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Steelworks control of residuals

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[Plate 1]

B.S.C. Sheffield Division, Steelworks Group, is a major producer of engineering carbon and alloy steels from a cold metal charge. The continued recycling of material, together with the necessity for tight property and processing requirements, from considerations both of the end user and the internal works, has increased the demands for residual control while maintaining cost competitiveness.

The restrictions imposed on the steel works are discussed together with their implications to production practice and their effect on overall scrap usage. In this context, the development and application of a mathematical model to describe the mechanism of residual enrichment is outlined along with the resultant imposition on scrap charging practices for special carbon steel grades. The effect of restrictions of this type are related to the overall works' requirement and the benefits shown of using a least cost mix charging practice for the arc furnace. Some consideration is given to the practical application of such a procedure and the likely effect of future restrictions in residual element content on scrap requirement.

1. Introduction

Metallic elements that remain in the steel in small quantities after refining is complete, and which are not deliberately added to the steel, are defined as residuals; they are always present to some degree. Some elements like copper and tin remain because they cannot be preferentially oxidized with the use of normal steelmaking methods. Chromium, on the other hand, remains because total removal of this element is a costly and time-consuming operation.

Steel that is continually recycled between furnace and consumable product without dilution from low residual material will tend to show an ever-increasing level of residuals, arising from both the original residual content of the steel and from non-ferrous contamination. Such scrap material generally constitutes a high proportion (80–100 %) of the material charged cold to electric arc furnaces and, since the practice of cold charging has been in operation for many years, it can be appreciated that without adequate control this practice may lead to high residual levels.

The British Steel Corporation has the highest steel output of any Company in Western Europe, last year totalling 17.25 Mt. As such it is also the largest consumer of ferrous scrap in Western Europe. A large proportion of this scrap is used as the basis of the charge for the Corporation's electric arc furnaces which now produce 20 % of the steel output. The major electric arc steel producers within B.S.C. are the Steelworks Group of Sheffield Division where, in five electric arc melting shops, an output of 2.5 Mt was achieved in 1977 from 15 furnaces. With further electric arc furnaces to be commissioned in the Sheffield Division in the current year, it is clear that the available electric arc furnace capacity will increase.

Expanding this to a wider context, a recent European Coal and Steel Community Commission

(E.C.S.C.) report (1977) has shown that steel produced in electric arc furnaces will constitute an increased proportion of the total steelmaking capacity throughout the Common Market over the next few years (see table 1). This report on investment shows that electric steelmaking potential is expected to increase from 36 Mt in 1976 to 44.5 Mt in 1980, an average annual increase of 5.4 %. By 1980, therefore, electric arc steelmaking should account for 21 % of the Community production potential compared with 71 % oxygen steelmaking, 6 % open hearth and 2% basic Bessemer. The demand for scrap to satisfy this increased potential will, therefore, increase although this may be partly offset by the reduction in open hearth steelmaking, which is scrap intensive, and the availability of direct reduced material.

Table 1. E.C.S.C. steel production potential

(Megatonnes, figures in parentheses are percentages of the annual total.)

crude steel	1973	1976	1980
basic Bessemer	14.9 (8)	7.3 (4)	3.4 (2)
open hearth	28.9 (17)	20.4 (10)	11.9 (6)
electric arc	26.4 (15)	36.0 (18)	44.5 (21)
oxygen blown	104.3 (60)	134.0 (68)	154.1 (71)
total	**174.5** (**100**)	**197.7** (**100**)	**214.0** (**100**)

Additionally, as members of the E.C.S.C. the B.S.C. is subject to the terms of a free trading agreement which allows all member nations to compete for all available scrap. This means that scrap availability within the U.K. reflects the situation in the E.E.C. rather than purely the home demand. To maintain a consistent and acceptable product, Sheffield Steelworks Group recognize that increased controls have to be applied to the scrap charged to the arc furnaces in order that residual levels should not become excessive.

2. The need for residuals control

The primary elements that affect properties and performance in carbon steels are carbon, silicon, manganese, phosphorus and sulphur. For alloy grades the basic composition also contains controlled additions of chromium, molybdenum and nickel.

In carbon steels, copper and tin are the residual elements of major concern, while arsenic, antimony and cobalt may have significance in alloy steels. It is important to note that the presence of residual elements in steels may be beneficial or detrimental, depending on the particular end application.

There are two main reasons for residual control: (*a*) property requirements of customers; (*b*) processing requirements of customers and Steelworks Group rolling mills.

(*a*) *Property requirements*

The steels produced by Steelworks Group of Sheffield Division are mainly carbon and alloy steels for the forging, rerolling and bright drawing industry for applications in the automobile, aircraft, engineering and nuclear power industries. These are particularly demanding market sectors where analysis and property control are critical. There is much published work (Naylor *et al.* 1978) which describes the effect of residuals on carbon and alloy steel properties, namely machinability, hardenability and ductility. As a result of these known effects, restrictions are placed on the permitted levels of residual element content. National or international specifications quote maximum residual levels for engineering steels although these are generally broad based and in practice other controlling factors may also apply. There are numerous instances where additional customer restraints are imposed which may be technically based to ensure property achievement, or to ensure uniformity of supply from a number of sources, or they may be traditional.

