On the nature of the so-called "ghost lines" in stand-cast steel

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Abstract
One of the defects which show up in strand-cast steel and persist in the rolled shapes and forgings, irrespective of the degree of hot plastic deformation, is the so-called "ghost lines". Because of their appearance on magnetic inspection of finite parts and macrographic etching, they are still termed "Innenrisse" (internal cracks) in Germany, and sometimes considered objectionable. In this study it is shown that they consist of segregated metal, enriched with sulphur and alloy elements, with the exception of carbon and nickel. Their influence on the mechanical behaviour of the steel, at least as long as their amount does not substantially exceed that present in our material is of little, if any, importance.

Riassunto
Sulla natura delle "ghost lines" negli acciai da colata continua
Uno dei difetti che appaiono nell'acciaio da colata continua e permangono nei laminati e nei forgiati, qualunque sia stata l'entità della trasformazione plastica a caldo, è costituito dalle cosidette "ghost lines". A causa del loro manifestarsi all'esame magnetico dei pezzi finiti e all'indagine macrografica essi sono ancora denominati "Innenrisse" (cricche interne) in Germania e talora considerati con grave sospetto. In questo studio si dimostra che consistono di metallo segregato, arricchito di solfuro e degli elementi di lega, ad eccezione del carbonio e del nichel. La loro influenza sul comportamento meccanico dell'acciaio, almeno finché la loro entità non supera sostanzialmente quella presente nel nostro materiale, è di importanza secondaria o nulla.

Introduction

Strand-cast, as opposed to ingot-cast, steel is spreading ever more rapidly throughout manufacturing industry (1-4). However, some reservations about its use for the production of the most critical parts, e.g. in the automotive industry, still survive, and apparently not entirely without reason.
In fact, neither an igot nor a strand is normally put to use in the as-cast condition, i.e. without previous hot plastic deformation. Since a strand has generally a smaller section than an ingot, it requires much more attention to ensure that it receives sufficient deformation in the process of being transformed into a part.
However, there are two types of "defect" that, when present in the as-cast strand section, no amount of plastic deformation will entirely eliminate, i.e. central segregation and porosity (Fig. 1) and the so called "ghost lines" (5). Enough is known of central segregation and the means to reduce it to a minimum, if necessary by the use of one or more magnetic stirrers (6-8), and for this reason we shall not deal with this matter in the present paper, bur will confine our discussion to the subject of ghost lines.

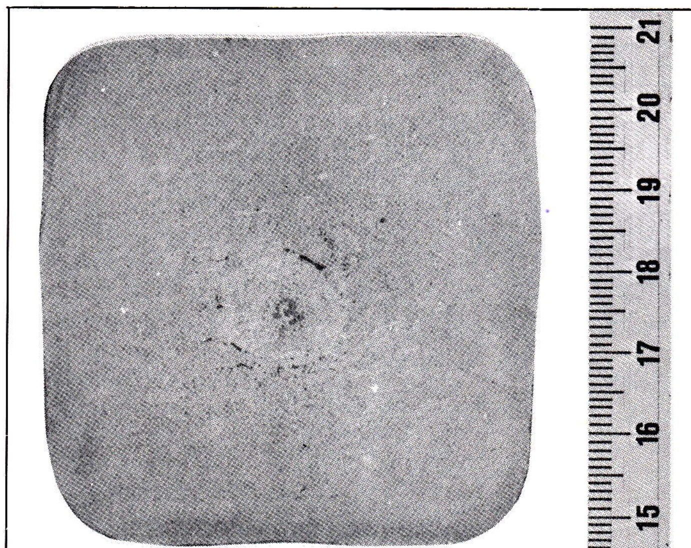


Fig. 1 - Central segregation and porosity in 65 mm SAE 4140 steel billet (deformation ratio 9:1).

