the overall saving in production costs is considered.

For shot-blast cleaning, Dill[18] has quoted operating costs on a plant in the U.S.A. and taking 7 s. 0d. as the equivalent price of a $ 1·00 the following figures have been obtained. For single strand cleaning of a ⅝" dia. rod at 200 f.p.m. using a 3-wheel installation, with shot size 0·007—0·11" dia., and an initial shot velocity of 14,000 f.p.m., the cost per ton at a plant efficiency of 100%=3 s. 4 d.

	s.	d.
Abrasive consumption per blasting hour ...	10	6
Spare parts for m/c., etc. ...	4	2½
Power ...	4	2½
Running cost per hour ...	18	11

This compared with the acid cleaning costs of 7s. 8½ d. per ton made up as follows:

Direct labour per ton ...	2	11
Acid per ton ...	4	6½
Lime per ton ...	0	3
	7	8½

The price of mechanical descaling is thus considerably less for this size of rod. On smaller rods, however, even if the rod is passed through the blasting unit twice, thus enabling the speed to be doubled, the price per ton increases to 4 s. 8 d. for a ⅜" dia. rod at 400 f.p.m. but it is still less than the cost of pickling. Although no figures are quoted for cleaning 5 SWG rod in the paper by Dill, they can be estimated from the cost of running the plant per hour. On this basis the cost of cleaning 5 SWG rod would be:

400 f.p.m. (passed through unit twice) @ 100% machine efficiency	14 s. 8 d. per ton.
600 f.p.m. (passed through unit 3 times) @ 100% machine efficiency	9 s. 8 d. per ton.
800 f.p.m. (passed through unit 4 times) @ 100% machine efficiency	7 s. 3 d. per ton.

One of these plants has also been used successfully in conjunction with an 18-strand patenting furnace, in which all the rods pass through one unit. The cost of cleaning this material has been quoted at 8 s. 11 d. per ton at speeds in the order of 30-60 f.p.m. It is rather unfair to compare these costs with normal cleaning as, generally speaking, in-line cleaning is more expensive than the batch process. Nevertheless, further information is required on operation costs to obtain a valid assesment.

Applications

It is necessary to consider the end use of the product before deciding on the use of mechanical descaling because the wire produced from a rod descaled by deformation is generally darker in colour than that from a pickled rod.

The majority of manufacturers, except those employing shot blasting, use descaling for common drawing work for such products as black annealed wire. Where the surface finish is important and the general appearance of the wire is used for sales purposes, chemical cleaning is still employed. Several nail manufacturers are producing nails satisfactorily from descaled wire with excellent results, as they claim that the extra care with lubrication in drawing helps to lubricate the nail making machines, but others have encountered severe die wear on the nail making machines and have had to revert to acid cleaning.

Several authors have reported that descaled wire is suitable for galvanising, but many other workers have found that although the rougher surface of descaled wire does help in bonding the coat to the base metal, elongated strings of "drawn in" scale cause trouble. The zinc will not wet the surface where these occur so that marks are visible on the surface of the finished wire, and therefore the mechanical descaling process, unless it is carried out very efficiently, is not recommended for galvanised wire.

The wire from a shot-blasted rod should have a better surface than that from a rod descaled by deformation, and, as stated above, the Americans claim that it is at least as good as that from a pickled rod.

PART II
THE STUDY OF SCALE ON WIRE ROD

Griffiths[26,27] investigated some of the conditions whereby adherent and non-adherent scales were produced. He showed that the character of the scale is determined by the geometry of specimens, the atmosphere and heating conditions under which it is produced and the composition of the parent metal. However, the thickness of the scales studied were much greater than those normally found on wire rod. His work was more applicable to the scale problems in the heat treatment of steel castings.

There is some evidence that the type of rod scale which may be adequate for one method of descaling may not necessarily be satisfactory for the other.

Stebbins[28] showed that a low coiling temperature of the rod was advantageous from the viewpoint of reducing the metal losses due to scaling and the cleaning time in pickling.

Knapp[29] found that rod cooled from 1,010°C at a cooling rate of 35·5°C/minute or faster produced a scale that was easily pickled off; brought the metal loss close to a minimum and produced a smooth surface on the rod. A cooling rate slower than 35·5°C/minute sharply increased the metal loss, increased the pickling time two or four times and produced a pitted surface.

The initial conclusion to be drawn from the work of Knapp and Stebbins is that the most advantageous scale for pickling is a thin one produced by a fast cooling or a low coiling temperature. However, this simple specification is incomplete. Knapp also pointed out that a rod finished at too low a temperature and obviously having a thin scale gives a scale that is difficult to remove in acid.

Although the above evidence suggests that a thin scale (with some exceptions) is favourable for the acid process, Eisenhuth[5] on the other hand has shown that of four rods with different scales, the most efficient removal of scale by mechanical means was obtained with a thick continuous scale. Although this rod had the lowest amount (by weight) of residual oxide after descaling, its performance was not the best in the drawing operation, as the die wear was the greatest.

Opinions expressed in America[2] indicated that a rod rolled with a high finishing temperature and a thick scale is the most appropriate for mechanical descaling.

In the work on the descaling of flat-rolled material by flame cleaning, Wiegand et al[3] found that the amount of scale removed was proportional to its thickness.

The Max-Planck Institute have also found that the mechanical bonding of the scale to hot rolled sheet decreases with increased scale thickness[31].

The formation of scale

In order to have a more adequate understanding of the numerous factors determining the properties of the scale on wire rod, it is appropriate to consider briefly some facts associated with the oxydation of iron.

Pfeil[32,33] found that the general structure of the iron scale produced at high temperatures was a layered one. Starting at the metal surface and moving outwards through the scale, the concentration of iron decreased and that of the oxygen increased. The innermost layer consisted of ferrous oxide, FeO* (wustite); the second one ferroso-ferric oxide Fe_3O_4 (magnetite) and the thin outermost layer of ferric oxide Fe_2O_3 (hematite).

A subsequent study of the kinetics of oxidation showed, however, that the relative proportions of the three oxides in a continuous layer of scale was dependent on the temperature of oxidation[34], Fig. 5. When formed under equilibrium conditions at temperatures between 700–900°C the scale was two-layered, with a large inner layer of FeO comprising approximately 90% of the scale and a thin outer layer of Fe_3O_4. Above 900°C the proportions of the oxides Fe_2O_3 and Fe_3O_4 develop rather rapidly at the expense of the FeO. When formed below 700°C, the scale was again two layers and the ratio of Fe_3O_4 to FeO increased, as the temperature decreased. At 570°C and below, the only oxide formed is Fe_3O_4.

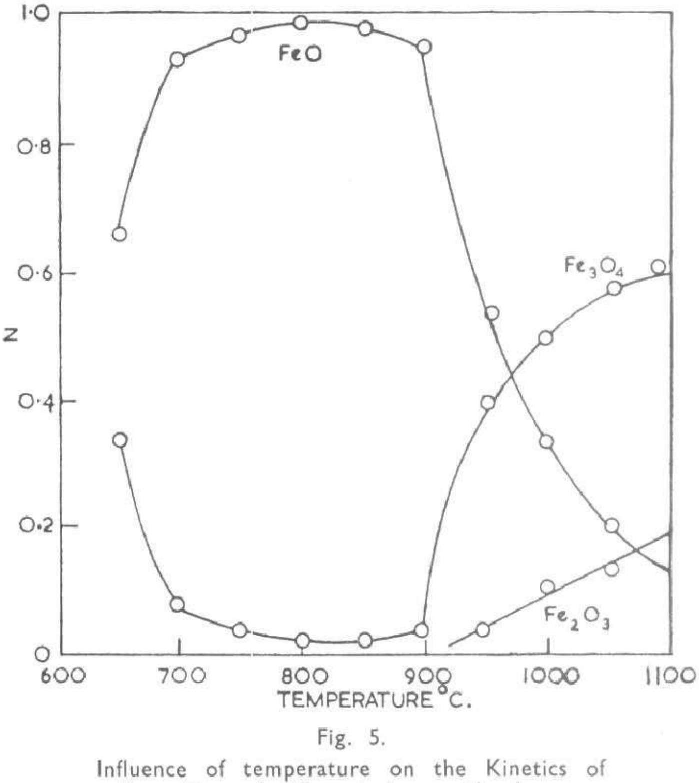


Fig. 5.

Influence of temperature on the Kinetics of formation of different iron-oxide layers.

After Benard and Coquelle. N = mole fraction of FeO, Fe_3O_4 and Fe_2O_3 respectively.

---

* For practical and historical reasons, it is normally considered as this is a stoichiometric compound, in fact, however, it is more closely described as $Fe_{1-y}O$ where y is the density of dislocations in the wustite.

The most recent study of the kinetics of oxidation of pure irons in air between 700° to 1,250°C by Paidassi[35] shows that with isothermal oxidation conditions and after the unstable initial growth, the adherent scale is always composed of three continuous and compact layers of hematite, magnetite and wustite. The relative thicknesses remain constant at 1%, 4% and 95% of the total scale thickness. However, up to 900°C oxidising temperature, the observance of Fe_2O_3 is not reported for times less than 15 minutes. Furthermore, the formation of scale in practice in a rod mill is appreciably different from the isothermal equilibrium experiments of the laboratory, done on chemically clean surfaces.

Ideally, oxidation proceeds according to the law $x^2=kt$ where $x=wt$ or thickness of metal consumed or found in the scale, t=time of oxidation and k= rate constant. However, the value of k varies with temperature according to the equation $k=Ae^{-Q/RT}$ where A, Q are constants; R=the gas constant; T=absolute temperature; e=base of natural logs[36]. Even though modifications to the theory are necessary for the non-ideal conditions and the allotropic change that occurs with iron, because of the increased diffusion rates with higher temperatures oxidation will occur more rapidly. The proportions of the various oxides present may change in practice according to the temperature of formation, but in general the higher the temperature, the thicker the total scale.