By close technical liaison with the customer the least restrictive residual requirements can be specified, thereby helping to reduce the low residual order load on the steelplant and assisting the customer to reduce through costs. For certain demanding engineering applications, customer requirements are such that more analysis control is necessary during steel production. Thus further restrictions are imposed on the steelmaker either to minimize residual content, for example to improve ductility, in cold forming operations, or to work to tighter residual ranges consistent with the requirements of hardenability.

(*b*) *Processing requirements*

The main processing problem caused by the presence of residual elements in carbon and low alloy steels is that of hot shortness.

(i) *The mechanism*

Hot shortness results directly from the fact that residual elements more noble than iron, such as copper, tin, nickel and antimony, are not oxidized when steel is reheated. Consequently, as iron is removed preferentially from the surface layers, these residual elements enrich progress-

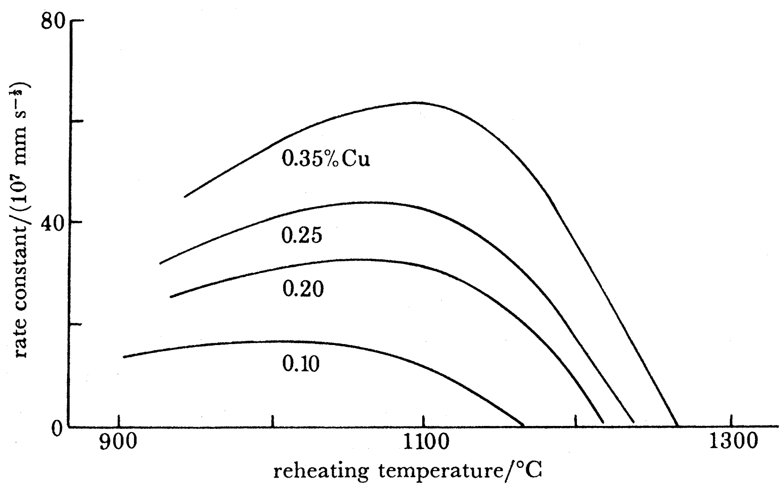

FIGURE 1. Calculated rate of formation of copper-rich phase, showing the effect of different initial copper levels.

ively in the subscale layer. Copper is the key element in this area since it can enrich to a level exceeding its solubility limit in austenite; without it, hot shortness does not occur. The rate of enrichment increases as the scaling rate increases with increasing temperature. However, enrichment of the surface by residual elements creates a concentration gradient between the surface and the bulk, down which the residual elements diffuse. Surface enrichment is further offset when enriched material is occluded into the scale by, for instance, preferential oxidation of the surrounding and underlying areas. This occlusion mechanism becomes increasingly important as the temperature increases. Depending upon the oxidation temperature and the initial residual element content, the rate of build-up due to oxidation may exceed the rate of dispersion due to both diffusion and occlusion, thereby causing surface enrichment (see figure 1).

If enrichment does occur and the solubility of copper in austenite is exceeded, copper rich phases, which are liquid at reheating temperatures, appear in the steel at the interface with the scale layer. The residual rich phases penetrate down the austenite grain boundaries (see figure 2, plate 1) giving rise to planes of weakness which can open during subsequent processing. This manifests itself in a number of forms during processing but is most frequently seen as surface break-up (see figure 3, plate 1). Although copper is the element which is of major concern, other elements such as tin, antimony and arsenic have been found to increase the susceptibility of steel to cracking during fabrication. Tin, antimony and, to a lesser extent, arsenic, reduce the solubility of copper in austenite and thus favour the formation of copper rich phases during reheating. These elements also dissolve in the copper rich phase and lower its melting point, thereby widening the temperature range over which cracking can occur. In contrast, nickel has been shown to have a beneficial effect since it increases the solubility of copper in austenite. In addition, the presence of nickel promotes occlusion of enriched material into the scale.

(ii) *Practical implications*

The degree of enrichment for a given steel depends on the reheating cycle, and the occurrence of hot shortness depends on the amount and rate of deformation. Therefore, the maximum tolerable residual levels of copper, tin, nickel, etc., to avoid hot shortness will vary from one rolling mill to another. This obviously applies to material supplied to external customers, both forgers and rerollers, and to the secondary processing mills within the Steelworks Group. There are numerous instances where restraints are imposed on the steel producer because the customer needs to ensure satisfactory hot working. In these cases, maximum copper and tin levels may be specified as a result of experience within the customer's own hot mills, although in some instances, as with property requirements, these limitations are traditional and may not be technically based. It is essential, therefore, that steel producers maintain a knowledge of customers' reheating conditions to ensure that hot shortness will not be a problem during hot working.

With a knowledge of these factors, attempts can be made to produce steels that have a residual element content particularly suited to a specific end application. Within the secondary processing mills of Steelworks Group, a knowledge of the metallurgical factors associated with hot shortness and its effect on hot working has made it possible to suggest practical measures to reduce enrichment effects. The alternatives available are: (i) produce low residual casts (total residual content less than 0.10 %); (ii) produce casts with a high residual nickel content; (iii) reduce scaling rates by furnace atmosphere control; (iv) minimize time at temperatures where enrichment is most rapid.