The origin of ghost lines

Ghost lines appear on macrographic etching as dark lines at some depth below the surface in macro-etched sections, even after considerable plastic deformation, as is apparent in Fig. 2. As anticipated, they persist on forging, as can be appreciated in Fig. 3. If they are brought to the surface in the process of forging or machining a part, magnetic-particle inspection returns sharp indications. For these reasons, they have long been considered as cracks, and termed "Innenrisse" (internal cracks) in Germany. The effect is due exclusively to their etching properties, in that they are composed of a material which is chemically more active than the bulk. This is proved most simply in Fig. 4, which is just an enlarged view (9 magnifications) of a typical area of Fig. 2. Fig. 5 is a micrograph of a ghost line in an SAE 4140 steel billet, whose cooling rate from the rolling temperature was fast enough to develop a bainitic-martensitic structure in the bulk. The term "ghost lines" is somewhat less misleading than "Innenrisse", though it also conveys the idea of a ghastly nature, which may be largely unwarranted.

Fig. 2 - Ghost lines in a 65 mm SAE 4140 steel billet,
Etchant: ammonium persulphate.

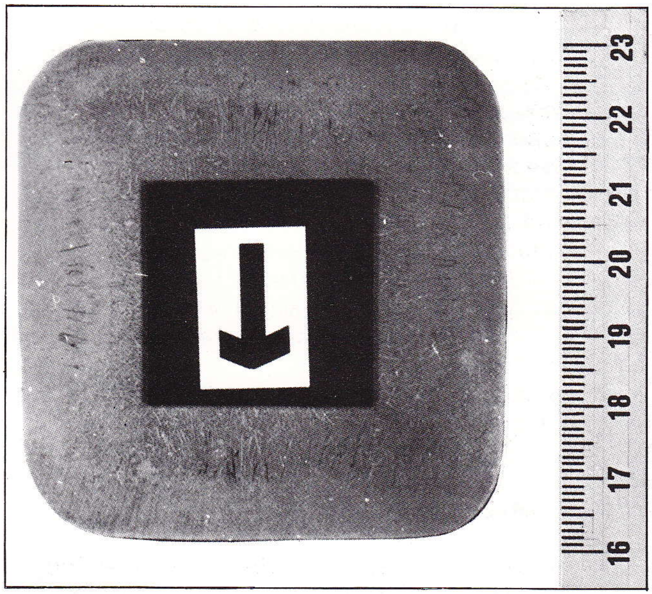


Fig. 3 - Ghost lines in a forging. Etchant: hydrochloric acid.

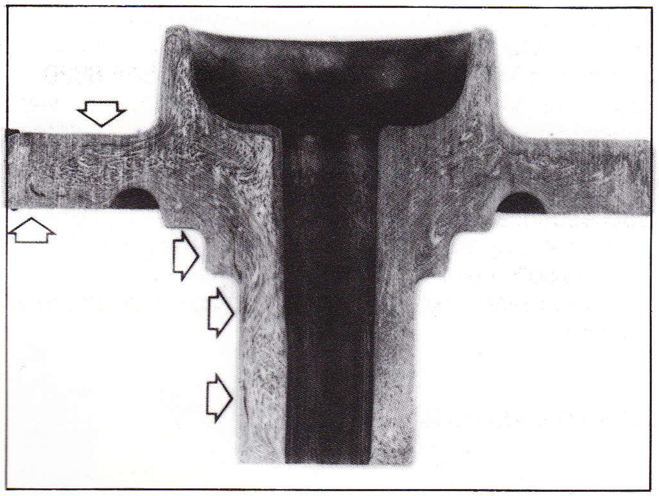
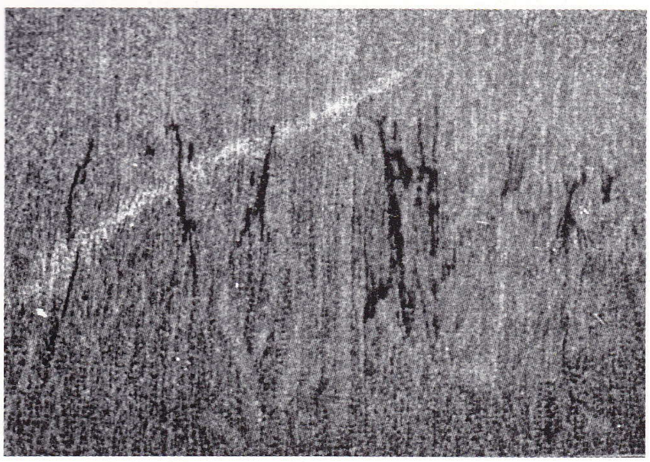


Fig. 4 - Same as Fig. 2, enlarged 9 times.