Although the scale on rod is not produced in equilibrium conditions with a constant temperature yet on a falling temperature and with various rates of cooling, it is obvious that one of the important factors that will determine the relative proportions of the oxides and hence the type of scale is the temperature history of its formation.

The above simple picture of scale structure is based on the assumption that it is controlled solely by the diffusion of iron and oxygen ions through coherent surface layers. In fact, the occurrence of pores, cracks and blisters modifies the simple layered structure and the properties of the scale.

During the oxidation of iron, its original volume increases by a factor of 1·76 when FeO is the product; in the case of Fe_3O_4 and Fe_2O_3 the volume will increase by factors of 2·1 and 2·4 respectively[37]. Because of this marked increase in volume large internal stresses occur in the oxide layers. Although the curved surface of a round rod is geometrically favourable for allowing the increased volume to accommodate itself, the internal stresses will still build up. These are responsible to a marked degree for the formation of fissures and cavities in the scale. In the case of cooling wire rod, the differential contraction between the parent metal and the oxides will also contribute to the rupturing of the oxide jacket.

The mode of occurence of the faults will be modified by the mechanical properties of the oxides and their adhesion to the parent metal[36].

If the cracks or cavities are open to the air, then providing the temperature is high enough and the rate of cooling slow enough for oxidation to progress, the higher oxides Fe_3O_4 and Fe_2O_3 can easily be formed in the inner layer of the scale and close to the parent metal.

Properties of scale

From the viewpoint of hardness or abrasiveness, it is worth noting that FeO is considered the softest and least detrimental of the oxides. The Fe_3O_4 and Fe_2O_3 are much harder and would do the most damage to the die if carried into it by the rod.

As far as behaviour in acid is concerned FeO is the most soluble, Fe_2O_3 only slightly and Fe_3O_4 almost insoluble[39, 40]. Although FeO is considered to be unstable in bulk below 570°C (breaking down to Fe_3O_4 and Fe) the rate at which it decomposes is dependent upon the temperature and hence on the rate of cooling[41, 42, 43]. It is not known whether the cooling rates of the rod after the last pass are slow enough to allow appreciable decomposition and therefore affect the abrasive and acid soluble properties of this oxide. A feature of some scales formed at high temperatures is the presence of a precipitate of Fe_3O_4 in the outer zone of the FeO layer. This relatively coarse precipitate is probably the product of the supersaturation of oxygen in this outer portion of FeO at the high temperatures and it is of pre-eutectoid origin. It is not due to the decomposition of the ferrous oxide below 570°C as originally believed by Pfeil[33].

Weight of scale

It is most probable that the bulk of scale on the finished rod originates after the rod passes through the last stand and is coiled. Measurement of the weight of the scale on samples of rod quenched in water soon after coiling supports this thesis. Figures quoted by Stebbins[28] showed that for coiling temperatures of 787° to 953°C, the quantity of scale per 1,000 ft.^{2} of rod surface varied from 25 to 50 lb. Rod examined by Eisenhuth and his co-workers[2] had from 14 to 31 lb of scale per 1,000 ft.^{2} of surface; the weights of scale on the quenched samples referred to above worked out to approximately 7 lb/1,000 ft^2. One would also expect with inefficient cooling that the weight of scale produced along the length of the rod will vary; in the hot coil the outer layers would tend to cool more rapidly than the inner ones.

Conclusions from previous work

The following factors appear to be the most obvious ones determining the ultimate composition and properties of the scale on the rod.

(a) *Finishing temperature and cooling rate*: The finishing temperature controls the rate at which oxidation initially occurs and will influence the path of the subsequent cooling history. The higher the finishing temperature, the thicker the scale, even if the cooling rates are equal. This occurs because the rod will be exposed for a longer time to the temperature range where oxidation rates are high.

In order to obtain scales of equal thicknesses with different finishing temperatures, a faster cooling rate is necessary for the higher temperature than for the lower one. If the finishing temperature is fixed, then the slower cooling rate will produce the thicker scale.

As the scale thickens, its internal stresses increase. This promotes the introduction of cracks and blisters. If the ratio of Fe_3O_4 to FeO is increased, the magnitude of the internal stresses would be even greater. Temperature history and the continuity of the scale or lack of it will determine the constituents found in the scale.

(*b*) *Metal surface conditions*: Conditions at the metal-oxide interface are important in so far as they determine the magnitude of the adherence between rod and scale. This in turn determines where the cleavage is going to occur as the internal lateral compressive stresses build up in the scale[38]. The locking characteristics of the metal surfaces are determined to some extent by the geometrical features of the surface imparted to the rod by the rolls during plastic deformation and to the unevenness with which the oxidation has penetrated into the metal, that is, whether rooting of the oxide film into the metal has occurred[26].

(*c*) *Composition of the parent metal*: Impurities in the steel can affect the oxidation process. It is known that elements such as copper, silicon, chromium, nickel, manganese and cobalt modify the scale formation of pure iron[12]. In steels with high carbon content, the possible evolution of carbon monoxide would encourage the formation of cracks and blisters[37]. However, most steels produced today contain minimum amounts of tramp elements, and one must accept this condition as normal. As long as they are kept within the specified limits the effect of minor elements on the scale process should be very secondary.

From the known properties of the oxide, one can specify in a general way some of the features of a scale that would be amenable to removal by pickling. There would not, however, be any penetration of the innermost layer of the scale by the higher, relatively insoluble oxides, and sufficient passages would exist through the outer acid resistant oxide layer or layers, to allow intimate contact of the acid with the soluble layer and the parent metal. Furthermore, Wever and Engell[44] have indicated that the most favourable electrochemical cell for rapid pickling is when a layer of wustite is in contact with the parent metal and both are in contact with the acid.

As shown by Eisenhuth[5,6] the removal of the bulk of the scale by mechanical means is facilitated by increasing the amount of the plastic deformation during the bending operation (i.e. by decreasing the size of the pulleys) and by having a thick scale. However, as previously noted, there must be some other factor or factors involved since it was shown that the rod with the minimum weight of residual oxide does not necessarily give the minimum die wear.

A more detailed knowledge of the scale properties, their structures and the conditions under which they are produced is essential to an adequate understanding of what comprises a satisfactory scale for each method of descaling.

Experimental work

(*a*) *Effect of formation temperature on the structure of scale*: The ideal method would have been to study the formation of scales under the actual rolling conditions in a rod mill. However, lacking this facility, an attempt has been made on a laboratory basis to simulate the oxidising history of the rod after it has passed through the mill so as to roughly establish the relationship between scale structure and its conditions of formation.

Samples of rod were heated in nitrogen to the specified temperature (equivalent to finishing or coiling temperatures of 750°C, 850°C, 950°C and 1,050°C). When the specimen reached the temperature of the furnace, air was introduced into the furnace tube and the rod was allowed to oxidise for a short period of time at the constant temperature. It was then cooled in air by transferring it to a cold zone of the tube.

The samples were cut from a coil of pickled low-carbon, mild steel rod (5 SWG).

Lime was removed from the surface by bathing the rod in a dilute HCl solution.

In practice when the rod is coiled, it already has a thin layer of oxide. To make the test conditions more simulative, the specimen rods were given a preliminary short-time oxidation of one minute at 700°C and cooled to room temperature in nitrogen. The thin scale produced in this preliminary treatment was composed mainly of FeO. The rod specimens were then stored in a dessicator until used in the experiments.

The normal method of mounting and polishing specimens for metallographic examination proved unsatisfactory. The scales were either broken away from the parent metal during mounting or were dragged out at the grinding or polishing stages. After an appreciable effort a satisfactory method was developed. The details are given in Appendix II.

The microscopic examination of the scales showed that the Fe_3O_4 and Fe_2O_3 increased with the temperature. The number of fissures, blisters and cracks also increased. The major differences in structure occured when the temperature was raised from 850° to 950°C. The photo-micrographs illustrate some of these pertinent features.

Fig. 6*a* shows the type of structure obtained at 850°C. It consists of an inner thick layer of FeO and an outer one of Fe_3O_4. The scale is is predominantly a continuous two-layer structure, even though it is thicker and more porous than the 750°C scale.

Fig. 6*b* illustrates the type of structure obtained

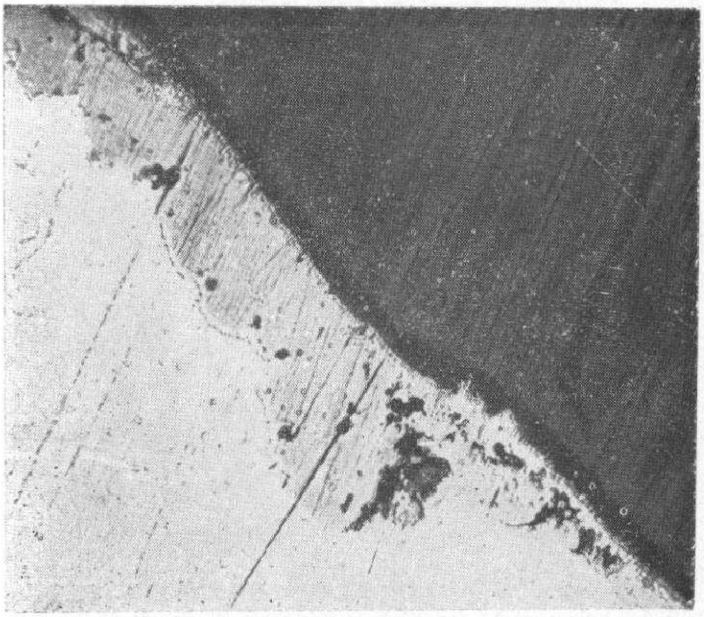


Fig. 6*a*.
Scale formed at 850°C ×500.

