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# Failure analysis of free–cutting grade steels: A case study

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## ABSTRACT

*Microsegregation, which is unavoidable during solidification, needs to be controlled as it causes a number of failures during hot working for producing semi-finished/finished products and subsequent cold-working to produce the finished products. The present work is aimed at achieving just the same, in free-cutting grade steels, by gaining a better understanding of the relative stability of different sulphide inclusions. FeS or Fe-rich (Fe, Mn)S inclusions are undesirable in free–cutting grade steels as their melting points are below 1000°C. They lead to hot-shortness and grain-boundary cracking during hot rolling and need to be transferred to beneficial MnS or Mn-rich (Mn, Fe)S which have higher melting points. In the present work, microstructural characterization by optical and scanning electron microscopy followed by XRD was carried out to identify the phases present in the as-cast and heat treated billets obtained through continuous casting. Hot rolled wire rods, of 7mm diameter, which exhibited surface imperfections were also examined to understand the cause of failure. Microstructural studies of the as cast billets confirm the presence of deleterious Fe-rich (Fe, Mn)S inclusions on the grain boundaries. In the heat treated billets, however, these deleterious sulphides were found to be present only in the central region. Regions away from the centre of the billet, showed the presence of stable Mn-rich (Mn, Fe)S on the grain boundary instead of the unstable Fe-rich (Fe, Mn)S. Therefore, it was concluded that the transformation of the Fe-rich ternary phase to a more stable Mn-rich ternary phase was not complete in the central region of the billet due to insufficient heat treatment. Also proposed are alternative soaking time and temperature to facilitate the complete transformation and improve the quality of the rolled products.*

## INTRODUCTION

Steels differ considerably in the ease with which they can be hot worked. In general, the higher the alloy content of a steel, the lower will be its hot workability as evidenced, for example, by the greater difficulty experienced in rolling stainless steels and high-alloy steels compared with plain-C and low-alloy steels. Howeve there are exceptions to this general rule, and one has to consider the specific effect of each alloying element. Since very small quantities of certain elements can resul in a marked change in hot workability, as well as machinability.

## Machinability

Machinability is defined as the quality or state of being machinable, or capabl of more suitable for being machined. Machinability is a commonly used but ofte misunderstood term that refers to the machining response of a material in terms o the state of the machined surface, the rate of material removal, the ease of chi disposal, and the duration of tool life. As such, machinability is not analogous t material properties such as hardness or tensile strength. Machinability means (a improved surface finish (b) reduced tool wear (c) reduced cutting forces (d) mor favourable chip formation. Addition of low melting point inclusions to ferrous an non ferrous alloys markedly improves their machinability. Improved machinabilit comes from melting of the inclusions at the workpiece - tool interface durin machining and the molten metals act as a lubricant reducing friction and adheranc between the tool and chip.

Machinability is an important stage in the production of most engineerin components and, in many automotive transmission parts, machining can accoun for up to 60% of the total production. The common machining processes includ turning, milling, grinding, drilling and braching and several of these operation might be carried out on an automatic lathe in the production of a single component Each of these processes differs in terms of the metal cutting action and involve different conditions of temperature, strain rate and chip formation. Therefore th machining performance of a steel cannot be defined by means of a single paramete However, some of the features that are often involved as measures of machinabilit are tool life, production rate (e.g. components/hour), power consumption, surfac finish of component, chip form and ease of swarf (chip) removal.

## Machinability Testing

A widely adopted laboratory test for machinability is the "Taylor Tool Lif Test", in which the life of the tool is determined at various cutting speeds. In eac of the laboratory tests for machinability, rigorous attention must be given t maintaining standard characteristics in the cutting tools in terms of grade, hardnes and tool geometry.

## Free-Cutting Steels– Machinable Steels

Over a period of many years, steel producers have conducted intensive researc programs to develop steels having improved machinability. The above effort has resulted in the production of low-C-free-cutting steels-containing sulphur or sulphur and lead or sulphur, lead and other additives. These steels are utilized extensively for the production of a wide variety of parts in automatic screw machines operating at high production rates.

## *Low-carbon free-machining steels*

1. Resulphurized steels (these steels are most commonly used).
2. Leaded resulphurized steels (they provide superior machinability for a relatively small increase in price, so they are also widely used).
3. Leaded resulphurized steel with special additives (they are more recent and are designed for higher level of machinability).

*Free-cutting steels for machining : chemical composition (%)*

| | C | Si | Mn | S | P |
|---|---|---|---|---|---|
| En 1A | 0.07–0.15 | 0.10 max. | 0.80–1.20 | 0.20–0.30 | 0.07 max. |
| En 1B | 0.07–0.15 | 0.10 max. | 1.00–1.40 | 0.30–0.60 | 0.06 max. |

The old En numbering system which became established after World War II has now been withdrawn. Free-cutting steels are also known as machinable steels and in these steels, the first 3 digits are in the range 200-240.

## *Applications*

Free-cutting steels are suitable for applications where good machinability is the prime consideration. They are therefore used for rapid production on single or multiple spindle automatic lathes and capstan lathes of finely finished components which will not be subjected to high stress in service, e.g., light duty studs, cycle components and many intricate parts for textile and printing machinery.

This type of steel cannot be relied upon to posses good transverse properties and should not be used for hollow parts which might be subjected to an internal pressure which would set up wall stresses dangerously near to the transverse yield stress. These steels are most widely used in the screw machine industry.

## *Machinability*

En 1A steel can be machined at rates over twice those used for normal mild steel (En 3). En1B has even better machinability and can be machined at rates approximately 50% more than those used for En 1A.

*Hot working and heat treatment temperatures generally adopted for free-cutting steels.:*

| | | | |
|---|---|---|---|
| Forging, rolling and stamping | : | 1250°C finish above 900° | |
| Annealing | : | 880-950°C | F/C |
| Normalizing | : | 880-950°C | A/C |

## Roll of Free–Cutting Additives

Various elements are added to steel in order to improve the machinin performance.