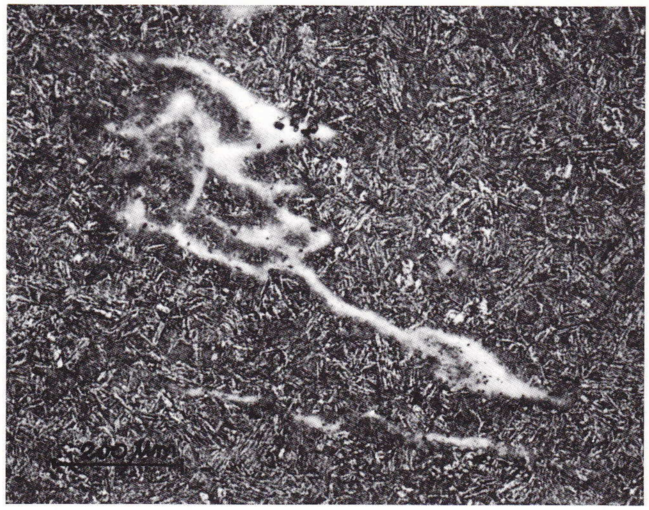


Fig. 5 - Micrographic appearance of a ghost line in a 55 mm SAE 4140 steel round bar (deformation ratio 15:1).
Etchant: 2% Nital.

An attempt to clarify the nature of ghost lines is contained in a study carried out at Mannesmann (9). The Authors suggest that cracks are generated in the inside portion of the earlier solidified shell of the strand because of some external action, e.g. as a consequence of the pressure exerted by the extracting rolls, as shown in Fig. 6. For this reason, they are given the allegedly improper name of "Quetschrisse" (squeeze cracks). Obviously the bending of the strand could have a similar effect, though ghost lines are seen in straight strands as well. Once cracks have formed, they become filled with liquid metal, which gets trapped between them and the advancing solidification front. The trapped liquid metal solidifies later, because of overmelting, the last part of it being obviously enriched with alloy elements. The segregated and interdendritic character of ghost lines is demonstrated in the Mannesmann study by a micrograph, in which use was made of Oberhoffer's etchant, which etches the zones richer in the iron darker, and duly lightens the ghost lines. The same study shows the existence of a critical roll pressure for any given strand shell thickness, below which no ghost lines are evident, and also a plot relating the ghost lines' location in the strand section to the shell thickness.
It is easy to envisage the dependence of the shell thickness on such factors as the liquid metal overheat at pouring, the secondary cooling rate and the casting rate, viz. practically all the operating parameters of the caster. In consequence, the Mannesmann study insists that ghost lines can be avoided, and gives guidance to this effect. Our experience, however, is that most of the strand-cast steel sold contains at least a limited number of them.
The Mannesmann Researchers maintain that they