Fig. 6*b*.
Scale formed at 950°C ×500.

when cooling from a temperature of 950°C. The scale is very porous; the proportion of FeO has decreased; the Fe_2O_3 phase is present. In the particular field photographed, the Fe_3O_4 has penetrated close towards the parent metal.

The 1050°C scale showed a greater discontinuity than the 950°C one, with increased numbers of large blisters.

The scales formed at 950°C and over contain definitely identifiable hematite and also a higher proportion of magnetite and pores than in the scale structures produced at 850° and 750°C. Having established that for short time oxidation cycles in the laboratory, the composition of the scales produced appear to roughly follow the curves in Fig. 5., the investigation was extended to a study of scales on commercial wire rod.

(*b*) *Investigation of scales on commercial wire rod*: Samples of wire rod were collected from various wire and rod mills. Their oxide scales were metallographically examined. Where a sufficient length of sample was available, the scale was evaluated from the viewpoint of adherence in a mechanical descaling operation.

Twenty-six samples of the 5-gauge rod were received. All were metallographically examined; the scales on only twenty of these wire evaluated for adhesion. Eighty specimens altogether were given a primary mechanical descaling treatment and then measured for residual oxide. The number of specimens from each sample varied from one to seven. Nine of the twenty samples were low carbon steel; ten were high carbon and the other one was a medium carbon steel. The six samples that were not evaluated for scale adhesion were from two coils of mild steel rod and the samples were obtained from the middle and both ends of each coil. They were examined metallographically and coarse mesurements of the scale weights were also obtained.

Metallographic study of the scales: The scaled specimens were mounted and polished by the method described in detail in Appendix II. There was a marked variation in the types of scales observed. On the basis of the preliminary laboratory work and the work of Benard and Coquelle, Fig. 5, some indication of the finishing temperature of the rod could be deduced from the observations on the scale and it was possible to grade the scales into two general types according to their probable thermal history.

A "low" temperature scale was one that had probably formed at below 900°C. It consisted of two phases in layers—wustite towards the parent metal and magnetite on the outside. Fig. 7*a* illustrates this type of scale.

Scales that contained a third phase, hematite and those that were apparently two-phased but contained a high proportion of magnetite precipitate in the wustite layer, were considered as "high" temperature scales. It is possible that this latter structure was due to a combination of an "intermediate" finishing temperature and a slow cooling rate. However, a more exact classification of the scales according to the thermal conditions origin was not possible.

Fig. 8*a* illustrates a high temperature scale. In the upper right hand part of the scale, where a blister was broken off, there is some hematite Fe_2O_3. Further signs of this ferric oxide were visible around the small cavities that had formed in the outer layer of magnetite. There was an appreciable amount of precipitate Fe_3O_4 in the wustite FeO which in this particular field was

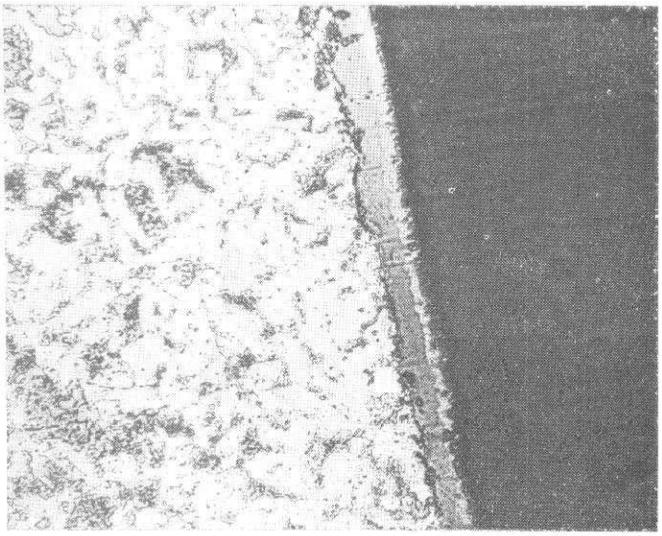


Fig. 7*a*.
"Low" temperature scale ×500.

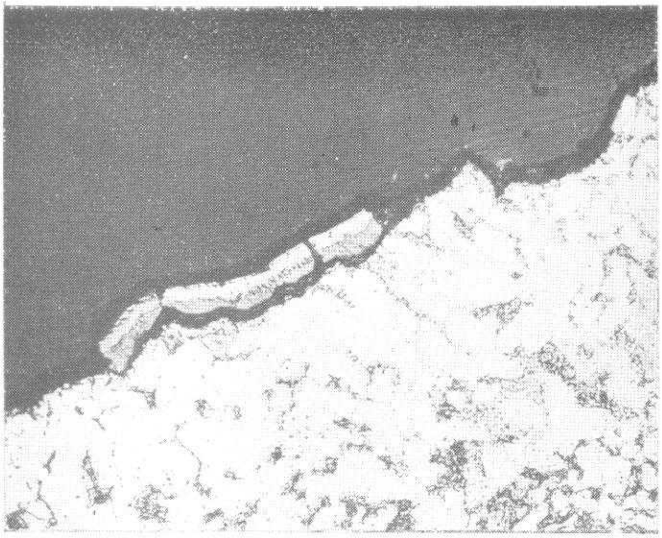


Fig. 7*b*.
"Low" temperature residual scale ×500.

apparently sandwiched between two layers of magnetite Fe_3O_4.

Figs. 9*b*, 10*a* and 10*b* also illustrate the types of high temperature scale that were observed. In this particular case they were all found on the same specimen along with the scale in Fig. 9*a* which was more like a low temperature scale, slowly cooled. This latter scale had a thick layer of wustite (FeO) containing some precipitate of magnetite (Fe_3O_4) and a thin layer of this latter oxide.

Fig. 9*b* illustrates a porous high temperature section of the scale. The outer layer of magnetite (Fe_3O_4) was thicker and the concentration of the precipitate in the wustite (FeO) was heavier. There appeared to be traces of hematite (Fe_2O_3) around the pores in this outer magnetite layer.

In Fig. 10*a* the scale had originally become detached from the parent metal at a high temperature and on the outer side of the blister it had been completely converted to the higher oxides—magnetite (Fe_3O_4) and hematite (Fe_2O_3.) The lighter-coloured phase was the hematite. Details of the thin scale layer attached to the parent metal could not be observed but it was reasonable to assume that there could be an extremely thin layer of Fe_2O_3 on the outside of the thin adherent scale.

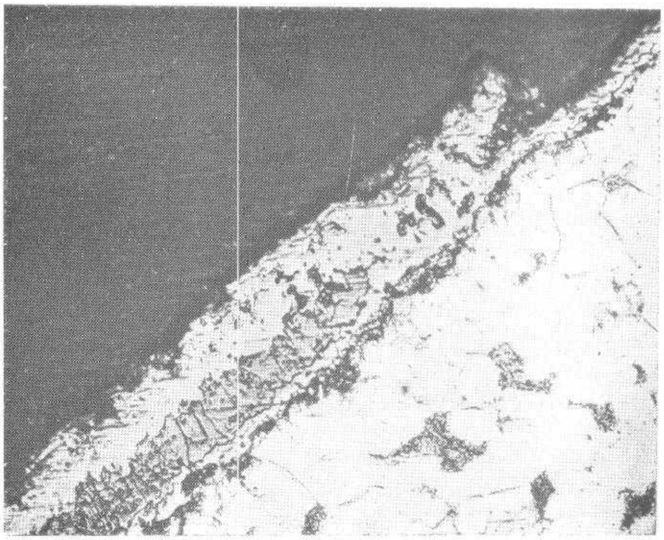


Fig. 8*a*.
"High" temperature scale ×500.

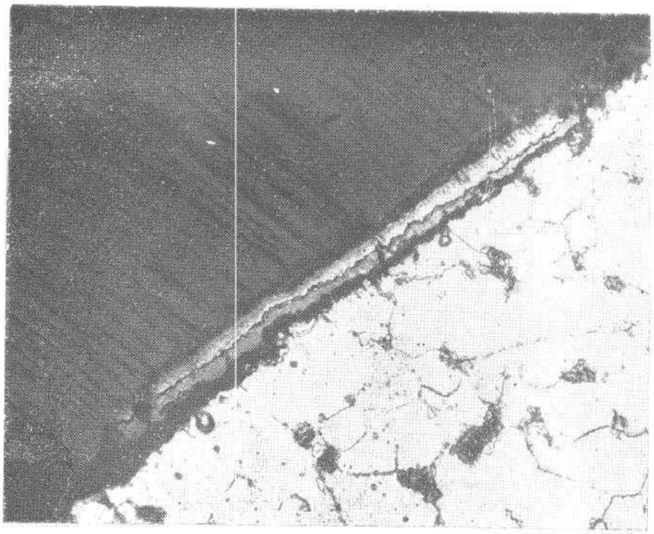


Fig. 8*b*.
"High" temperature residual scale ×500.

A high concentration of the magnetite precipitate in the wustite layer, the intermediate magnetite layer and the outer layer of hematite were features of the scale shown in Fig. 10*b*. At the top right hand corner a blister and a large patch of the light coloured hematite were observed.

It was very difficult to determine the presence of a thin external layer of the hematite at the surface of some of the high temperature scales, even though needles and patches of this oxide were visible elsewhere within the scale. Once the temperature of formation was sufficiently high for this ferric oxide to form within, it was to be expected that a surface layer of hematite should also be present. It must be assumed that the metallographic technique was not always successful in detecting it.