The production of low residual casts is neither economic nor feasible on a routine basis with a 100 % charge of purchased merchant scrap. However, if this were possible it would obviate the need for control. Higher residual nickel contents are generally unattainable without an increase in other residual element contents, and the specific addition of small quanities of nickel is uneconomic. In addition, the higher nickel levels may lead to difficulties in meeting property specifications. A slight reduction in scaling rate by furnace atmosphere control is feasible to some extent, although other practical limitations often mean that the overall effect is small. Of more practical use is the minimization of holding times in the temperature range where

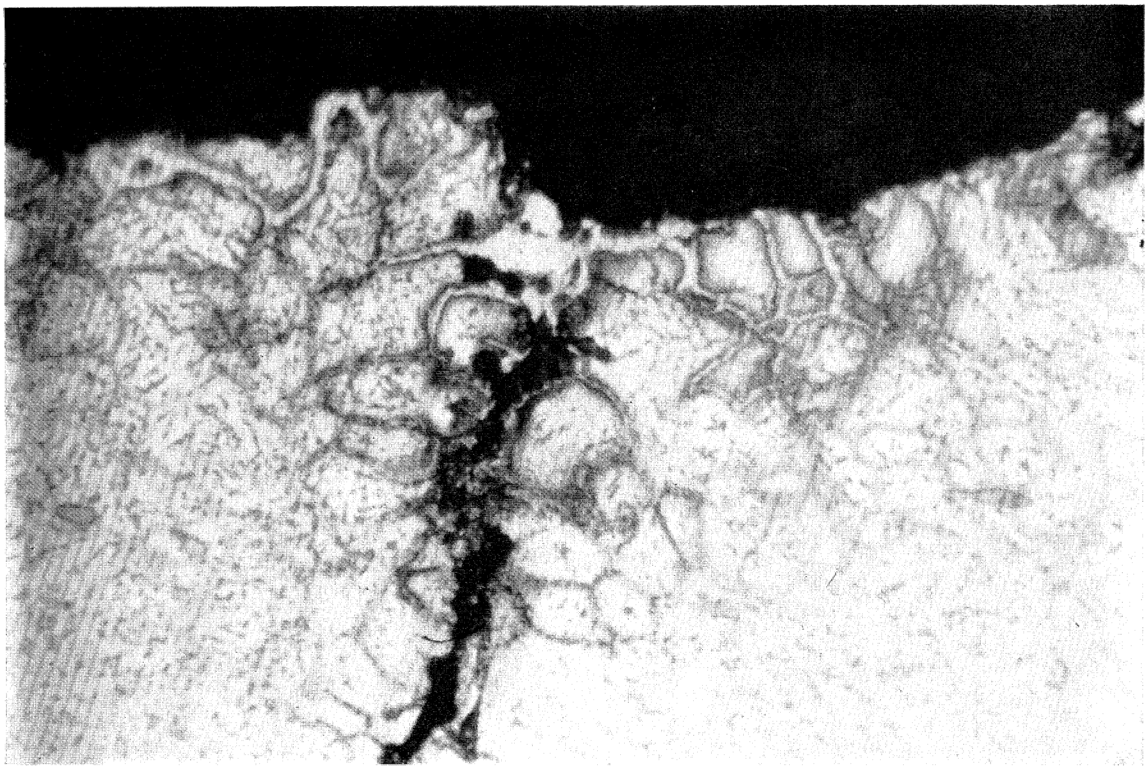

FIGURE 2. Photomicrograph of the surface of a reheated billet, showing penetration of residual-rich phase down austenite grain boundaries.

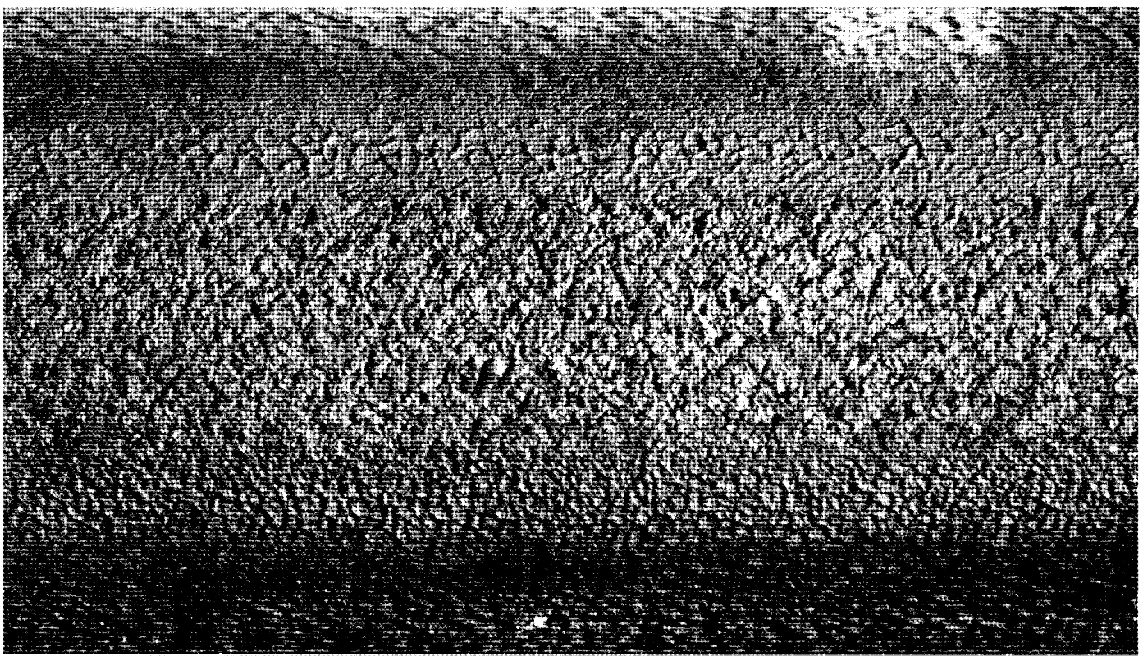

FIGURE 3. Surface break-up on a rolled bar resulting from surface residual enrichment.