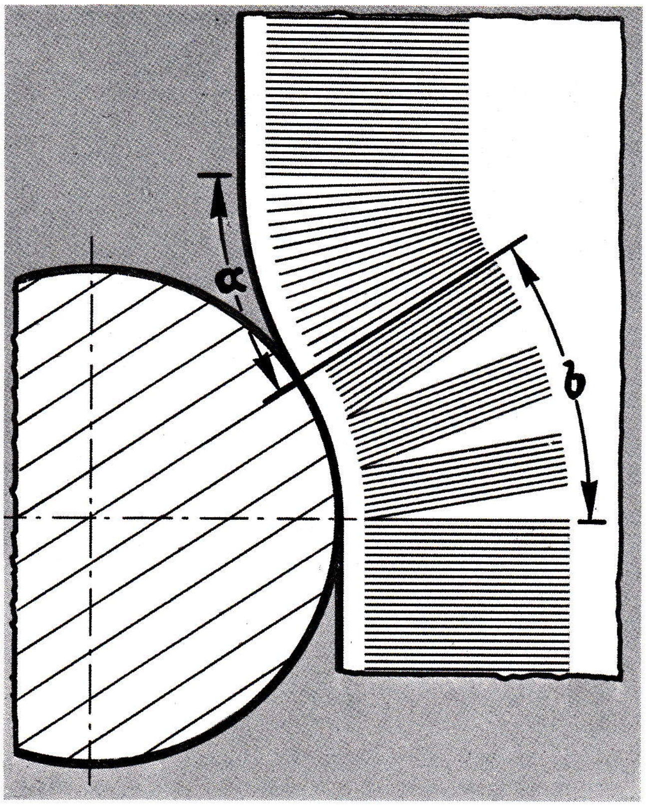


Fig. 6 - Theoretical model for the formation of ghost lines (schematic). Source: Bungeroth and vom Ende (9).

could never find any influence of the presence of ghost lines on the technological properties of the affected materials, though no evidence is offered for this statement, and insist that the Manufacturer considers them as "Schoenheitfehler" (beauty spots). We thought that further investigation was still in order, specially as the Mannesmann study was carried out on as-cast strand material rather than on rolled shapes or forgings.

Materials used in the present study

Since, as stated above, we were interested in ghost lines present in parts, rather than in strands, we carried out our study on low-alloy steel round bars and billets rolled from 190 mm square strands at deformation ratios between 5 and 15. We ascertained that, upon cooling down from rolling to room temperature, such shapes could develop a variety of structures, from pearlite and ferrite to bainite and martensite. For this reason we assumed billet and bar slugs to be representative also of forgings as far as we were concerned.

We selected two widely used steel grades, namely constructional grade SAE 4140 and case hardening grade SAE 8620. For reasons which will become evident in the following, the former was investigated somewhat more extensively.

The chemical compositions of our materials are shown in Table 1.

Microhardness Measurements

Fig. 7 shows that, in the case of SAE 4140 steel, the material constituting the ghost lines is considerably harder than the bulk. This extra-hardness is retained only in part after a conventional hardening heat treatment (quenching in oil from 870° C, followed by tempering for 3 h at 600° C). In the case of SAE 8620 steel, the extra-hardness in the as-rolled condition was much less, but the heat treatment, meant to simulate case-hardening (3 h at 920° C, then down to 1 h at 820° C, quenching in oil and tempering for 2 h at 150° C), succeeded, as expected, in raising the matrix hardness and increasing the difference between the ghost lines and the bulk. Data concerning all the hardness measurements taken on selected areas are collected in Table 2.

Microanalysis

Fig. 8 shows details of a portion of SAE 4140 steel specimen containing a large ghost line. The high concentration of sulphide inclusions is immediately apparent.

Fig. 9 represents SEM X-Ray emission profiles across a ghost line (broken line) and in the matrix (solid red areas). The higher concentration of Mn and Cr in the ghost-line material shows up clearly.

We confirmed the previous observation making use of the JENA LAM -10 laser microprobe of the FIAT

TABLE 1 - Chemical compositions (% weight) of the steels

SAE grade	C	Mn	Si	Cr	Ni	Mo	S	P
4140	.40	.74	.31	.98	tr.	.15	.108	.019
8620	.21	.63	.32	.36	.43	.16	.022	.018

TABLE 2 - Microhardness measurements

SAE grade	Ghost lines ($HV_{.05}$)		Matrix (HV_1)	
	Before H.T.	After H.T.	Before H.T.	After H.T.
4140	470	412	321	313
8620	237	401	191	317