Fig. 9*a*.
"Low" temperature scale ×500.

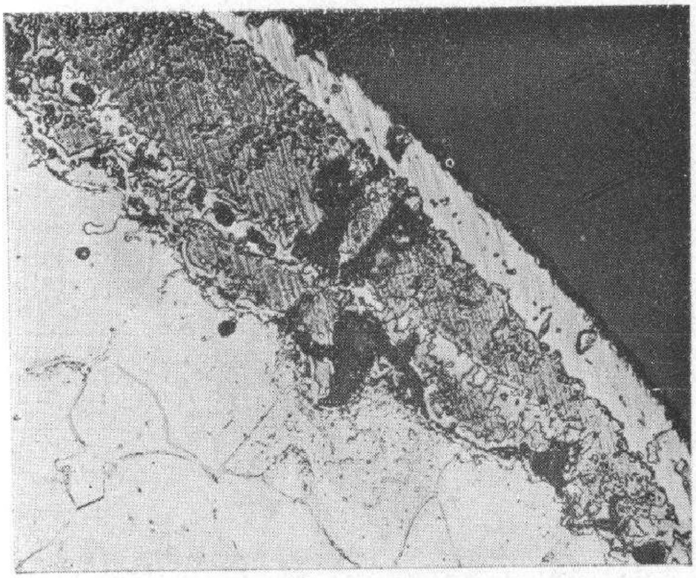


Fig. 9*b*.
"High" temperature scale ×500.

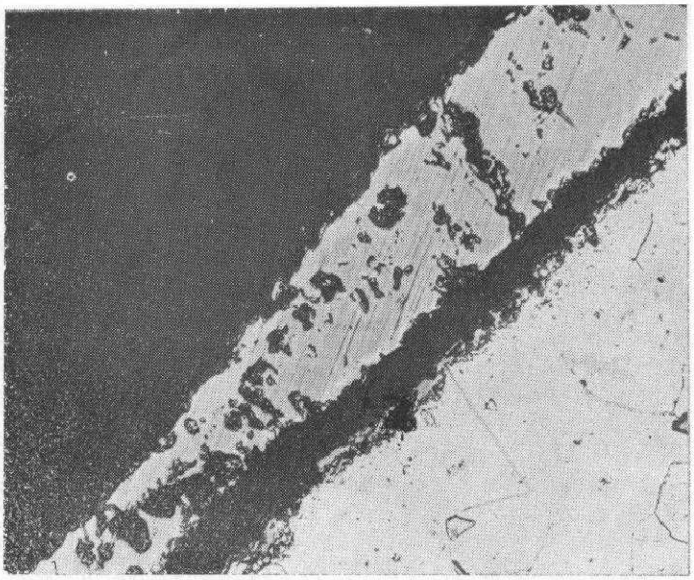


Fig. 10*a*.
"High" temperature scale ×500.

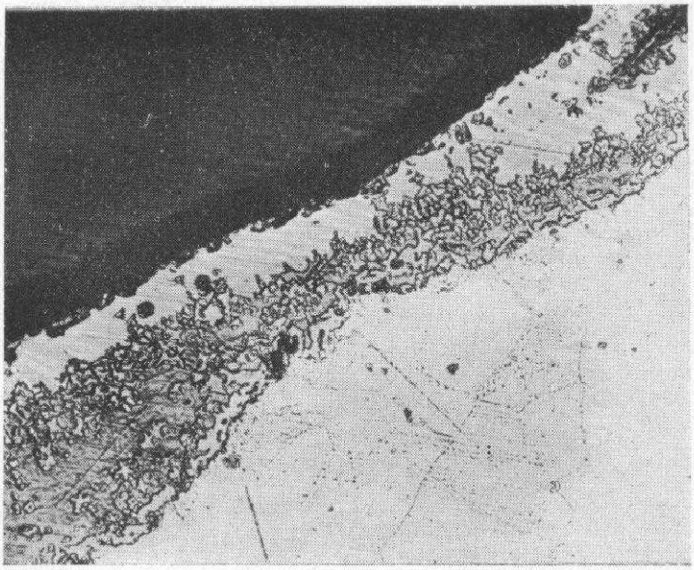


Fig. 10*b*.
"High" temperature scale ×500.

Mechanical descaling and residual scale weights

Specimens were coarsely descaled by pulling them 5% in tension, and the adherence of the scale was gauged by the amount of residual oxide, which was measured by a further cathodic descaling of the rods. This procedure was as follows: The coarsely descaled specimen was cathodic in a dilute solution of HCl and a graphite rod was used as the anode.

The solution was 20 : 1 by volume, water to concentrated acid ; a current density of 150–200 amps/ft², a voltage of 6–7 volts and an anode of graphite were used : the time of descaling was 15 minutes.

The results of the twenty samples are summarised in Table I. In general the figures for the total scale are on the low side because the samples in most cases probably originated from the ends of the coils and usually the scale was not intact after transit.

Values of the total scale on individual specimens varied from 4·9 lb/1,000 ft.² to 49·3 lb/1,000 ft². The thicknesses of these scales observed on the microscope ranged from 1/4 to 3 thousandths of an inch.

Table II shows the wide variation in the weights and thicknesses of the scale that existed along the lengths of two coils of mild steel rod. Due to the widely different rates of cooling in the coil, two to three times as much scale was formed in the middle as compared to the ends, but the metallographic examination showed very little difference in the scale structure. The ratio of thicknesses of the wustite layer to the magnetite layer was increased and a higher proportion of magnetite precipitate was found in the wustite at the centre of the coil.

Structure of residual scale

As indicated by the results in Table I, an appreciable portion of the scale remained on the rod specimens after the tensile descaling. It ranged from 0·7 to 5·6 lb/1,000 ft.² on the individual specimens. To examine the structure of this adherent portion of the scale, rod specimens from both

TABLE I

Sample	No. of specimens	Type of scale	Thickness of scale inch	Total scale weight		Residual scale weight		Type of steel
				Range I lb/1,000	Average sq. ft.	Range I lb/1,000	Average sq. ft.	
C-1	3	Low temp.	0·00025–0·0005	11·5–27·1	19·2	1·8–2·9	2·4	High Carbon
C-2	4	Low temp.	0·0005 –0·001	14·4–30·5	20·2	1·4–2·9	2·1	,,
C-3	4	Low temp.	0·00025–0·001	15·7–25·0	19·9	1·0–1·2	1·1	,,
C-4	4	High temp.	0·0005 –0·001	10·9–26·8	17·4	0·7–2·0	1·4	,,
C-5	3	High temp.	0·001 –0·0015	18·7–49·3	29·6	1·0–1·2	1·1	,,
C-6	3	Low temp.	0·00025–0·00075	17·6–18·6	18·0	1·6–2·6	1·9	,,
C-7	4	Med. high temp.	0·00025–0·00075	19·4–21·2	20·4	3·6–5·6	4·4	,,
C-8	4	Med. high temp.	0·00025–0·0005	10·7–13·2	11·7	2·5–2·9	2·7	Medium Carbon
C-9	6	High. temp.	0·0015 –0·003	27·5–44·8	35·3	1·7–4·0	3·1	Low Carbon
C-10	5	Med. high temp.	0·0005 –0·001	18·7–38·5	29·5	1·3–4·7	3·2	,,
C-17	7	Low temp.	0·0003 –0·00075	13·2–20·6	17·5	0·8–3·8	2·2	,,
C-18	7	Low temp.	0·00075–0·001	16·3–31·6	24·6	1·7–4·2	2·8	,,
C-19	5	High temp.	0·00075–0·0015	19·9–31·8	26·2	1·4–2·9	2·1	,,
C-20	3	Low temp.	0·00075–0·0015	4·9–14·8	9·0	1·1–1·2	1·2	High Carbon
C-21	4	Low temp.	0·0005 (Uniform)	7·6–17·3	11·0	1·2–1·7	1·4	,,
C-22	1	Low temp.	0·00075–0·001	—	18·8	—	3·4	Low Carbon
C-23	1	Low temp.	0·00025–0·0005	—	9·1	—	4·0	,,
C-26	4	Low temp.	0·0005 –0·00075	14·0–19·7	16·7	1·1–1·7	1·4	High Carbon
C-28	4	Low temp.	0·0005 (Uniform)	10·6–20·6	14·6	1·2–3·6	2·5	Low Carbon
C-29	4	Low temp.	0·00025–0·00075	13·7–22·3	17·5	0·8–1·6	1·3	,,

TABLE II

Sample	Number of specimens	Position in coil	Type of scale	Thickness of scale inch	Approx. scale weight lb/1,000 ft.²	Type of steel
C-11	2	Back end	Low temp.	0·0005 – 0·00075	14	Mild steel
C-12	2	Middle	,, ,,	0·003	51	Mild steel
C-13	2	Front end	,, ,,	0·00075 – 0·001	27	Mild steel
C-14	2	Back end	,, ,,	0·001 – 0·00125	22	Mild steel
C-15	2	Middle	,, ,,	0·0015 – 0·003	41	Mild steel
C-16	2	Front end	,, ,,	0·00075 – 0·001	19	Mild steel

high and low temperature samples were mechanically descaled, and then mounted and polished for microscopic examination.

Fig. 7*b* shows a particle of low temperature scale that had remained on the rod.

Fig. 8*b* shows a particle of high temperature scale that had not been removed during the descaling. This was obviously a thin layer of scale that had originally been located underneath a blister. It was predominantly magnetite (Fe_3O_4) and wustite (FeO).