### Sulphur

Sulphur is very effective and cheap and therefore, it is most widely used additiv in steel. In most of the engineering steels, the 'S' content is restricted to 0.05 max. but in these free-cutting steels, up to 0.35% S is added deliberately for th purpose of improving machinability. This effect is most often seen in terms higher allowable machining speeds for any given value of tool life. Steel is usuall resulphurized by adding 'S' to the molten steel during tapping of the heat into th ladle. Sulphur may have a beneficial effect on the quality of some steels in that tends to suppress the evolution of carbon monoxide. Thus, 'S' acts somewhat as 'Killing" agent and reduces the tendency for 'blow holes' to form during solidificatio of the low-C free machining steels. In these steels, sulphur forms required volum fraction of sulphide inclusions and enough Mn is added (upto 1% or more) ensure that all these sulphides are MnS.

### Manganese

In commercial resulphurized steels manganese (upto 1% or more) is added counteract the hot shortness effect of sulphur and in there steels, the sulphur present mainly as (Mn, Fe)S inclusions, the Fe content of which is about 2–5%.

### Lead

After sulphur, lead is the most common additive and additions of 0.15–0.35 lead are incorporated in free cutting steels. Such levels are soluble in molten stee but are precipitated as discrete particles of lead during solidification. Due to i high density, major precautions have to be taken in the production of leaded steel in order to avoid segregation effects. Again lead reduces the frictional effects at th tool-chip interface, where it becomes molten at the elevated temperatures generate during cutting. Lead is also thought to have an embrittling effect in the primar shear zone, thereby shortening the chips and improving surface finish. The lea particles are often present as tails to the MnS inclusions.

Lead is basically added to these low-C-free cutting steels in order to achieve high level of machinability. For example, those couplings and automotive spark plug bodies are examples of such components which are mass produced at high machining rates. Substantial improvements in machinability are achieved by addition of Pb upto 0.25%. Lead has little effect on the mechanical properties of steels at ambient temperature since it is generally present as a globular constituent.

*Liquid Metal Induced Embrittlement (LMIE)*

LMIE refers to the loss of ductility of normally ductile metals and alloys when stressed to produce plastic deformation whilst in contact with a liquid metal. Although this phenomenon known to occur since 1874, it has not been as extensively investigated as other more common forms of environmental fracture, such as hydrogen embrittlement, temper embrittlement and stress corrosion cracking. As a consequence, it has remained an unfamiliar failure mechanism for many materials engineers and LMIE failures are still often encountered in practice.

*Conditions for LMIE*

1. The metals involved do not form stable high-melting intermetallic compounds.
2. The metals have no significant mutual solubility
3. The surface of the solid metal must be wettable by the lqiuid metal.

LMIE : cracking originates at the solid-liquid metal interface which in some cases may be internal (e.g., in high machinability alloys which has low melting point inclusions).

Low melting point inclusions such as lead and bismuth have been used to improve the machinability of both ferrous and non-ferrous alloys. This has been achieved without any deleterious effects on the room temperature mechanical proprieties of these materials. The mechanism by which these inclusions improve machinability is LMIE and in this connection, LMIE can be regarded as technologically useful.

Under certain cutting conditions, the temperature in the secondary deformation/ shear zone may be high enough to melt the free machining additives to form a viscous film between the cutting tool and the steel, thus reducing the friction. Therefore faster feeds and speeds are possible when leaded carbon steels are used instead of the standard grades. Surface finish is also generally better for leaded free-machining steels than for the standard steels. Traditionally, ingot-teemed steel with high oxygen content (200 to 300 ppm) promoted globular MnS + Pb inclusions and produced the best machining of UNS G12L140 grade.

## Other Elements (Trace Elements)

In order to achieve the optimum hardness, residual elements such as Cr, Ni an Cu need to the controlled, because hardness of low-c-free cutting steels is importan and the effect appears to be associated with the achievement of an optimu embrittling effect for chip formation. There is a compromise in these steels betwee hardness and the machinability. Also, phosphorus and nitrogen are added i achieving the desired embrittlement effects. Above the critical hardness level embrittlement and ease of chip formation give way to increased abrasion and reduce tool life.

### *Carbon*

Whereas AISI and SAE specifications permit 'C' contents as high as 0.13% i resulphurized, low-c, phosphorus bearing steels, most of these steels are currentl made to 'C' levels slightly below 0.10% this is because above and below this value the machinability index decreases.

In addition to increased machinability, maintaining low-c-contents improve the performance of partssubjected to cold-working operations such as crimping. I some applications, good cold working performance is as important a requiremen as good machining performance.

### *Silicon*

Silicon, even in minute amounts, has a very detrimental effect on th machinability of steel under consideration. Silicon impairs machinability in tw ways (1) When it is present as abrasive silicate inclusions or stringers, tool life i drastically reduced, (2) Silicon influences the shape of MnS inclusions, as the silico content is increased, the proportion of desirable globular sulphides decrease, fo e.g. from 0.004% Si to 0.044% Si, the machinability index dropped from 177 t 101. Silicon in added in the form of Fe-Si. That's why, the free-machining steel were developed keeping silicon and carbon very low because these two element have large adverse effect (even when they are present in minute amounts) o machinability.

Because of adverse effects of silicon on sulphide morphology it is believed t be related to the deoxidizing effect of silicon because it reduces the oxygen conten like any other deoxidizers, steel making practices are managed in such a way tha silicon levels in the low-carbon free-machining steel is maintained uniformly at a absolute minimum. Therefore low silicon Fe-Mn is used for this purpose.

*Oxygen*

Sulphide inclusion characteristics are affected by the oxygen levels of the steel. Oxygen promotes the formation of sulphides exhibiting the desired globularity. The machinability also increases as oxygen to sulphur ratio increases.

## Formation of MnS Inclusions

This is a very important chemical aspect of solidification of steel which indicates the formation and distribution of sulphide inclusions (MnS) in the casting. If sufficient equilibrium data is available, it is possible to estimate the manganese and sulphur concentrations in the enriched interdendritic region required for the formation of MnS during freezing. In the case of the Mn-steels, MnS begins to form after about 94% solidification and almost all the 'S' is precipitated in the interdendritic regions of the casting. Upon reaustenitizing a casting by heat treatment, these sulphide bearing interdendritic regoins become the grain boundaries in the steel. Some investigated the solubility of MnS in Fe-Mn-S alloys at 1200°C and 1335°C. It is also to be noted that MnS inclusions in steel may act as markers delineating the position of the interdendritic liquid which is last to freeze. Since 'S' in solution in austenite at the solidus temperature is expected to be small, e.g. ~0.002%, the amount of sulphide inclusions formed during subsequent cooling of the solidified steel will be small in comparison to those formed from the liquid in the last stages of freezing.