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enrichment is most rapid (typically 1050–1150 °C). This forms an integral part of any reheating strategy.

(iii) *Mathematical model*

While residual element limits to minimize hot shortness problems have been established over a number of years both for customers and for secondary processing within the works, these rules have been based on empirical results. Consequently, these practices cannot predict accurately and rapidly the variations in the pattern of residual element enrichment which accompany changes in reheating practices. This factor became apparent during the modernization of the Roundwood 11 inch (28 cm) Continuous Bar Mill where major changes in reheating conditions were necessary to accommodate an increased furnace throughput rate resulting from the increased billet size (from approximately 0.5 t to 2 t). These changes of heating practice had to be incorporated into the standard process without major disruption of steelmaking requirements and without detriment to product quality.

A similar situation arose when the Brinsworth strip mill at Rotherham Works opened some years ago. In this case, residual enrichment produced defects that were clearly visible on the surface of the strip. At that time, a computer model was constructed (Hewitt & Meadows 1968) which was based on an analytical solution of the relations involved in the mechanism of residual enrichment. This model produced results which explained practical observations but did not take account of the effect of nickel or the effect of occlusion at high temperatures. In order to allow the method to be used for more varied situations with increased accuracy and incorporating more up-to-date data on occlusion and the solubility of residual elements in iron, the model has been further developed and is now capable of quantifying the degree of enrichment under all reheating conditions.

The revised model is based on numerical methods and uses an iterative method to calculate the amount of enrichment due to scaling. Allowance is made for the effects of occlusion and diffusion and, in the latter case, a finite difference method is used to solve the diffusion equations. The model takes into account the effect of copper, tin and nickel on surface enrichment since, as explained previously, all these elements can have a pronounced effect on the severity of cracking in hot shortness. Considerable effort has been expended to test the validity of this approach in the laboratory, and works trials have just commenced on one of the bar mills within the Steelworks Group. It is possible by using the model to establish the calculated amount of enrichment occurring during reheating which could produce break-up. By knowing this level, the method can be used to examine the maximum residual levels that can be tolerated during normal processing and to determine the optimum reheating practice for delay situations such that hot shortness is not encountered.

3. Achieving control of residual elements

To achieve the required control of residual elements at the source of production, the steelmaking furnace, can be an extremely demanding problem. In basic oxygen steelmaking, the high input of low residual blast furnace hot metal, at a level of at least 65 % of the total charge, ensures low and consistent residual levels in the final steel with little need for complex control procedures. By contrast, the electric arc furnace usually operates with a 80–100 % cold scrap charge comprising blends of merchant and own-arising material. In Sheffield Division the balance of the charge is usually cold blast furnace iron. In the development of continuous charging to the electric arc furnace up to 40 % of the charge may be granulated blast furnace iron or reduced material (or a blend of these), providing a considerable diluting effect on steel residual levels.

In a plant using a total cold metal charge, the own-arising scrap consists mainly of discards taken from primary and secondary processing areas, has a broadly known residual level and is easily segregated. However, this own-arising scrap is not as low in residual element content as blast furnace iron or scrap from basic oxygen steelmaking plant.

In order to rationalize the numerous residual limits imposed by customers, the melting shops of Sheffield Steelworks Group employ working rules governing the scrap mixtures necessary to meet specification requirements. These rules differ between melting shops depending on the individual markets and circumstances. For example, the working rules relating to carbon steel production differ from those governing scrap mixtures for alloy steels. In general, the most demanding residual specification requires a furnace charge of almost 100 % low residual material. This is provided by a mixture of blast furnace iron and merchant low residual scrap. The least demanding specification, however, can normally be met without the use of any low residual material.

(*a*) *Trends in residual levels*

Figure 4 shows the manner in which residual element levels at Templeborough melting shop have risen over the past 60 years.

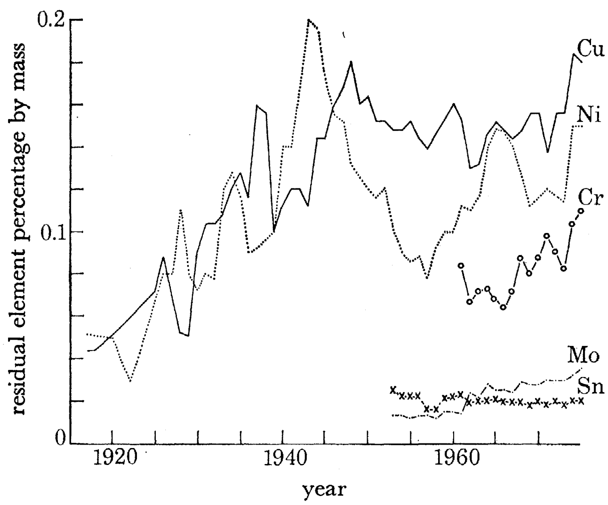

FIGURE 4. Residual element trends in Templeborough Melting Shop, 1920–75.