Figs. 11*a*, 11*b* and are also pictures of pieces of residual scale from low and high temperature scales respectively. These illustrate the important differences in the properties that can exist between the two residual scales. In Fig. 11*a*, the residual was two-phased, magnetite and wustite; the high temperature residual in Fig. 11*b* was three-phased and contained some hematite.

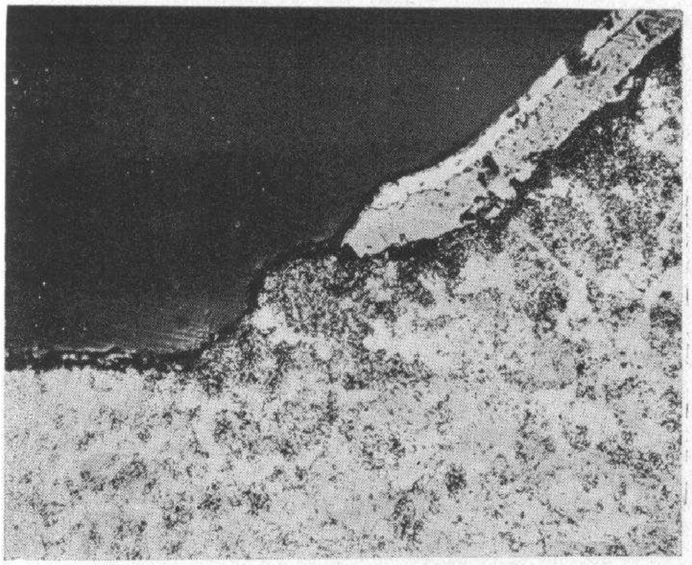


Fig. 11*a*.
"Low" temperature residual scale ×500.

Fig. 11*b*.
"High" temperature residual scale ×500.

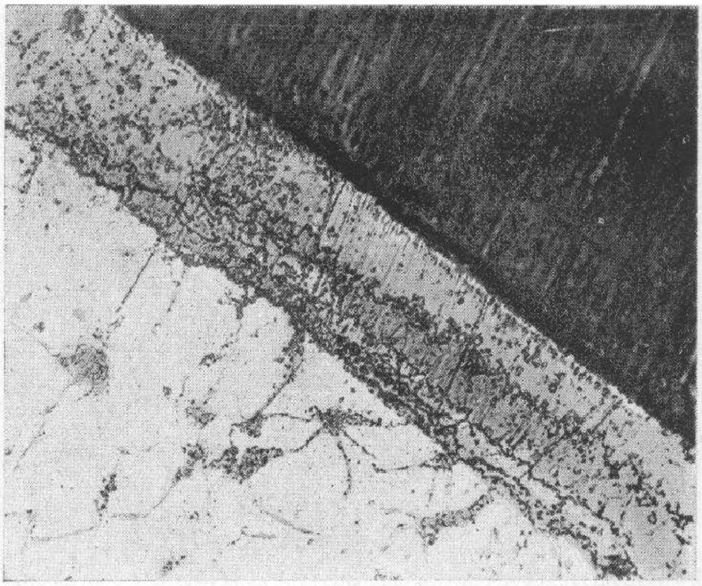


Fig. 12*a*.
Intrusion of magnetite towards parent metal ×500.

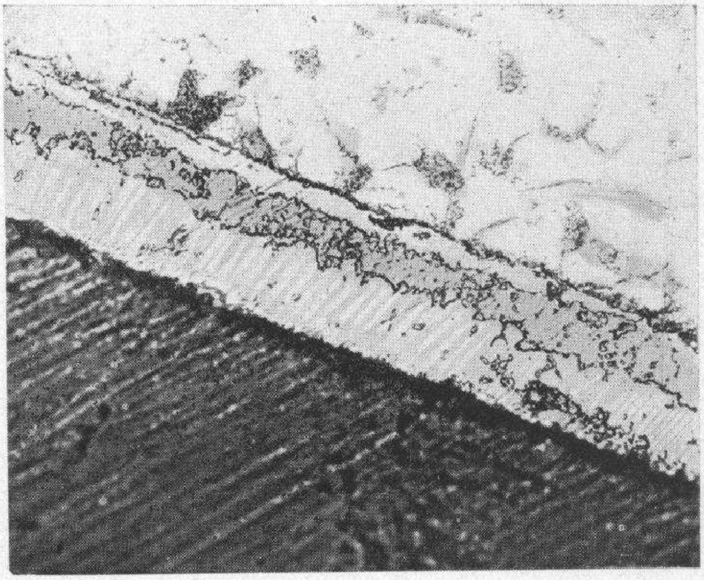


Fig. 12*b*.
Intrusion of magnetite towards parent metal ×500.

Normally, the penetration of a higher oxide towards the parent metal is associated with porosity or blisters in the scale; that is, with a high temperature origin. A structure with a peculiar intrusion of the higher oxide magnetite towards the parent metal was observed in one sample. It is illustrated in Figs. 12*a* and 12*b*. In this particular case the

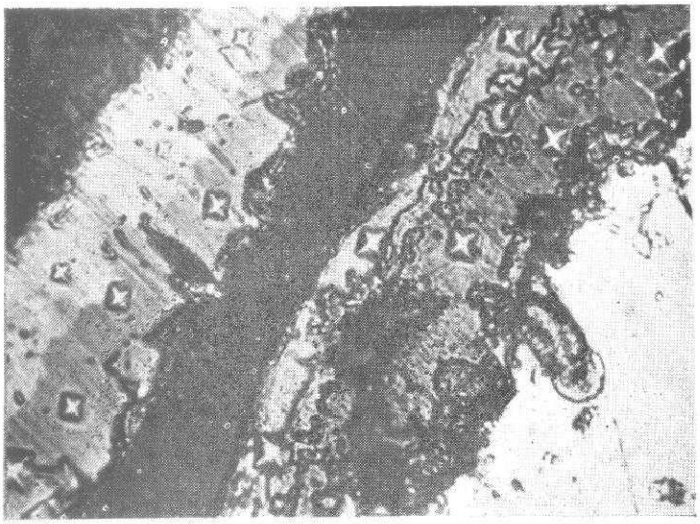


Fig. 13*a*.
Micro-hardness tests on "high" temperature scale ×1000.

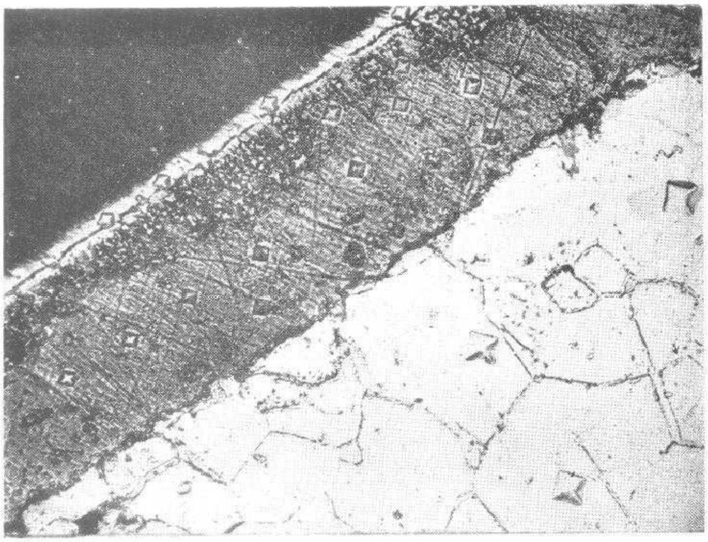


Fig. 13*b*.
Micro-hardness tests on "low" temperature scale ×500.

scale appeared solid and was in intimate contact with the metal. After a mechanical descaling operation, the residual part of this type of scale should consist almost wholly of magnetite.

Hardness of the oxide phases

In order to confirm the hypothesis that the residual scales containing a greater proportion of the higher oxides could be more detrimental to die wear than the low temperature, two-phase residual scale, micro-hardnesses of the oxide constituents were obtained. A Vickers Micro-hardness Tester, with a 5-gram load was used.

In Fig. 13*a* the diamond pyramid impressions indicate the relative hardnesses of the various oxides. The hematite (Fe_2O_3) was the hardest; the magnetite (Fe_3O_4) had an intermediate value, and wustite (FeO) was the softest. Measurements of the diagonals of the impressions and the calculations showed that the hardnesses were of the following order:

Hematite, Fe_2O_3	...	1,030 D.P.H.
Magnetite, Fe_3O_4	...	420–500 D.P.H.
Wustite, FeO	...	270–350 D.P.H.

In Fig. 13*b*, which was a low temperature scale probably slowly cooled, the micro-hardness impressions show the relative hardness of the parent metal, the wustite and the magnetite. The D.P.H. of the metal was 76.

A thin two-phase low temperature scale was checked for micro-hardness (Fig. 14*a*). The hardnesses

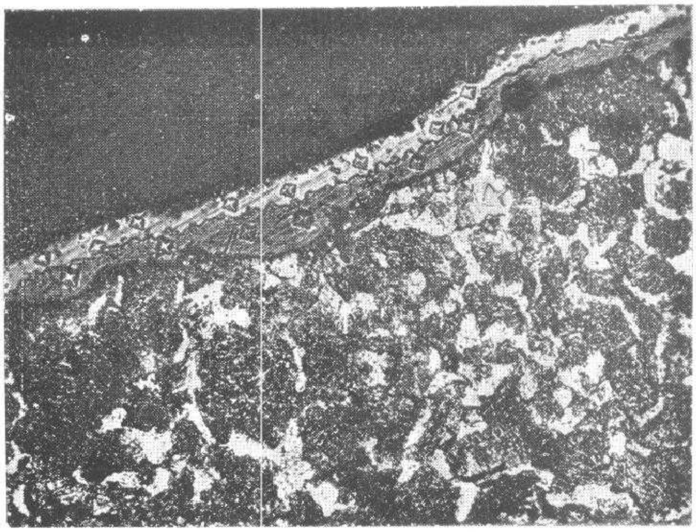


Fig. 14*a*,
Micro-hardness test on "low" temperature scale ×500.