While studying microsegregation in steel it was informed that the sulphide inclusions appear as a network and often have a eutectic-like grouping. This, plus the tendency for shrinkage cavities to be associated with them, indicates that they are formed in enriched liquid during final solidification. It is also possible that some of the smaller particles in linear arrays may have formed during cooling after solidification. However, as pointed out earlier, the amount of MnS formed in the solid steel with decreasing temperature is expected to be small. Based on the chemical aspects of **microsegregation**, that in, steels containing Mn and S, most of the sulphide inclusions as Mn (Fe)S form in the enriched dendritic liquid at the last stages of freezing.

## Morphology of MnS

The great majority of sulphide inclusions in steel are of the α–MnS type. This phase is cubic. The amount of oxygen in solution in liquid steel can cause a change in solubility of the sulphide which in turn has a marked effect upon the distribution of the MnS in the steel after solidification. MnS inclusions were classified according to three types : I, II and III, which form as the result of different steel deoxidation practices.

***Type I:*** form as isolated globular particles and have the highest oxygen content This arises because the inclusions are precipitated from the solidifying steel a globular of liquid rich in 'S' and $O_2$ by a monotectic reaction. MnS inclusions occu in a wide range of sizes in close proximity. This reflects their formation over a extensive temperature range during solidification of the steel. The largest one th first to form and since they contain the highest concentration of $O_2$ they occur a duplex inclusions, the MnS being associated with large proportiions of a MnO MnS eutectic phase. The smallest inclusions are the last to be precipitated and ar usually wholly MnS. These are found in non-killed or semi-killed plain carbo steels and are generally conceded to be the most desirable form of sulfide fo improving machinability.

***Type II:*** appears as a eutectic distributed in grain boundaries. Traditionall type II MnS were thought to be formed simply as a eutectic between iron and MnS However, it has now been suggested that they are a co-operative monotectic due t the melting point of the sulphide being depressed by the presence of iron and othe elements in solution. They are formed in fully-killed steels as rod-like networks o MnS in the interdendritic spaces. During hot working of the steel, these sulfide have a high ductility and deform with the matrix to form the long thin string sulfides commonly associated with fine grain steels. They also improv machinability but not like Type I.

***Type III:*** appear as idiomorphic and have the lowest oxygen content (irregula angular inclusions. They occur as perfect octahedra. The angular morpholog indicates that they are precipitated as a solid from the molten steel and they ar simply pro-eutectic constituent. They are found in fully-killed steels with ver high aluminium contents. Since most steels produced for machining application are not made with large Al additions, the effect of type III sulfides on machinabilit was not extensively studied.

## Role of MnS On Machinability and Chip Formation

The role that MnS play in improving the machinability is related to their effec on chip formation. It is generally agreed that the MnS inclusions act as stress raiser in the machining shear zone to initiate cracks that subsequently lead to fracture o the chip. Thus, the chip breakability is improved as the volume fraction of MnS i increased. For optimum machinability then, it is important to control th thermodynamic conditions to avoid solution hardening of the sulfide, morphologica features are also important with a large globular sulfide preferred. This is readil achieved with MnS by controlling melting practice and maintaining low silico content to produce a high steel oxygen sulfur ratio. Finally, steels with large amount of MnS have a large number of softer particles available for microcrackin and this enhances machinability, whereas abrasive oxide inclusions are detrimental.

The MnS inclusions deform plastically during chip formation into planes of low strength which facilitate deformation in the primary shear zone, generally the greatest portion of the heat is carried away by the chip by the low-interfacial energy between the sulfide particle and the ferrite matrix. Therefore, low strain rates are required to initiate microvoids at the MnS particle–matrix interface. During the high strain of turning they continue to grow and coalesce into microcracks, thus the cutting forces are drastically reduced. The MnS inclusions also exude into the tool-chip interface, acting as a lubricant and also forming a protective deposit on the tool. The effect is a reduction in cutting forces and temperatures and substantial reduction in the tool wear rate.

The tool wear rate decreases as increase of volume fraction of MnS inclusions. (atleast the volume fraction greater than 1.5%). It further increases as 'S' increase further, and also machining performance is far more effective if large globular inclusions present than elongated inclusions.

**FeS Inclusions**

Of the different iron sulfides, only the hexagonal troilite type, FeS, has been indentified as an inclusion phase. This phase is disastrous to the steel and its precipitation in modern steels is avoided by manganese additions. In the solidification of low-c-steels, there is first formed a mixed sulfide with a high Fe content, quite often even separate FeS phase. By rapid cooling of the steel after solidification, sulfides rich in Fe are retained. Practically, Fe-rich sulfides would be expected in steel castings and generally in steels, made in small ingots or continuous casting and not properly heat treated prior to rolling.

FeS inclusions generally present in the grain boundaries, so, offers a large area of contact towards ferrite and they not only form as a slag inclusion but also as a solid solution in the ferrite. The effect of FeS is greater because (1) higher solubility of FeS in the matrix of steel (2) the higher electrical conductivity of FeS.

**Surface Imperfections**

Most carbon steel and alloy steel hot rolled bars and shapes contain surface imperfections with varying degree of severity. In virtually all cases, these defects are undesirable and may in some applications affect the integrity of the finished product. Currently it is not technically feasible to produce defect-free hot rolled bars. With the current demand for high-quality bar products, it is becoming increasingly common to subject hot-rolled bars to a cold finishing operation, such as turning or grinding, coupled with a sensitive electronic inspection. With the process route, it becomes possible to significantly reduce both the frequency ar the severity of surface defects.