Many factors affect the variations in residual element levels shown in this figure, but a large influence is the quality and availability of the basic steelmaking raw materials. Experience over recent years has shown that at a time of high demand for steel a general increase in steel residual content is observed. This effect is shown in figure 5 which demonstrates the upward trend in residual levels over a period where steel demand from Templeborough was high.

The average usage of low residual material (including iron) over the four financial years shown was constant at 40 %. In fact, the proportion of cold blast furnace iron in the total low residual category had increased from 6 to 16 % during this period, thus increasing its dilution capacity in residual terms. The increase in residual levels shown in figure 5 was due to the general scrap shortage which created a decline in the quality of merchant basic scraps and a decrease in the availability of merchant low residual material. The increased usage of cold blast furnace iron was aimed at remedying this situation. However, the use of blast furnace iron in this way is a relatively expensive way of ensuring the attainment of particular residual levels and does not allow an optimum balance of resources and end user requirements.

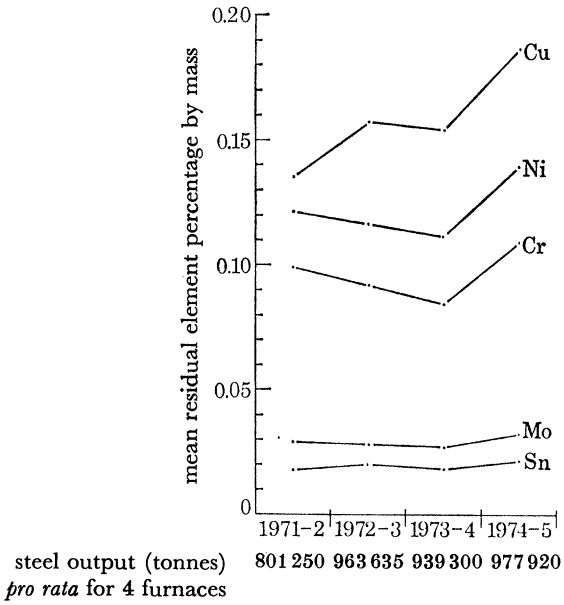

FIGURE 5. The effect of increased steel demand on mean residual element content at constant low residual material usage.

(*b*) *Assessment of scrap quality*

It should be clear from these comments that within Sheffield Steelworks Group a systematic effort is made to make the best and most economic use of the available scrap, and the quality control of scrap has become of major importance. From a practical viewpoint, however, this is a complex problem. For example, Templeborough melting shop produces approximately 26 000 t of steel per week from four arc furnaces at normal activity levels. To maintain this production rate, it is therefore desirable to maintain reserve scrap stocks at approximately 200 000 t. These stocks are kept in segregated areas and the quality of each incoming batch of scrap must be known. All scrap deliveries are scrutinized by examiners to the extent that the uppermost layers in wagons or on lorries will be removed, and some loads tipped onto a prepared surface for examination. In addition, random analysis checks may be made particularly on low-residual material, or trial melts may be carried out comprising solely the scrap under investigation.

A combined effort by Steelworks Group and Sheffield Research Laboratories has been directed towards assessing scrap quality. Many melt tests have been carried out both on a laboratory furnace scale and a production scale to establish the range of yields and residual analyses that could be expected from many types of merchant scrap. The various categories of scrap assessed, together with typical residual analyses of the particular varieties are shown in table 2.

Internally arising scrap, merchant new production scrap and certain heavy merchant scraps (for example from rails or shipbreaking) are of an approximately known residual level. The residual problem arises from the lower grades of merchant scrap (e.g. fragmented scrap, pressed or sheared scrap, basic turnings, no. 5 bales), since it is within this group of materials that the greatest variation in residual element content is observed. It should be noted that the data in table 2 are mean analyses and that in the lower grade materials variations of ± 40 % on this mean have been obtained. These low grades of scrap are derived from consumer durables, scrap cars, etc., and contain the main non-ferrous contaminants, copper and tin. The copper arises from electrical components, wiring and pipework, while the tin is present in cans, boxes, solders and enamels. Almost all of the copper and tin is recovered in the steel during steelmaking. Basic turnings can be a mixture of carbon, alloy and free-cutting steels and hence their composition is variable and residual levels may be high. These residual levels may be to the advantage of the alloy steelmaker but not to the special carbon steel manufacturer.