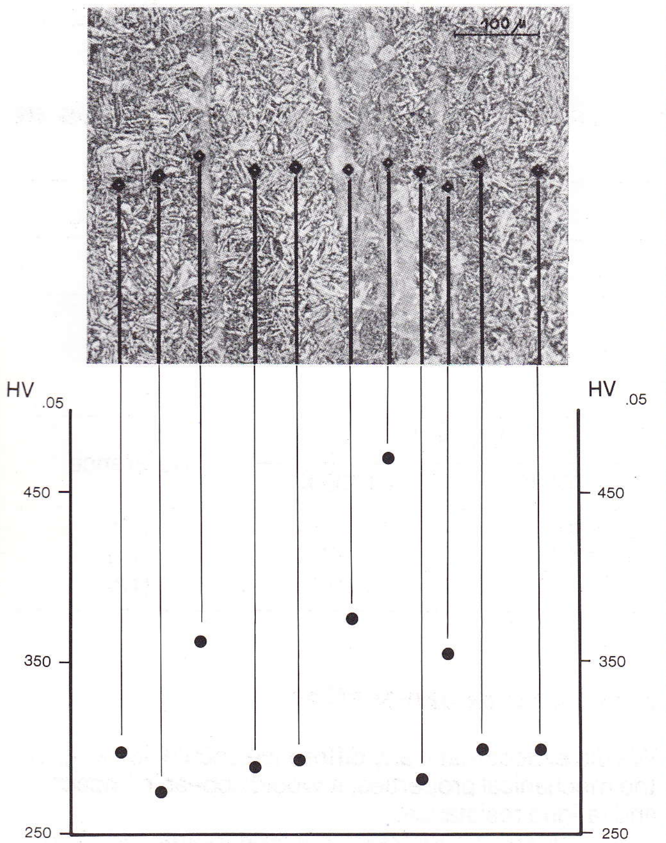
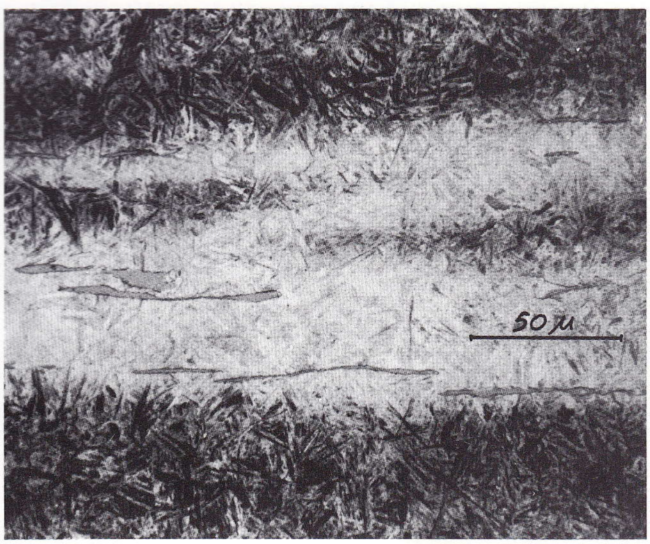


Fig. 7 - Microhardness in a ghost-line-affected region of a 55 mm SAE 4140 steel round bar.
Etchant: 2% Nital.

Fig. 8 - Sulphur containing ghost line in SAE 4140 steel.
Etchant: 2% Nital.



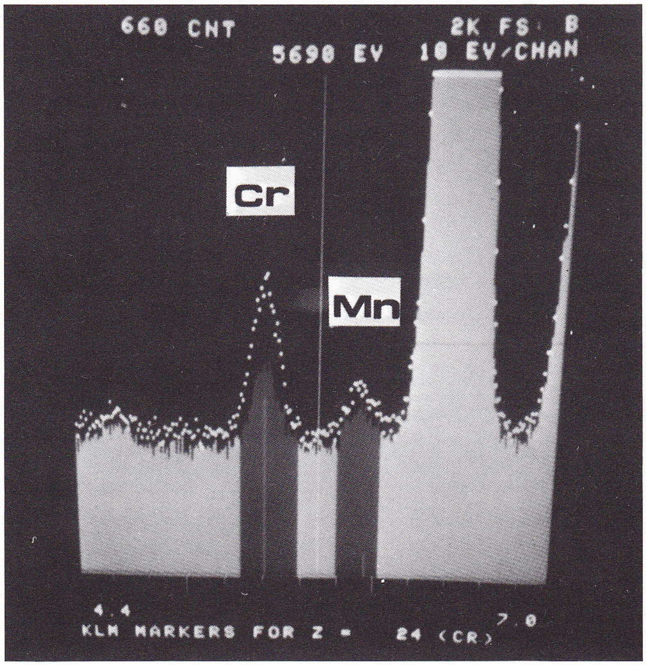


Fig. 9 - SAE 4140 steel: SEM X-Ray emission profile through a ghost line and in the matrix.