Seams, laps and slivers are probably the most common defects in the hot-rolle bars and shapes. Although there is no specific metallographic definition of sliver metallographic examination can be used to determine the origin of these defects

Experience has shown that when purchasers order hot-rolled or heat-treate bars that are to be machined, it is advisable for the purchaser to make adequat allowance for the removal of surface imperfections and to specify the size accordingly. Hot-rolled low-carbon and medium-carbon steel bars and shapes ar often used in the as-rolled condition.

### *Slivers*

Any imperfection consisting of a very thin elongated piece of metal attache by only one end to the parent metal into whose surface it has been worked. The are sharp pointed projections of metal that rise from the surface of the wire. The may be caused from any one of a number of sources including the ingot and rollin practice.

## CASE STUDY

Wire rod of 7.0 mm diameter (free-cutting steel) exhibited slivers i.e., surfac imperfections (chips) produced during hot rolling of 110 x 110 mm continuousl cast billets.

### Material

Free-cutting steel (with and without lead)

Chemical Composition (wt. %)

| C | Mn | Si | P | S | Cu | Pb |
|---|---|---|---|---|---|---|
| 0.07 | 1.11 | 0.08 | 0.052 | 0.26 | 0.02 | 0.25 |

### Experimental Details

Optical and SEM techniques have been used to study the as received chips wire rods (transverse and longitudinal sections) and billets (soaked and unsoaked) In case of billets, both central and edge position (transverse section) were examined EDX analysis have been carried out to find out the composition of the inclusion Sulphur printing experiment was also performed to understand the distribution o sulphur in the billet.

## Results

a) *Optical :* An optical micrograph of the as-received free-cutting steel wire rod in the transverse section is presented in Fig. 1, which shows recrystallized ferrite grains and blocky pearlite located at these ferrite grain boundaries. The sulphide inclusions are also observed in this micrograph which are uniformly distributed throughout the matrix both at the grain boundaries as well as inside the grains. The optical micrograph in Fig. 2, has been recorded on the as-received wire rod in the longitudinal section, which indicates similar features seen in Fig. 1, except that the inclusions are elongated rather than globular. Fig. 3, is an optical micrograph of the specimen from the centre portion of the as-received billet (transverse section (after soaking) showing blocky pearlite at the ferrite grain boundaries with globular inclusions sitting at grain boundaries as well as inside grains.

b) *Scanning Electron Microscopy :* Figs. 4 & 5 are scanning electron micrographs of the central portion of the unleaded steel billet, before soaking and after soaking respectively. Both figures show resolved pearlite at the grain boundaries of ferrite. The sulphide inclusions seen in these figures are identified as MnS and (Fe, Mn)S inclusion. MnS inclusions are found inside the grains whereas (Fe, Mn)S inclusions at the grain boundaries. It is also noted that the soaking did not bring any significant changes.

Fig. 6 & 7 are scanning electron micrographs of the edge portion of the unleaded steel billet, before soaking and after soaking respectively. Here also resolved pearlite is seen located at the grain boundaries in addition to the inclusions located at grain boundaries and inside grains. EDX analysis confirmed that the unsoaked billet contains only ternary Fe-rich sulphide inclusions (Fe, Mn)S whereas soaked billet transformed all these (Fe, Mn)S inclusions into purely MnS inclusions.

Scanning electron micrographs shown in Fig. 8 are recorded on the specimens collected from the closed portion of the slivers on the as-received wire rods. The specimens from the transverse section (Fig. 8a) indicates the resolved pearlite at the recrystallized ferrite grains in addition to the MnS inclusions (inside the grains) and (Fe, Mn)S inclusions preferentially at the grain boundaries. Fig. 8b is the longitudinal section of the above specimen exhibiting the banded microstructure indicating the differential manganese distribution as low as 0.4% in some regions. Fig. 8c is another SEM of the longitudinal section of the above specimen confirming that the elongated MnS inclusions located at grain boundaries as well as inside grains whereas ternary sulphide inclusions (Fe, Mn)S located at grain boundaries preferentially.

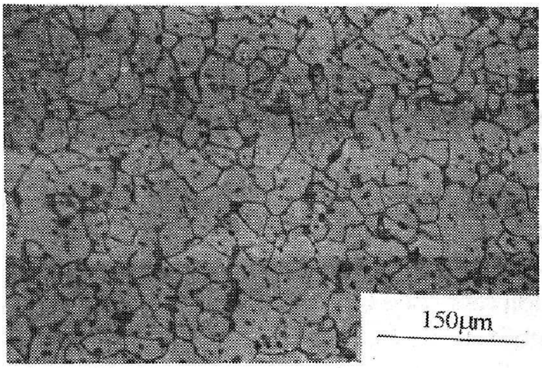


*Fig. 1 : Optical micrograph of the as-received wire rod (transverse section) illustrating blocky pearlite at the recrystallized grains of ferrite and sulphide inclusions at grain boundaries as well as inside grains*

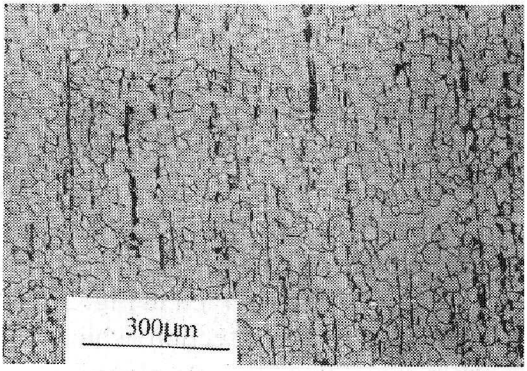


*Fig. 2 : Optical micrograph of the as-received wire rod (longitudinal section) showing blocky pearlite at the recrystallized ferrite grains and elongated sulphide both at grain boundaries and inside grains*

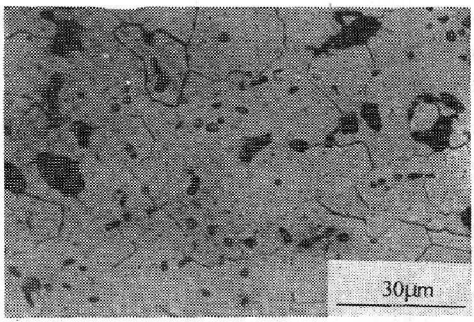


*Fig. 3 : Optical micrograph of the specimen from the centre portion of as-received billet (after soking) revealing blocky pearlite at the ferrite grain boundaries and globular inclusions at grain boundaries and also inside the grains*