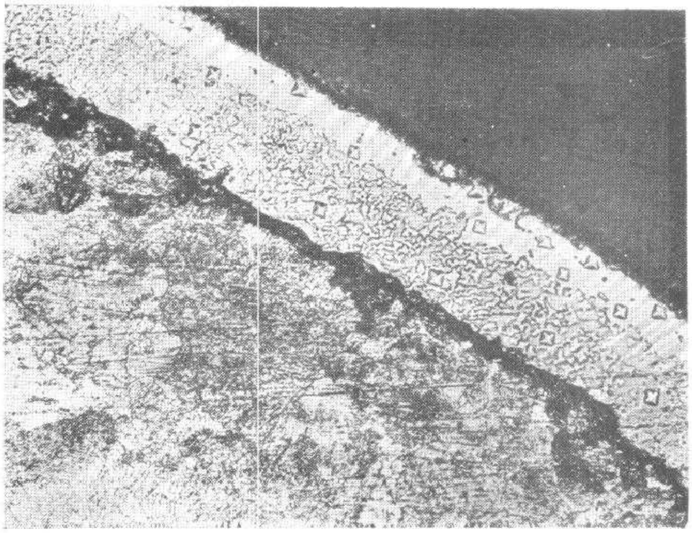


Fig. 14*b*.
Micro-hardness test on "high" temperature scale ×500.

obtained were 140 D.P.H. for the metal, 270 D.P.H. for the wustite and 460 D.P.H. for the magnetite. In the thicker high temperature scale (Fig. 14*b*), the hardnesses were for the parent metal 182 D.P.H.; for the wustite with a high concentration of magnetite precipitate, 350 D.P.H., and for the magnetite layer, 460 D.P.H.

The wide differences in the hardnesses of the three oxide phases should explain the anomaly reported by Eisenhuth[5], who found that the greatest amount of die wear was not necessarily caused by the mechanically descaled rods carrying the largest amounts of residual scale. Apparently the specific abrasive character of the residual scale must be taken into account besides its quantity. With hardnesses of approximately 1,000 D.P.H. and 500 D.P.H., hematite (Fe_2O_3) and magnetite (Fe_3O_4) are bound to be more abrasive than the wustite, hardness 300 D.P.H. Therefore, the residual scale pictured in Fig. 11*b* was bound to be more detrimental than the one in Fig. 11*a*.

Considering descaled rods with equal amounts of residual scale, rods that had the high temperature scales can be expected to give a poorer performance in the drawing operation than those that originally had low temperature scale. Not only should die wear be increased by the high temperature rods but more heat than usual will be generated at the die. The sub-surface defects would also contribute to this phenomenon, besides acting as stress raisers and reducing the ductility.

Effect of surface finish

During the microscopic examination of the rods, it became apparent that besides the radical differences in their scale structures, the quality of the rod surfaces varied widely. Sub-surface defects were also noted in some specimens. Figs. 15*a* and 15*b* illustrate these defects which were probably due to poor rolling techniques.

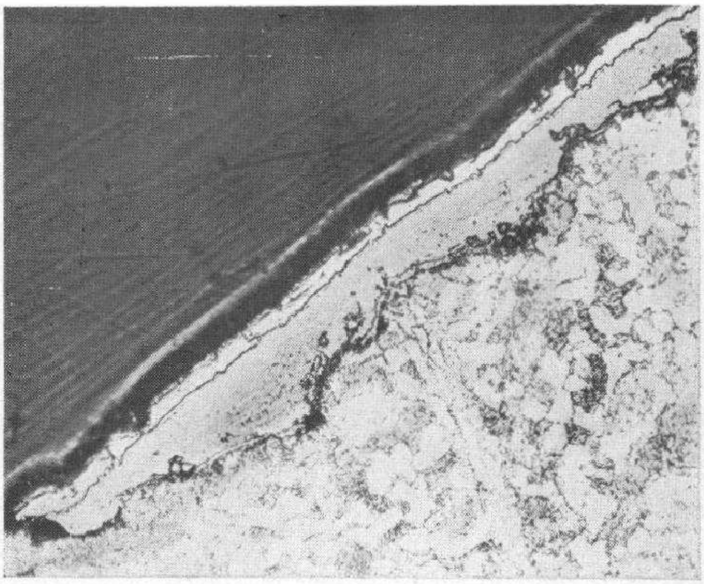


Fig. 15*b*.
Sub-surface defect ×500.

The cathodically descaled surfaces were examined and the specimens were graded according to their surface quality into five different categories—Excellent, Good, Fair, Poor and Bad. Figs. 16*a*, 16*b* and 16*c* are examples of the Excellent, Fair and Bad specimens.

A statistical analysis of the residual scale results and the gradings of the surface roughness of the specimens showed a good correlation. The results were then separated according to whether the rods

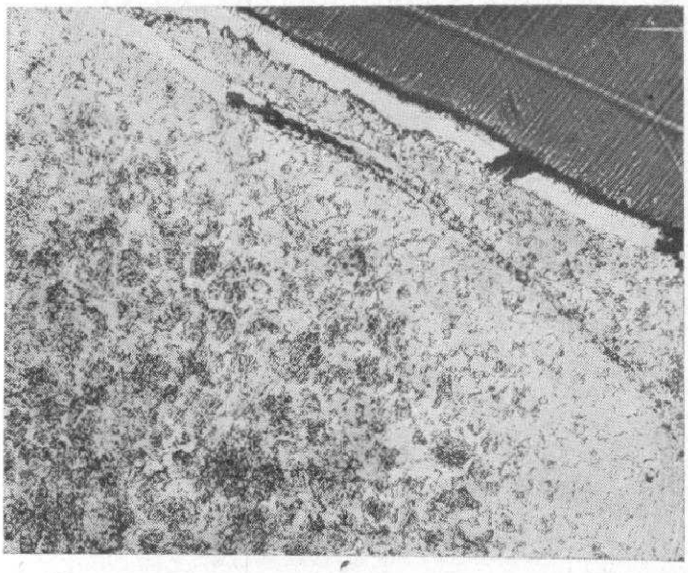


Fig. 15*a*.
Sub-surface defect ×250.

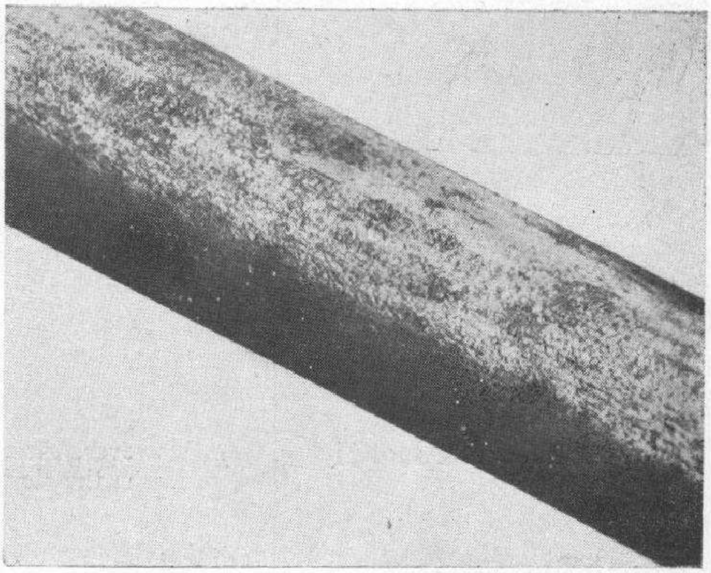


Fig. 16*a*.
Excellent surface ×6.

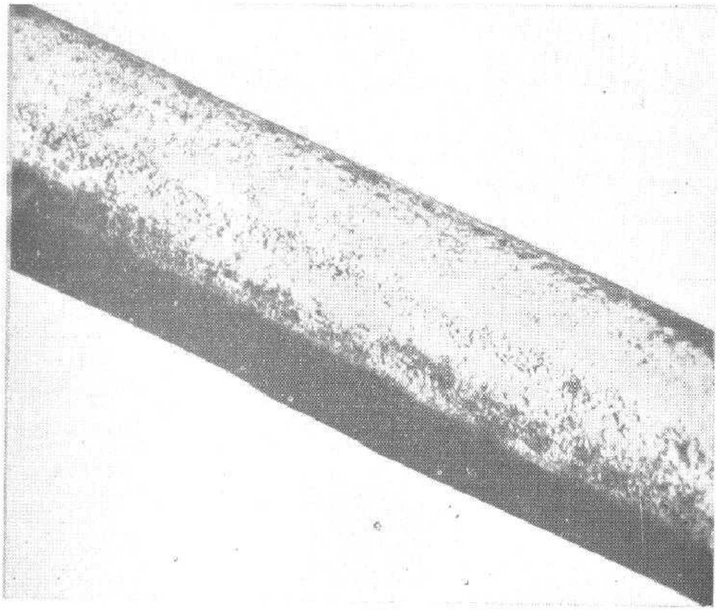


Fig. 16*b*.
Fair surface ×6.