Research Centre (CRF) at Orbassano. This instrument consists of a spectrophotometer, which analyses the vapour produced by an extremely thin (about 40 μm in diameter) laser beam impinging on the specimen surface. Typical tests made on SAE 4140 steel specimen are shown in Fig. 10 and the results of the chemical analysis are given in Table 3.
As can be seen in Fig. 10, the spots are relatively large, as compared with the width of the ghost lines, so that the segregations are certainly higher than they appear. In the case of SAE 8620 steel, the maximum concentrations of alloy elements determined corresponding to ghost lines are listed in Table 4 (see Table 1 for comparison).
A short comment is in order. The molybdenum content is probably too low for any appreciable segregation to become noticeable, while nickel has a negligible tendency to segregate because the solidus and liquidus lines lie too close together in the nickel-iron phase diagram. The fact that carbon apparently does not segregate can be explained in terms of its high mobility throughout the stability range of the γ- phase (approximately 1700-1200 K). In fact, the activation energy for carbon diffusion is much lower, and the diffusion coefficient much higher, than for Mn and Cr. The relevant data are shown in Table 5.
Considering that the diffusion mean free path is given by the formula $\tau = (D\,t)^{1/2}$ it is found that carbon can diffuse at a distance of the order of 100 μm if the steel is held for some 100 s in the γ-phase upon cooling from the melt, while both manganese and chromium are

TABLE 3 - Chemical composition (% weight) in the spots indicated in Fig. 10

Test No.	C	Mn	Cr	Mo
1	.41	*1.08*	*1.38*	.16
2	.40	.69	.92	.15
3	.41	.73	.98	.15
4	.39	.76	.99	.16
5	.40	.72	.94	.16
6	.40	.71	.89	.15
7	.41	*.97*	*1.49*	.17
8	.40	.69	.94	.16
9	.40	.70	.98	.15

TABLE 4 - Maximum alloy element concentration (% weight) in ghost lines in SAE 8620 steel

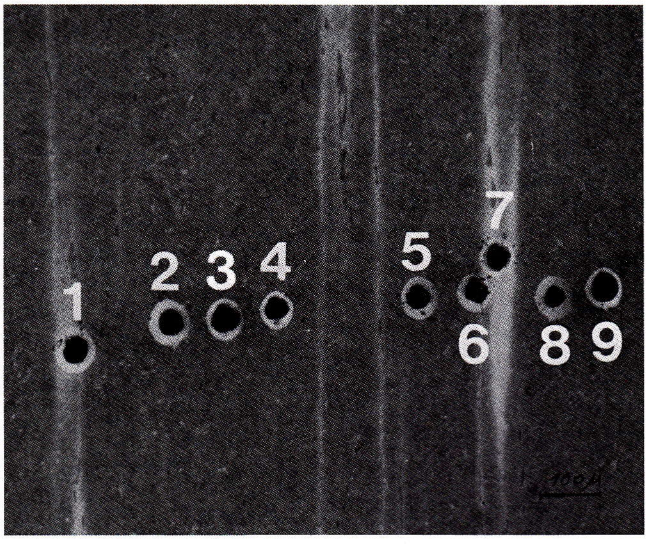
C	Mn	Cr	Ni	Mo
.22	.79	.47	.46	.16

TABLE 5 - Diffusion parameters in γ-iron

Element	D_0, m^2s^{-1}	Q,kJ mol^{-1}	D, m^2s^{-1}		Reference
			at 1700 K	at 1200 K	
C	10^{-5}	135.6	$6.80 \cdot 10^{-10}$	$1.25 \cdot 10^{-11}$	(10)
Mn	$1.60 \cdot 10^{-5}$	261.6	$1.46 \cdot 10^{-13}$	$6.53 \cdot 10^{-17}$	(11)
Cr	$1.08 \cdot 10^{-3}$	291.8	$1.17 \cdot 10^{-12}$	$2.15 \cdot 10^{-16}$	(12)

much less mobile. Thus, if carbon segregates with the other alloy elements on solidifying, it will have equalized its concentration before transforming to the α-phase.
The higher concentration in alloy elements in the ghost line material makes it more hardenable. Since the cooling rate from the melt is rather high, if not comparable to that typical of quenching, it is reasonable that the ghost-line material should acquire a higher hardness than the matrix.