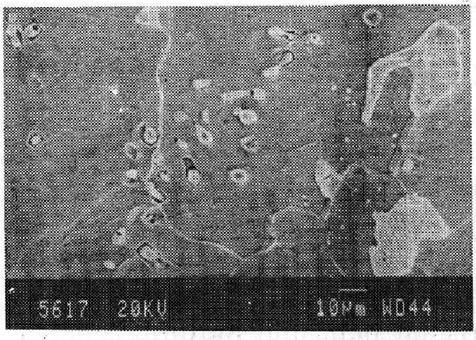


*Fig. 4 : Scanning electron micrograph of the specimen taken from the central portion (transverse section) of the unleaded steel billet (before soaking) showing resolved pearlite at the grain boundaries. Note that the inclusions type features are observed both at grain boundaries as well as inside grains. EDX analysis (Fig. 9a) confirmed that some of these are purely MnS inclusions and other are (Fe, Mn)S inclusions observed preferentially at the grain boundaries*

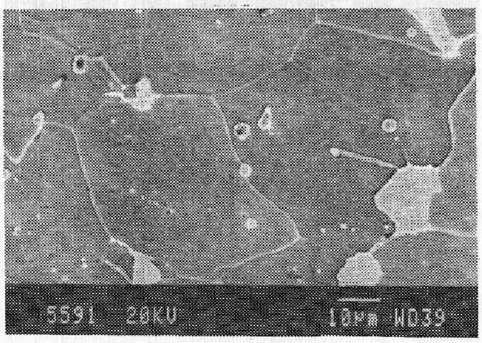


*Fig. 5 : SEM of the specimen as shown in Figure 4 but after soaking and illustrating the similar features. Soaking did not lead to any significant changes in the microstructure. EDX analysis (Fig. 9b) confirms two types of sulphide inclusions*

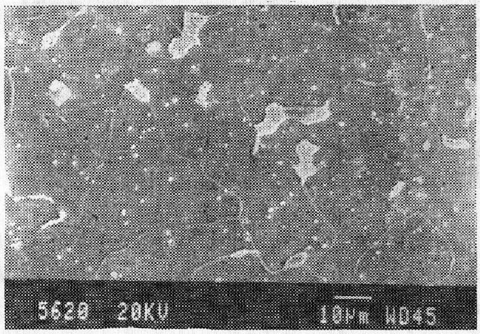


*Fig. 6 : SEM of the specimen taken from the edge portion (transverse section) of the unleaded steel billet (before soaking) exhibiting resolved pearlite at the grain boundaries. Note very fine and uniformly distributed sulphide inclusions both at grain boundaries and also inside the grains. EDX analysis (Fig. 10a) confirmed that all of the these are ternary sulphide inclusions (Fe, Mn)S. Also note that pure MnS inclusions are totally absent*

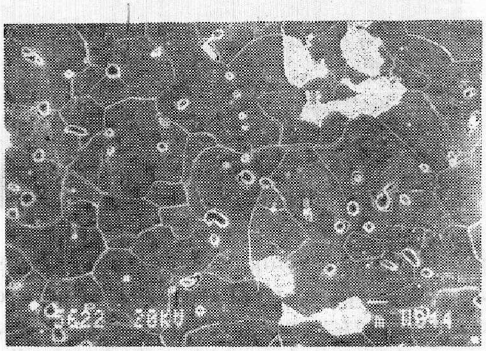


*Fig. 7 : Specimen shown in figure 6 but after soaking. Soaking converted almost all the ternary sulphide inclusions Fe-(Fe, Mn)S into purely MnS inclusions (Fig. 10b)*

c) EDX Analysis : Fig. 9 to 11 are EDX analysis plots confirming the type of inclusions discussed in the above sections.

## Discussion

The present study clearly indicates that there are three kinds of sulphide inclusions present in the ferritic microstructure containing blocky pearlite at the grain boundaries. They are (i) purely MnS, which are the beneficial nonmetallic inclusions in steel. Depending on their type, size, shape, distribution and volume