Table 2. Mean melt analyses for various scrap types

(Figures are residual element analyses; percentages by mass.)

scrap type	Cr	Mo	Ni	Cu	Sn
mixed low residual	0.03	0.01	0.04	0.06	0.007
no. 4 bales	0.03	0.02	0.08	0.08	0.009
new production scrap	0.11	0.05	0.11	0.13	0.014
heavy basic scrap	0.11	0.05	0.15	0.25	0.025
fragmented scrap	0.08	0.02	0.14	0.26	0.036
pressed or sheared scrap	0.13	0.03	0.18	0.51	0.049
no. 5 bales	0.13	0.02	0.16	0.68	0.073
basic turnings	0.53	0.10	0.42	0.38	0.032
plate iron	0.02	0.015	0.015	0.011	0.005

Particular interest has arisen in the lower qualities of material originating from consumer durables and scrap cars, particularly in view of the proliferation of shredder plants installed in the U.K. since 1968, and the increasing tendency towards investment in processing plant such as balers and shear balers by the scrap industry. The product from shredder plants is of interest to Steelworks Group since the size range after screening is particularly suited to the new development of continuous feeding to arc furnaces although it also exhibits a high variability in residual content. It is apparent, therefore, that without control of the proportions of each scrap type charged to the furnace, the production of a consistent product capable of meeting customer property and processing requirements would be fortuitous.

(c) *Least through cost mix model*

In conjunction with the work on scrap quality, a computer based 'least through cost mix' model (l.t.c.m.) has been developed at Sheffield Research Laboratories. This model may be used to find the best combination of all the available grades of material that will have a chosen probability of meeting a given residual specification. In choosing the optimum mix, the model takes account of the price of each raw material, its estimated residual analysis range, the metallic yield on melting the different scrap types and the cost of processing the non-metallic or 'gangue' content of each material offered for selection. Constraints can be applied to the amount of each scrap grade used, and thus restricted availability or any other limitation on the use of any type of scrap can be accommodated.

The variability of residual content is important, particularly in the low grade materials and this is the reason for adopting an optimization technique in the model, which involves a probability approach to meeting residual specifications. As work on scrap quality progressed, it became apparent that the level of some residual elements in certain scrap types followed a skew distribution (see figure 6) and appropriate modifications were incorporated into the computer program.

Trial casts of carbon steels with the use of mixes produced by the model have been made at two melting shops in the Sheffield Steelworks Group, 41 casts at Templeborough and 148 casts at Aldwarke. The trials were a success in terms of achieving reductions in raw material costs without deleterious effects on processing costs or output rates, and the success rate achieved was close to that predicted by the model. Copper was the controlling residual element in most casts, with the other residual elements normally falling well within specification. This is in line with historical works experience, since the most common reason for casts exceeding the residual specification is the copper content.

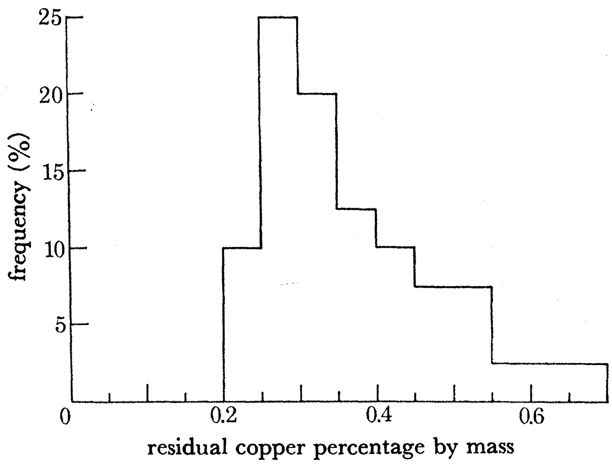

FIGURE 6. Distribution of residual copper level in batches of basic turnings.

Perhaps surprisingly, the model tended to specify certain low grade materials in quantities that would not normally have been used. Although obviously of benefit from a cost point of view, these materials are particularly unappealing to the steelmaker because of their low yield, high non-metallic content, and high residual content. Their use did pose certain handling problems because of their low density and, in some cases, was responsible for high sulphur levels in the melt, which the model had not allowed for. However, on balance, the incorporation of these materials into the charge mix in strictly controlled quantities was found to be economically advantageous, indicating the usefulness of the l.t.c.m. approach as an aid to the steelmaker.

(*d*) *Value in use assessment*

Complementary to the l.t.c.m. model is a value in use (v.i.u.) model which aims at providing a measure of the value of a scrap type to the arc furnace steelmaker. As in the least through cost model, the factors that affect this value are the residual element analysis of the material, its gangue content, the yield loss that occurs on melting, together with any special factors that may apply, such as density and suitability for continuous feeding. The predominant factor is usually residual element analysis since this determines the level of dilution required from expensive low residual material in the arc furnace charge mix.

For any prevailing scrap price situation, it is possible to provide a ranking order of scrap value which may be considered when scrap purchases are made. Ultimately, of course, commercial judgement will prevail when deciding how much of a particular material to buy at a particular time.

A further application of the value in use model is in indicating the value of new materials which may appear on the market, an example of current interest being hot briquetted steel turnings.

Both types of model illustrate the considerable effort being made to obtain the optimum economic benefit from the use of the raw materials available to the arc furnace steelmaker. The information on scrap characteristics, both chemical and physical, is still being collected for quality assessment purposes and for use in the two mathematical models. In addition, techniques are being developed to sort and separate certain types of scrap into their component parts at the point of delivery so that rapid quality checks can be made on incoming material.