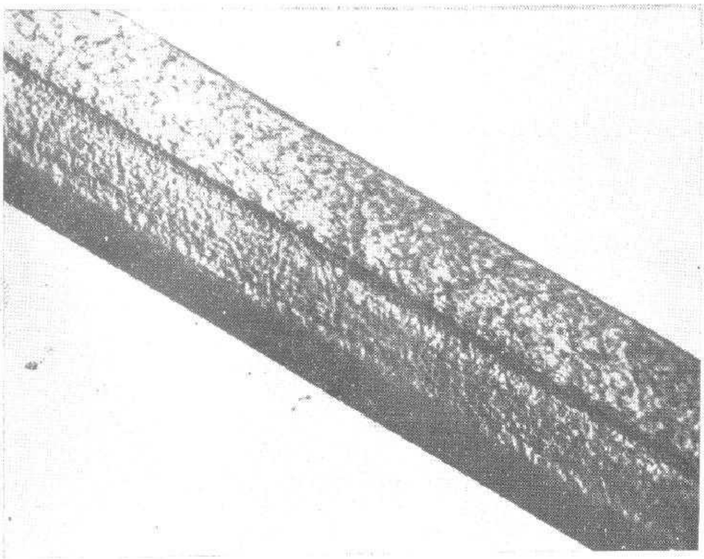


Fig. 16*c*.
Bad surface ×6.

originally had high or low temperature scales. The analysis was repeated and it was found that for the high temperature rods, there was an excellent correlation between the surface roughness and residual scale. These results are plotted in Fig. 17. However, there was no significant correlation found with the low temperature results, which are plotted in Fig. 18.

General conclusions

1. It is probable that the mechanical descalers employing bending that are now available could be applied to a greater range of products than at present with a resultant saving in cost. Care is needed in their use and for some high quality wire they may not be suitable until better methods of secondary scale removal are developed.

2. Shot blasting is a promising method which, although more expensive than the deformation methods, gives a reliable result, and may possibly still compete in cost with pickling.

3. Examination of samples from various sources showed that there is a wide variation in the quality of surfaces produced on wire rod. In order to extend the use of mechanical descaling, rolling practices

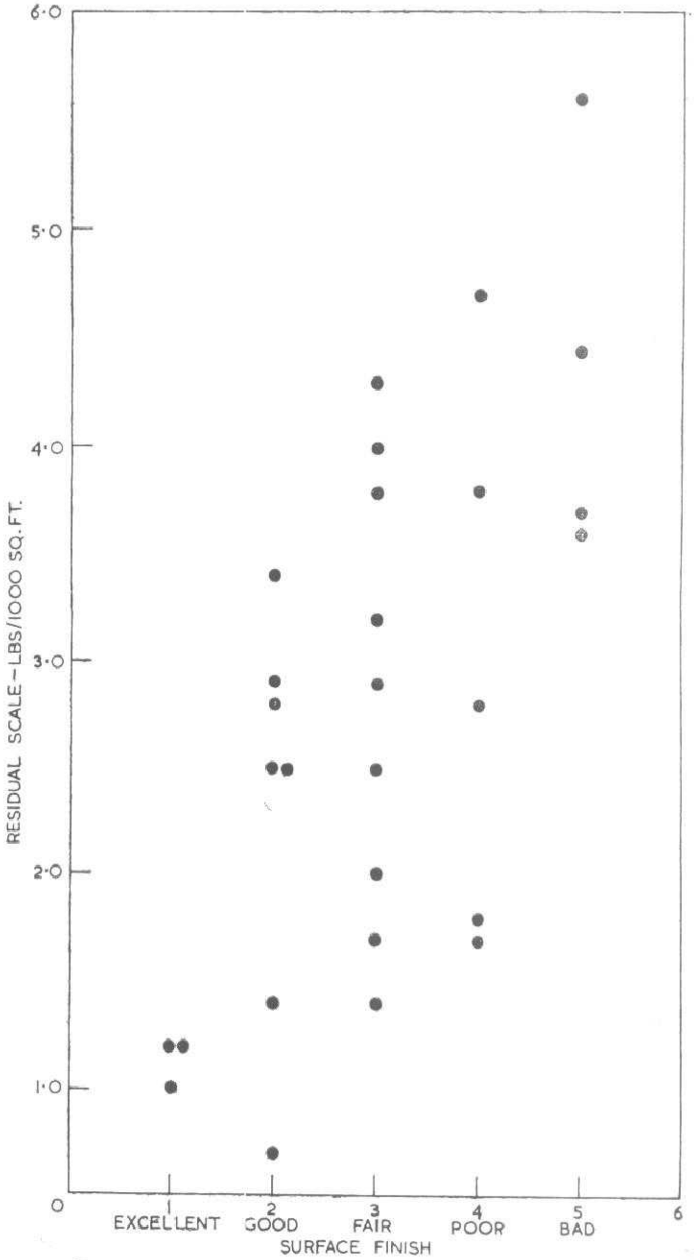


Fig. 17.
Rods with "high" finishing temperature scales.

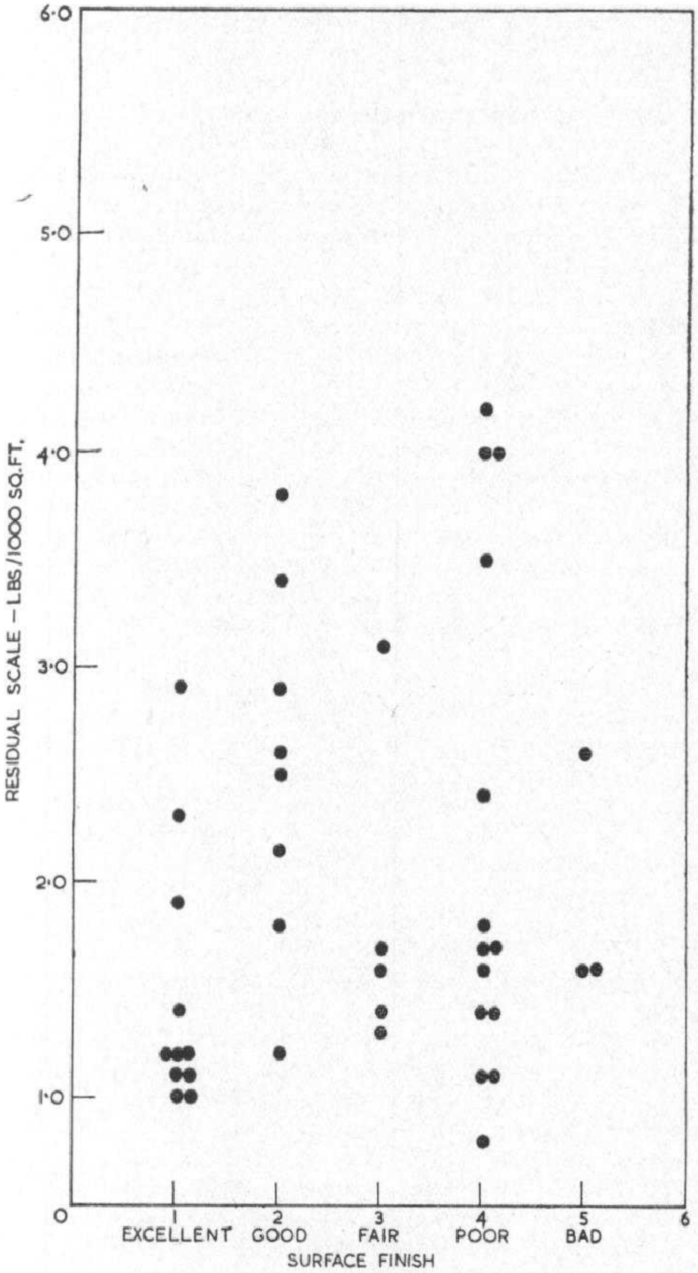


Fig. 18.

Rods with "low" finishing temperature scales.

and rolling mill equipment must be improved to consistently produce rod with both a smooth surface and an absence of sub-surface defects.

4. There are important differences in the structures and hence the properties of the various scales on wire rod. Scales of rods that were finished in the mill at a high temperature contain the extremely hard oxide hematite (Fe_2O_3) and higher proportions of magnetite (Fe_3O_4) than scales produced with a low finishing temperature.

5. The indications are that the differences in the scale structure between rods finished at high and low temperatures are greater than the differences between the structures found at the ends and centre of the same coil. However, there is from two to three times the amount of scale in the middle of the coil as compared to the ends. The fact indicates the need to obtain a more uniform cooling of the coiled rod.

6. Taking everything into consideration, it is difficult to see why mechanical descaling has not had a greater application than has so far been achieved.