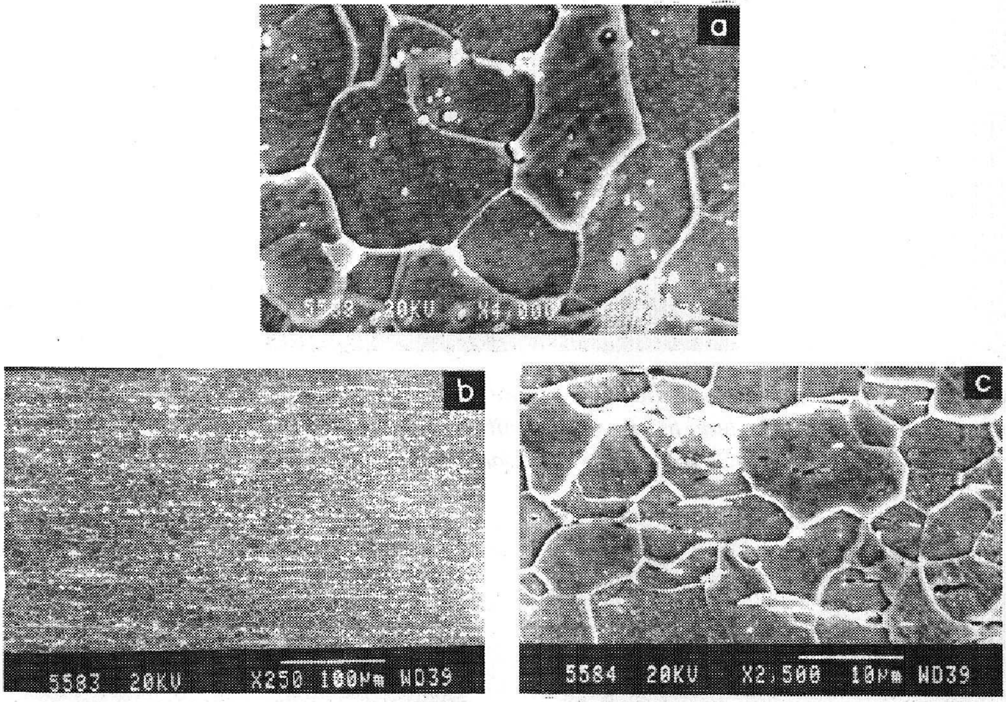
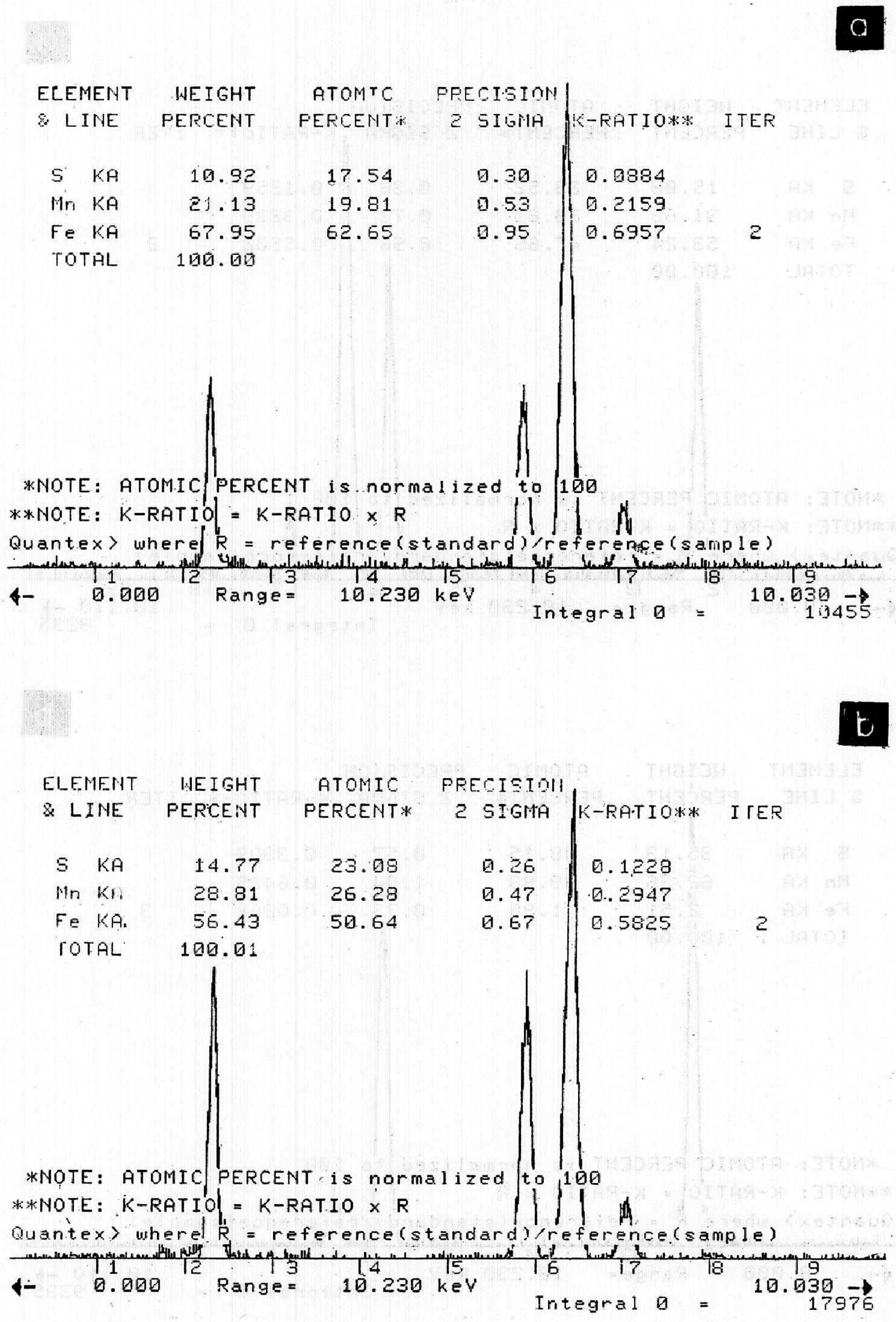


*Fig. 8(a,b,c) : Scanning electron micrographs of the specimens taken from the close portion of the SLIVERS on the as-received wire rods:(a) transverse section illustrates resolved pearlite at the grain boundaries and globular MnS inclusions inside the grains, also note ternary sulphide inclusions at the grain boundaries, (b) longitudinal section shows banded microstructure revealing differential Mn distribution (as low as 0.4% in some regions) and (c) longitudinal section illustrating resolved pearlite at the grain boundaries and elongated MnS inclusions inside grains. Note ternary sulphide inclusions at the grain boundaries*

fraction, they can be either beneficial or detrimental to machinability, (ii) Mn-rich (Mn, Fe)S and (iii) Fe-rich (Fe, Mn)S. While the MnS inclusions are found to segregate preferentially inside the grains, Fe-rich (Fe, Mn)S inclusions are seen at the grain boundaries (in most of the cases). However, occasionally, (Fe, Mn)S inclusions are also seen inside the grain. It is to be emphasised here that the commonly observed binary FeS inclusions which are found to cause hot shortness problems in steel, are not observed in the present investigation. This is in conformity with the results reported in literature on continuous casting process which points out the rare occurrence of FeS inclusions in concast billets.