Fig. 10 - Laser microprobe tests taken on a SAE 4140 steel specimen. Etchant: 2% Nital.



Mechanical properties

We did expect that if any difference should show up in the mechanical properties, it would appear in impact and fatigue resistance.
Fig. 11 shows the locations in a heat treated (HB 341) 65 mm square billet, where Charpy U testpieces were cut. Piece A was flawless, whereas pieces B and C contained ghost lines. Table 6 shows the results of the tests.

Fig. 11 - Locations of impact testpieces in a billet section.

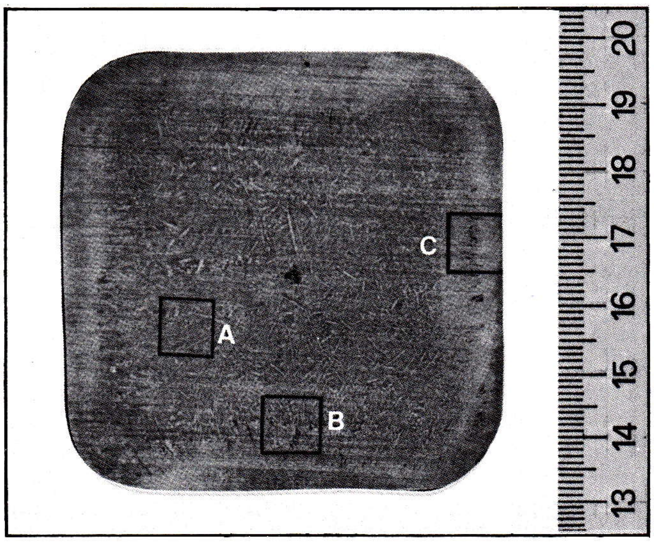
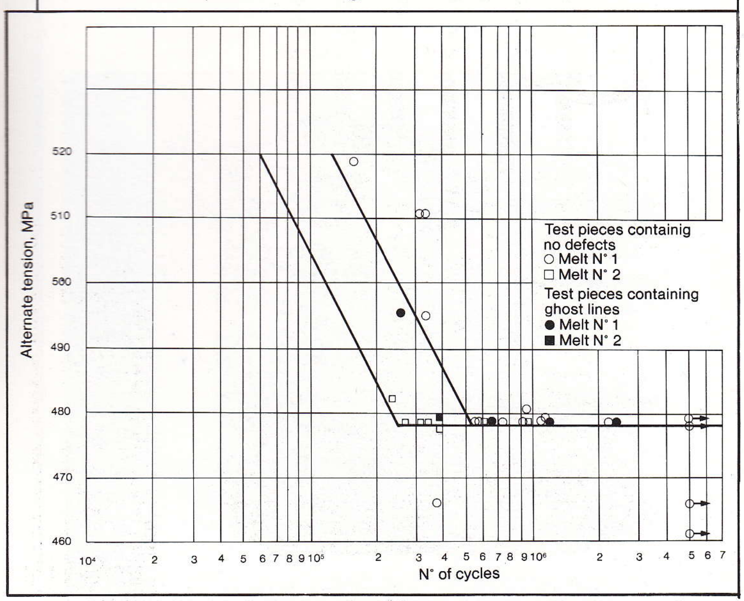


TABLE 6 - Results of the impact tests

Piece	Energy absorbed, J
A	30.5
B	30
C	30

Quite visibly, the expected difference did not exist. We also cut rotary bending testpieces from two heat treated (HRc 25.4 and 26.5) 80 mm square billets rolled from 190 mm strands cast from two different melts. We ensured that some of the testpieces contained ghost lines and some did not. The relevant Woehler plots are presented in Fig. 12. Again, no difference is discernible.
Since, as observed above, the ghost lines consist of material which is unquestionably harder than the matrix, one wonders, why they don't behave like any other hard inclusions, at least in contributing to brittleness. The answer can be found in Fig. 13, which shows that the crystals in the matrix extend themselves across the border inside the ghost lines (which the reagent etches dark). This means that there is no sharp boundary between ghost lines and matrix. A diffused grain boundary is likely to be unable to stop the movement of dislocations, while the volume fraction of the ghost lines is probably not large enough to have any appreciable influence on the overall mechanical properties of the material.