References

1 A. Line, Wire Industry, 1953, V. 20, Jan. pp. 66–70,83.
2 Symposium. "Wire and Wire Products", V. 29, 1954, p. 501.
3 H. F. Sanderson, "Wire Industry", V. 21, 1954, p. 53.
4 S. Hajek, Hutnik, V. 6, 1956, p 271.
5 C. Eisenhuth, Stahl u. Eisen, V. 77, 1957, p. 323.
6 C. Eisenhuth, Stahl. u. Eisen, V. 75, 1955, p. 1092, Translation appeared in Wire and Wire Products, V. 31, 1956, p. 421.
7 British Patent No. 736,217.
8 New Descaling Machine "Argentina", Draht, V. 4, 1953, p. 95. Abridged Translation, Wire and Wire Products, Dec., 1953.
9 P. Ewald, "Draht" (English Ed.), V. 27, 1957.
10 British Patent 782, 153.
11 German Patent 909,562.
12 British Patent 798,925.
13 L. Marsden, "Wire Industry", V. 24, 1957, p. 1039.
14 P.E.R.A. Report on Mechanical Descaling of Ferrous Wire, Jan. 1955.
15 U. S. Patent No. 2804,196.
16 Mechanical Descaling Equipment, "Draht" (English Ed.), V. 7, 1957, p. 31.
17 G. J. Sorace, "Wire and Wire Products", V. 132, 1957, p. 1478,
18 G. D. Dill, "Wire and Wire Products", V. 32, 1957, p. 1473.
19 G. D. Dill, Iron and Steel Engineer, V. 34, 1957, p. 123.
20 G. D. Dill, Wire and Wire Products, V. 26, 1951, p. 910.
21 E. Jacnucher, A. Duphom, H. Krautmachen, and W. Pugel, Stahl. u. Eisen, V. 77, 1957, p. 1785.
22 L. Doty. Wire and Wire Products, V. 24, 1949, p. 1034.
23 BISRA Summary No. 123.
24 G. M. Sturgeon and G. H. Tattersall, BISRA Report MW/D/75/56. (To be published later).
25 J. G. Wistreich, Proceedings of the Institution of Mechanical Engineers. V. 169, 1955, No. 35.
26 R. Griffiths, J.I.S.I. V. 130, 1934, p. 377.
27 R. Griffiths, Cqrnegie Schol. Memoirs, V. 26, 1937, p. 165.
28 R. A. Stebbins, Wire and Wire Products, V. 29, 1954, p. 1141.
29 Earle L. Knapp. Wire and Wire Products, V. 31, 1956, p. 873.
30 H. Wiegand, K. Schear and F. Nieth, Metalloberflache, V. 9, 1955, p. 162A.
31 Private correspondence from W. Lueg,
32 L. B. Pfeil, J.I.S.I. V. 119, 1929, p. 501.
33 L. B. Pfeil, J.I.S.I., V. 123, 1931, p, 237.
34 J. Benard and O. Coquelle, Comptes Rendus, V. 222, 1946, p. 796.
35 J. Paidassi, Acta Metallurgica, V. 6, 1958, p. 184.
36 A. S. M. Metals Handbook (1948), p. 223.
37 O. Kubaschewski and B. E. Hopkins, Oxidation of Metals and Alloys, 1953, Butterworth, London.
38 U. R. Evans, Institute of Metals Symposium on Internal Stresses in Metals and Alloys, (1947), p. 291.
39 Handbook of Chemistry and Physics, 38th Edition, Chem. Rubber Co., Cleveland.
40 A. B. Winterbottom and J. P. Reed, J.I.S.I., V. 126 (1932), p. 159.
41 G. Chaudron, Ann. Chimie, V. 16. (1921) p. 221.
42 R. Collongues, R. Sifferlen and G. Chaudron, Revue de Metallurgie L, (1953), p. 727.
43 A. Fischer, A. Hoffman and R. Shimada, Archiv fur das Eisenhuttenwesen, V. 27, (1956), p. 521.
44 F. Wever and H. J. Engell, Archiv. fur das Eisenhuttenwesen, V. 27, (1956), pp. 475–486.

APPENDIX I

CIALLY AVAILABLE DESCALING MACHINES

A brief description of the mode of operation of various commercially available descaling machines is given below. Unfortunately, no data are available to compare their relative efficiencies as regards percentage of scale removed with various types or sizes of rods.

Argentina descaling machine (Germany)

The machine described in Draht[1] is designed to cope with rods up to $^3/_8$″ diameter, but further machines are being developed to cope with larger rods. The machine is made in two units. The coarse descaling unit consists of 6 scale breaking rolls in each half of a hinged drum so arranged that closing the drum to various degree will adjust the degree of bending of the rod. Two pairs of guide rolls at right angles are placed at each end of the drum to guide the wire and also to assist in scale removal. The fine descaling unit consists of a vertical cylinder full of steel grit, the wire passing up the centre and through a type of rubber pulley to prevent carry over of scale, etc. and so on to the die box. The size of grit depends on the material being cleaned and varies between 5 and 10 mm. The scale dust and worn grit are allowed to fall out at the bottom of the tube and are collected in a pan. This unit can be tilted into the horizontal position and opened to facilitate threading. The floor space required is approximately 16 ft. × 3 ft.

The Budenheim descaling machine (Germany)

Designed for descaling mild steel material up to 10 mm. (0·394″) and carbon steel up to 8 mm. (0·315″) diameter. The machine is totally enclosed and a window is fitted in the cover so that all the working parts can be observed whilst the machine is running. There are 5 scale breaking rolls in one plane which are adjustable and so arranged that they impart a small degree of twist to the rod as it passes through. The secondary stage consists of two adjustable, independently driven brushes of unique design. Several small tassels are attached to a pulley wheel on the motor shaft by chain to form a complete brush. By this method, the wire receives a beating action as well as brushing.

De Gorcy Descaling machine (France)

This machine is widely used in this country and therefore only a brief decription is necessary. The coarse descaling is accomplished by two pulleys in planes at right angles to one another. Rotating wire brushes which also revolve about the rod axis and are driven by the descaling pulleys are used in the secondary descaling operation prior to the rod entry into the first soap box on the drawing

Fuhr descaling machine (Germany)

Two pairs of rollers at 90° to one another guide the wire into the machine and one of the horizontal rolls is hinged to facilitate threading up. These are followed by two pairs of triple rollers at right angles to one another and the centre rolls are adjustable so that various sizes of rod and wire can be accommodated. Small adjustments can be made on the other rollers to facilitate smooth running. The rod then passes through 2 boxes of steel wool, mounted on a system of levers so that pressure is applied to the wool to prevent channelling. Before passing into the soap box the rod is given a final clean in a box of cotton waste which is also designed to prevent channelling.

Hanche descaling machine (Germany)

Three rollers form the wire inlet and are followed by mix scale breaking rolls, two of which are adjustable. The rod is then passed through a box of granulated steel or steel wool which is vibrated to eliminate channelling and scale dust. The drive for this box is provided by the last scale breaking roller. Adjustable plastic wiping pads are fitted immediately in front of the soap box which has a special lubrication.

Krollman descaling machine (Germany)

A guide nozzle and roller steer the wire over two adjustable scale breaking pulleys in two planes. The wire is then passed through motor-driven brushes with the axes parallel to the rod. The brushes rotate at 2,000 r.p.m. and revolve around the rod 850 r.p.m. Polishing brushes can be fitted as an extra to the brush spindles, and steel wool or rag is placed in the wiping box prior to soap box.

Marshall Richards descaling machine (England)

The scale is broken by 2 pulleys in planes at right angles to one another. The first pulley drives a rotating drum which is either filled with granite or quartz chippings. A foam rubber pad or compressed air jet can be fitted to ensure the removal of fine scale and any dust from the chippings.

Mill descaling machine (Italy)

The scale is broken by two sets of three rollers at right angles to one another and the centre roll in each case in adjustable. The final stage consists of a steel wool wiping station.

Ratz descaling machine (Germany)

The scale is broken by conventional pulleys but the use of brushes and grit, etc., is avoided as the makers claim that these components tend to smooth the surface of the rod and hence adversely affect soap pick up. In this machine, the secondary descaling is achieved by vibrating the wire and passing it through a strong magnetic field.

Salvi descaling machine (Italy)

The scale is broken by five rollers mounted on a plate in one plane, the centre one being adjustable so that the degree of bending can be adjusted to suit various types of scale and sizes of rod. The final descaling is accomplished by two adjustable cylindrical brushes rotating in opposition to one another. They are applied to the wire alternately by means of a special planetary gear and rotate at high speed. A special soap box is used in conjunction with this machine and employs several small rollers to press the lurbricant on to the wire as it runs through the box into the die.

Wheelabrator mechanical cleaning process (U.S.A.)

A conventional staightening machine can be used to crack the scale in front of the shot blasting unit. Several high speed centrifugal blasting wheels are arranged in a cabinet in such a manner as to provide as wide a coverage of shot as possible. A typical single strand machine would employ three such wheels. These units can also be used on multi-strand work such as cleaning wire or rod from a multi-strand patenting furnace.

APPENDIX II

Because of the friable nature of the thin scales found on wire rod, a careful technique of mounting and polishing must be utilised in order to retain the scale.

Mounting the specimens under the normal thermal-pressure method tends to dislodge the oxides. Therefore, a liquid polyester resin is used as a mounting medium (Bakelite Polyester Resin S. R. 17497).

The specimen is dipped into a "hard" mixture of the resin. Due to its low surface tension, the plastic penetrates into all the cracks and cavities of the scale that are open to the atmosphere. After this initial coating has polymerised, the specimen is then embedded in another mixture of the same liquid resin, containing smaller proportions of catalyst and accelerator. This second bulk-coating of resin is made "softer", otherwise the volume change on polymerisation would initiate cracks throughout the hardened resin.

The mounted specimen is then left for 5 or 6 days to allow the plastic to harden fully. This time can be decreased by using slightly elevated temperatures.

A fine saw (No. 45 Eclipse) is used to cut the encased specimen. With care, very little disturbance of the scale occurs, thus necessitating a minimum of grinding.

If the examination of more than one cross-section is desired, the required pieces are mounted together in a cold-setting resin to give an overall shape satisfactory for handling and polishing.

The wet grinding treatment on an automatic polishing wheel, using SiC wet papers is as follows :

(*a*) 15 min. on a 240 grit paper,
(*b*) 15 min. on a 400 grit paper,
(*c*) 15 min. on a 500 grit paper,

The time at stage "a" might have to be increased if the depth of the disturbed scale due to the sectioning is excessive.

Hand polishing is used on wheels running at moderate speeds (500-600 ft/min. linear speed). The stages are :

(*d*) 2–10 min. with 8 micron diamond paste on cotton poplin.
(*e*) 2–10 min. with 1 micron diamond paste on metcloth.
(*f*) 2–10 min. with ¼ micron diamond paste on metcloth.

The specimen should be thoroughly washed between each grinding and polishing stage.