While the study on edge portion (transverse section) of unsoaked billet revealed mostly Fe rich (Fe, Mn)S, the same billet after soaking revealed mostly MnS inclusions, which can be plastically deformed at elevated temperature. However, the central portion of the billet after soaking did not show the similar transformation to Mn-rich sulphides. Further, our studies on chips that have come out from the



a

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ELEMENT   WEIGHT    ATOMIC    PRECISION
& LINE   PERCENT   PERCENT*   2 SIGMA   K-RATIO**  ITER

 S  KA    10.92     17.54      0.30      0.0884
 Mn KA    21.13     19.81      0.53      0.2159
 Fe KA    67.95     62.65      0.95      0.6957      2
 TOTAL   100.00

 *NOTE: ATOMIC PERCENT is normalized to 100
**NOTE: K-RATIO = K-RATIO x R
Quantex> where R = reference(standard)/reference(sample)
        1     2     3     4     5     6     7     8     9
<-  0.000    Range=   10.230 keV                    10.030 ->
                                     Integral 0  =   10455
```

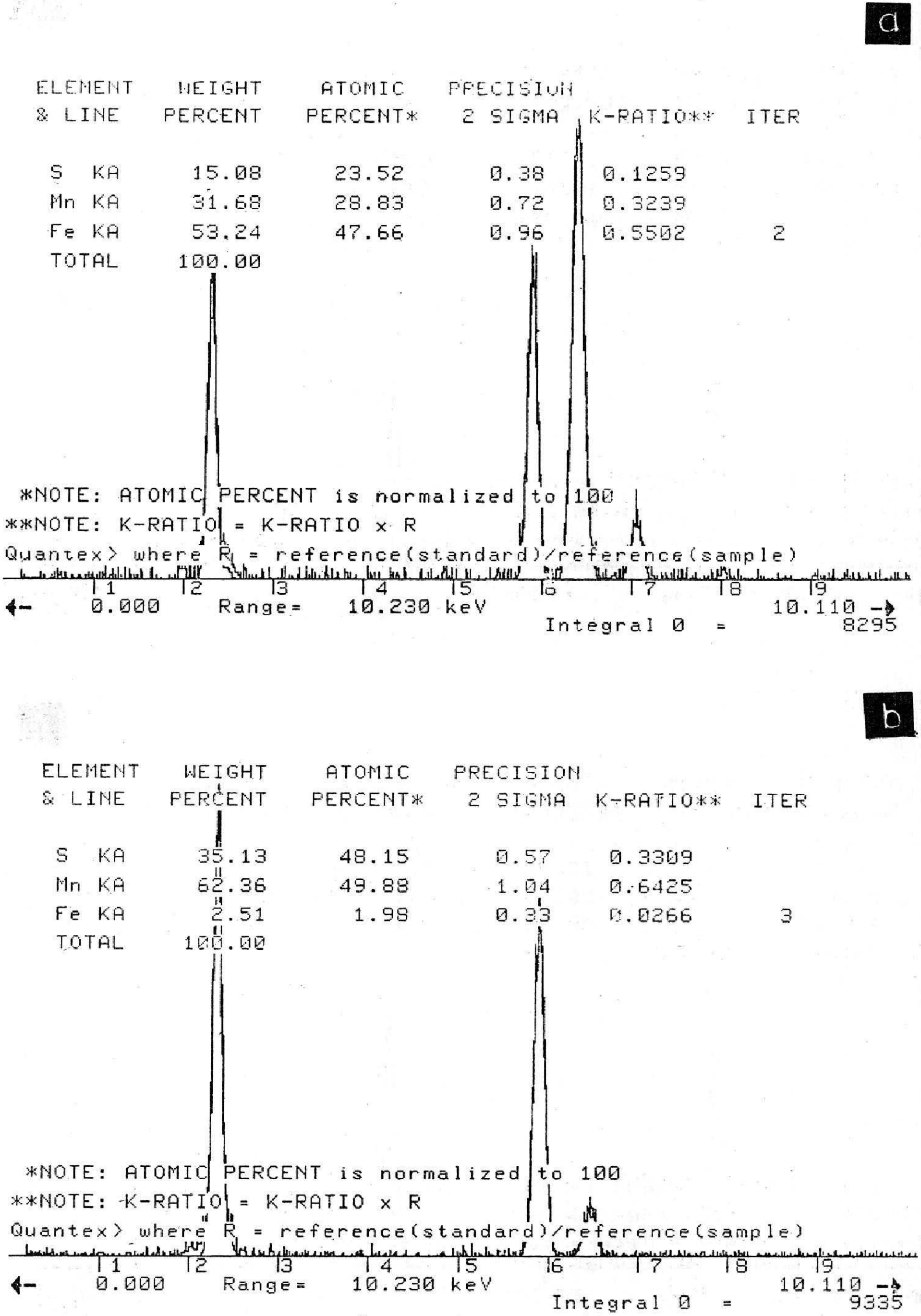
b

```
ELEMENT   WEIGHT    ATOMIC    PRECISION
& LINE   PERCENT   PERCENT*   2 SIGMA   K-RATIO**  ITER

 S  KA    14.77     23.08      0.26      0.1228
 Mn KA    28.81     26.28      0.47      0.2947
 Fe KA    56.43     50.64      0.67      0.5825      2
 TOTAL   100.01

 *NOTE: ATOMIC PERCENT is normalized to 100
**NOTE: K-RATIO = K-RATIO x R
Quantex> where R = reference(standard)/reference(sample)
        1     2     3     4     5     6     7     8     9
<-  0.000    Range=   10.230 keV                    10.030 ->
                                     Integral 0  =   17976
```

*Fig. 9(a,b) : EDX analysis of grain boundary inclusions present in the central portions (transverse section) of the unleaded steel billet showing Fe-(Fe, Mn)S type : (a) before soaking, (b) after soaking*



```
ELEMENT     WEIGHT      ATOMIC     PRECISION
& LINE     PERCENT     PERCENT*     2 SIGMA   K-RATIO**   ITER

 S  KA      15.08       23.52        0.38      0.1259
 Mn KA      31.68       28.83        0.72      0.3239
 Fe KA      53.24       47.66        0.96      0.5502        2
 TOTAL     100.00