Fig. 12 - Woehler plot for testpieces cut from billets pertaining to two different melts. Part of the pieces did contain ghost lines.



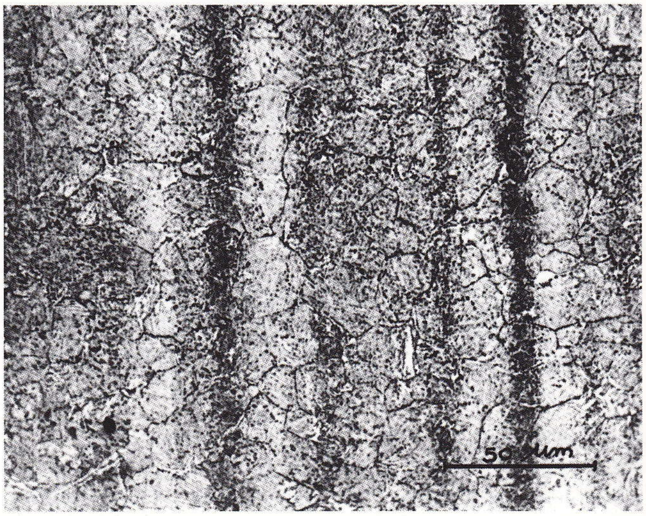


Fig. 13 - Crystals extending across ghost-line boundaries. Etchant: Bechet-Beaujard, modified (13).

Conclusions

Ghost lines are typical defects present in strand-cast steel, and are bound to survive any hot plastic deformation. As such, they are regarded with suspicion by some people in manufacturing industry. This study shows that they are composed of segregated metal, enriched with sulphur and alloy elements, with the exception of nickel and, most notably, carbon. Their influence on the properties of steel shapes and forgings, which have undergone enough hot plastic deformation, is negligible.

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REFERENCES

(1) Vom Ende, H., and K.G. Speith. ***Zeitschrift f. Metallkunde, 60*** *(1969), 258.*

(2) Bauer, K.H., H. vom Ende, and F. Regnitter. ***Stahl u. Eisen, 93*** *(1973), 233.*

(3) Wasmuht, J.T.. ***Das Stranggiessen von Stahl.*** *Verlag Stahleisen MBH, Duesseldorf, 1975.*

(4) Kruger, L.G. ***Metal Progress, 109*** *(Oct. 1979), 48; ibid.* ***111*** *(Oct. 1981), 46.*

(5) Backer, L., and P. Gosselin. ***J. Metals, 23*** *(May 1971), 16.*

(6) Alberny, L., L. Backer, J.P. Birat, P. Gosselin, and M. Wanin. ***Electric Furnace Proceedings, 31*** *(1973), 237.*

(7) Ayata, K., T. Mori, K. Narita, and T. Ohnishi. ***Revue Métall., 80*** *(1982), 371.*

(8) Schewertfeger, K. ***Stahl u. Eisen, 98*** *(1978), 225.*

(9) Bungeroth, A., and H. vom Ende. ***Ueber Fehlerarten beim Stranggiessen.*** *Mannesmann Forschungberichte N. 465, 1968.*

(10) Gruzin, P.L., V.G. Kostogonov, and P. Platanov. ***Dokl. Akad. Nauk SSSR, 100*** *(1955), 1069.*

(11) Nohara, K., and K. Hirano. ***Proc. Intern. Conf. Sci. Tech. Iron and Steel, 7*** *(1970), 11.*

(12) Bowen, A.W., and G.M. Leak. ***Metall. Trans., 6*** *(1970), 1965.*

(13) Antona, P., A. Maracich, C. Giorcelli, and R.L. Colombo. Unpublished.