4. Future trends in residuals

It is extremely difficult to assess the future residual requirements in terms of the pressures that will be imposed upon the steel producer from the user market. However, some conclusions can be drawn from the trends observed in the last few years. As engineering expertise and technology advance, there is a continual market requirement for consistency of product. This arises so that tighter specifications can be met and also for ease of production, possibly associated with the installation of fully or semi-automated techniques. In these cases, identical material response is essential both for processing and for consistent property attainment after treatment.

A particular area where tight control has been imposed over the last few years is the cold forging industry. Steels suitable for processing in this manner require high levels of ductility and consistency, and the residual content therefore needs to be controlled to low and restrictive levels. However, it is reasonable to assume that innovations in the next few years will require tighter internal control of scrap and also possibly better quality scrap.

There is at present no comprehensive statistical information on expected residual trends for scraps. However, certain comments on future trends can be made in the light of experience. With structural changes in U.K. industries during the 1960s and early 1970s, the availability of certain scrap types has been influenced by scrap yields from railways, coal mines, textile and machine tool industries and the electricity generating stations. Such changes were a 'one-off' phenomenon and increased the availability of certain heavy types of scrap during the period. Much of the replacement structures involved in these areas will not, owing to technological changes (such as the use of reinforced concrete) yield the same quality and tonnage of scrap in the future.

The lighter scrap from domestic sources, on the other hand, has become more readily available with increasing consumption of consumer durables. It is these materials that require upgrading in order to release their ferrous content for steelmaking use, otherwise their consumption in electric arc furnaces must be very strictly controlled to avoid future upward movements in steel residual levels. The growth in fragmentation plant capacity over the last 10 years

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is an example of the response by the scrap industry to this demand. A further factor influencing residual contents may be the reduced availability of own-arising scrap and scrap from steel users as technological improvements in processes lead to reduced yield losses. This is exemplified by increased usage of continous casting. The E.C.S.C. estimate that the capacity of continuous casting plant will increase from 42.6 Mt in 1976 to 57.7 Mt in 1980. This is an increase from 22 to 27 % of maximum possible crude steel production and is not dissimilar to world estimates that 33 % of production will be by continuous casting by 1980. While savings by continuous casting effectively result in increased production capacity, they also result in a decrease in the production of internally arising scrap. The total scrap arising from a particular cast using an ingot production route can be as much as 20 % and this can be halved by continuous casting. There will be a resultant increased demand on merchant material to make up the shortfall brought about by yield improvements, with a concomitant increase in steel residual levels. It is possible that this effect may be balanced by the development of continuous charging to electric arc furnaces, which use granulated blast furnace iron and direct reduced iron, both of which are low residual materials. Prediction of the overall result, however, is still not possible and the outcome will depend on the demands of the end user market.

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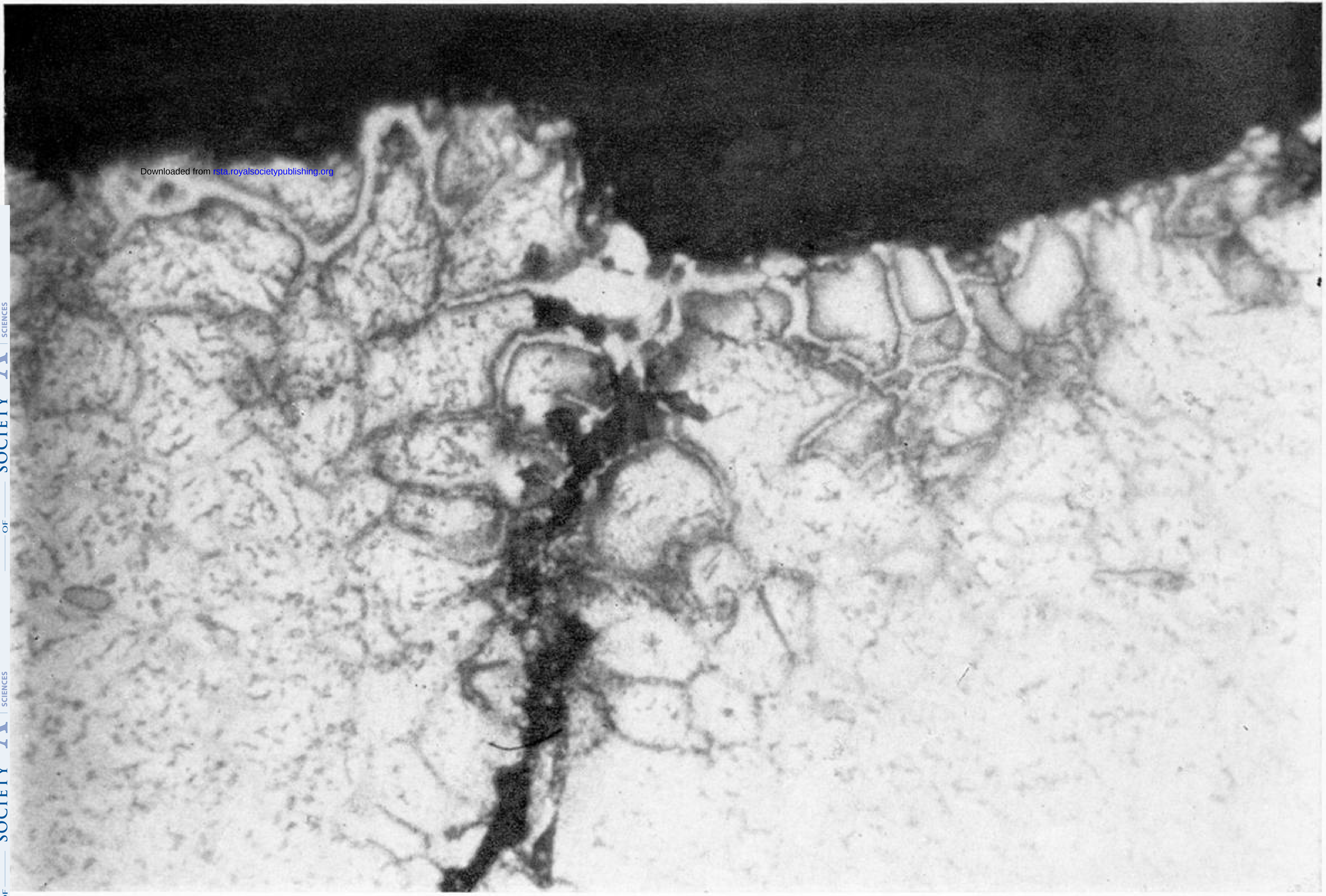