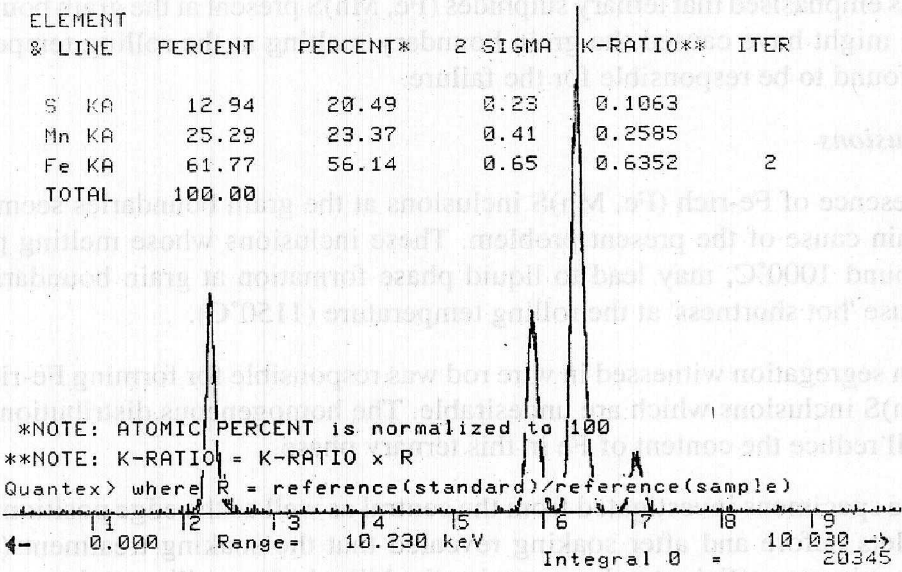
 *NOTE: ATOMIC PERCENT is normalized to 100
**NOTE: K-RATIO = K-RATIO x R
Quantex> where R = reference(standard)/reference(sample)
       1     2      3      4      5      6      7      8      9
<-   0.000     Range=    10.230 keV                       10.110 ->
                                      Integral 0   =         8295
```

```
ELEMENT     WEIGHT      ATOMIC     PRECISION
& LINE     PERCENT     PERCENT*     2 SIGMA   K-RATIO**   ITER

 S  KA      35.13       48.15        0.57      0.3309
 Mn KA      62.36       49.88        1.04      0.6425
 Fe KA       2.51        1.98        0.33      0.0266        3
 TOTAL     100.00

 *NOTE: ATOMIC PERCENT is normalized to 100
**NOTE: K-RATIO = K-RATIO x R
Quantex> where R = reference(standard)/reference(sample)
       1     2      3      4      5      6      7      8      9
<-   0.000     Range=    10.230 keV                       10.110 ->
                                      Integral 0   =         9335
```

Fig. 10(a,b) : EDX analysis of grain boundary inclusions present in the edge portion (transvers section) of the unleaded steel billet exhibiting (a) Fe-(Fe, Mn)S type before soaking; (b) nearly MnS type after soaking



```
ELEMENT
& LINE   PERCENT   PERCENT*   2 SIGMA  K-RATIO**   ITER

 S  KA     12.94     20.49      0.23    0.1063
 Mn KA     25.29     23.37      0.41    0.2585
 Fe KA     61.77     56.14      0.65    0.6352       2
 TOTAL    100.00

*NOTE: ATOMIC PERCENT is normalized to 100
**NOTE: K-RATIO = K-RATIO x R
Quantex> where R = reference(standard)/reference(sample)
       1       2       3       4       5       6       7       8       9
<-  0.000    Range=   10.230 keV                          10.030 ->
                                     Integral 0   =        20345
```

*Fig. 11 : EDX analysis carried out on the specimen collected from the close portions of the chips indicating Fe-(Fe, Mn)S type inclusion*

rolled rods revealed the occurrence of partial melting and overheating in some regions which may be attributed to the partial melting of Fe-rich (Fe, Mn)S inclutions along the grain boundaries.

From the data on phase diagram Fe-Mn-S system, reported in literature, it is realized that when excess iron is present, the invariant point of liquid formation is 997+3°C which seems to be responsible for the so-called hot shortness which in turn leads to surface imperfections (chips problem).

In order to avoid the liquid phase formation at the present rolling temperature (~1150°C) the content of Mn in the ternary, (Fe, Mn)S compound should be more than 70% as estimated from the phase diagram. SEM and EDX analysis suggest that there is segregation of manganese in the material. The estimated Mn content has been found to be between 0.44 to 0.88% whereas the total Mn content in the steel was ~1.1%. This microsegregation occurred in spite of the continuous casting process used for producing resulphurized steel as sulphur is supposed to be present more uniformly in the continuously cast billets than the ingot processed billets. This result indicates that due to lack of sufficient amount Mn in some regions, sulphur present is forced to form iron rich ternary sulphides (undesirable inclusions) rather than Mn-rich ternary sulphides which are not detrimental and advantageous in the free-cutting grade of steels.

It is emphasised that ternary sulphides (Fe, Mn)S present at the grain boundaries which might have caused the grain boundary melting at the rolling temperature were found to be responsible for the failure.

## *Conclusions*

1. Presence of Fe-rich (Fe, Mn)S inclusions at the grain boundaries seems to be main cause of the present problem. These inclusions whose melting point is around 1000°C, may lead to liquid phase formation at grain boundaries and cause 'hot shortness' at the rolling temperature (1150°C).

2. Mn segregation witnessed in wire rod was responsible for forming Fe-rich (Fe-Mn)S inclusions which are undesirable. The homogeneous distribution of Mn will reduce the content of Fe in this ternary phase.

3. The specimens investigated from the central as well as the edge positions of the billets before and after soaking revealed that the soaking treatment (mainly time) is not sufficient to homogenize the billet before rolling and to transform all Fe-rich (Fe-Mn)S inclusion into either Mn-rich (Fe, Mn)S or purely MnS inclusions.

4. Similar findings were also observed in the case of leaded steels.

## *Recommendations*

1. Soaking time should be increased : soaking temperature can be maintained very close to the rolling temperature, i.e., 1150°C (usually this is the proper rolling temperature). Mn should be uniformly distributed in order to convert the ternary sulphide inclusions into Mn-rich sulphide inclusions or completely MnS. Actual soaking time which is required to convert undesirable sulphide inclusions to desirable ones, can be ascertained by doing soaking experiments on as-cast billets.

2. Cooling rate during continuous casting should be as low as possible in order to give more time to avoid banding or nonuniform Mn-distribution.

3. Thought can be given on possible increase of Mn or marginally decrease of S content, without hampering much on the property of the final product.

4. Optimise the process parameters e.g., Mn and S content of the alloy, cooling rate during solidification, soaking time and temperature etc. which will ultimately result in quality product free from surface imperfection.

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