FIGURE 2. Photomicrograph of the surface of a reheated billet, showing penetration of residual-rich phase down austenite grain boundaries.

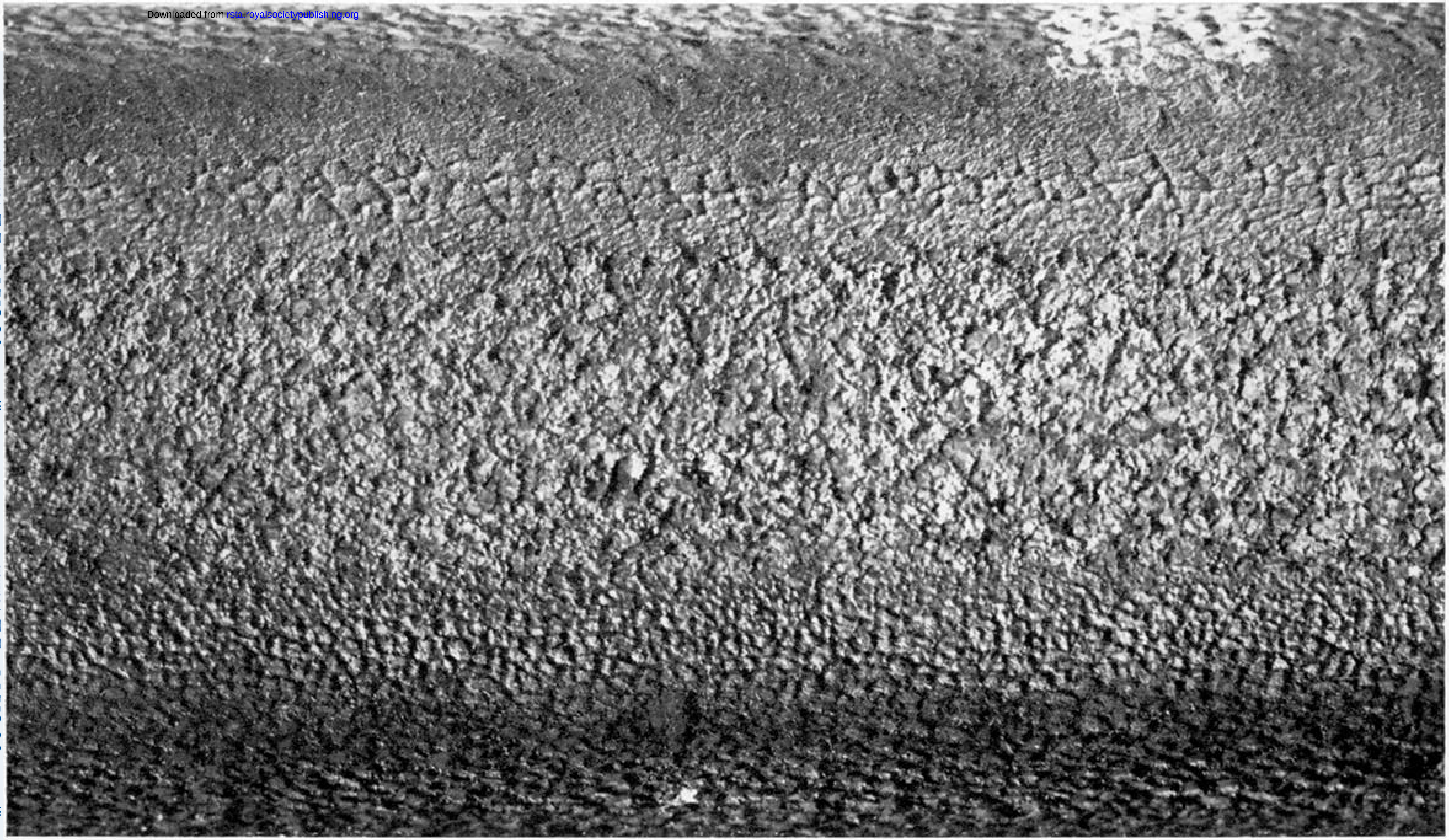

FIGURE 3. Surface break-up on a rolled bar resulting from surface residual enrichment.

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