Split Ends during Long Products Rolling: Billet Quality or Rolling Process?

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Keywords: Split ends, Long products, Rolling, Billets, Cracking, Rebar, Bar, Shapes, Wire Rod, Hot ductility

INTRODUCTION

During rolling of long products in continuous or semi-continuous mills, end splitting (alligatoring, split ends) and central bursting may occur, with an impact on productivity and quality. In figure 1, the typical aspect of this defect is presented. This phenomenon may occur in the roughing passes of the roughing mil, particularly in open mills. Steel grades affected include free cutting steel, rebar, wirerod and shapes. Although out of the scope of this paper, this problem is also known in flat rolling of steel and aluminum.
As an example, in figure 1 the aspects of bars opened in stand 10 of a rebar rolling mill of Tata Steel Jamshedpur (departing from 130 mm square billets), and the state of the bars after rolling, is presented [1]. It can be seen that a cobble may take place, with safety risk, or a defect in the product may be generated.

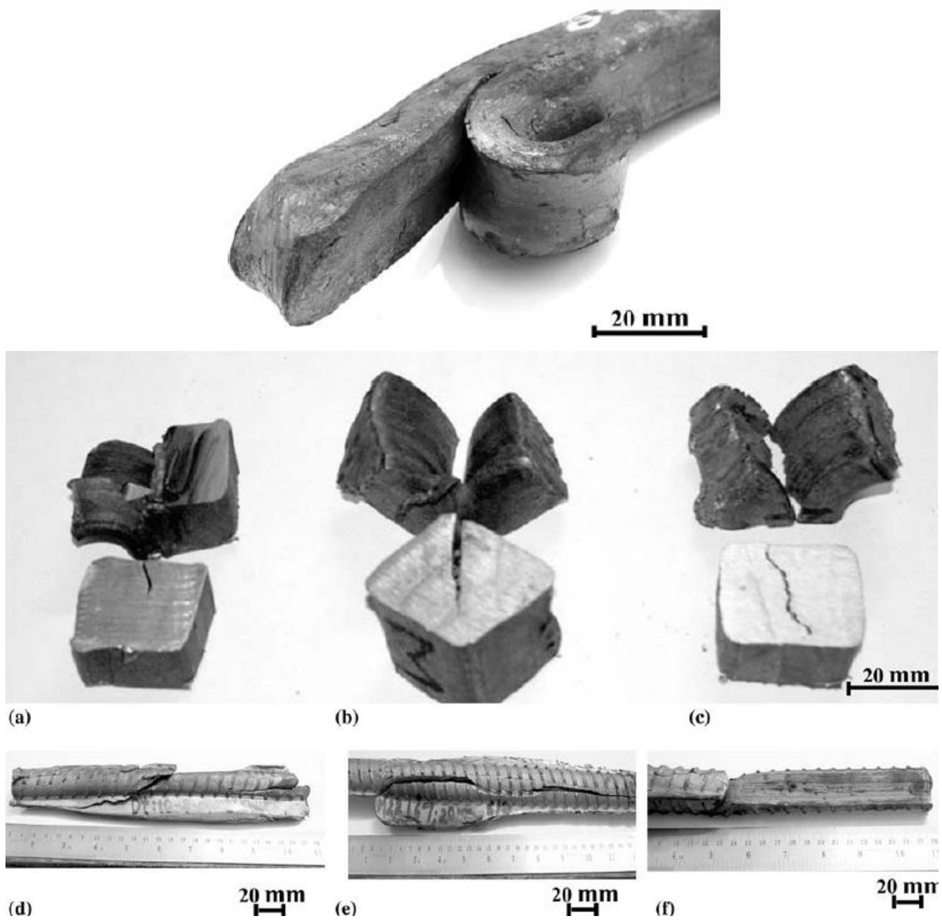


Figure 1. Top: Split end from a bar cobbled in stand 10 of a Tata Steel rolling mill, with 130 mm square billets as raw material. Middle: others bars with end split in stand 10. Bottom: rolled bars with splitting ends, at the end of rolling, after stand 14 [1].

At times, central bursting may occur simultaneously with end splitting or separately. Cobbles may arise as a consequence of the splitting. In figure 2 the aspect of this defect (left) and of a cobble caused by split end during rebar rolling is presented.

Figure 2. Central bursting during rebar rolling. Right: Cobble originated in central burst.

In this paper, the causes of this operating/quality trouble are discussed, regarding the quality of the billets being rolled, as well as the influence of the rolling conditions.

BILLET QUALITY

Some intrinsic aspects affect billet hot ductility. Other influencing factors are related to rolling conditions. In this paragraph, the focus is on billet quality factors. Two billet quality issues often blamed of originating splitting are the quality of the transverse cut, and the presence of coarse inner cracks. A plant reported some synergy between these two factors, influencing split ends [2]. The occurrence of a coarse central crack (figure 3), gives place to the formation of an important bas-relief (figure 4, left). This was verified by simulating the defect by means of oxygen cutting, obtaining split ends (figure 5).
A research in the UK, carried out in the 80s, is by far the most detailed work on end splitting. The focus is on leaded and not leaded free cutting steels. This research includes a detailed experimental assessment of the influence of the end shape [3]. The experimental work is based in tests at a pilot rolling mill, where bars of 68 mm diameter and 200 mm length were tested. The tendency to end splitting was assessed by the number of passes supported by the stock without splitting, within 15 passes.
To evaluate end shape influence, cutting with shear, oxygen and saw were tested, as well as the coating of the cut with metallic alloys and cement, and machining of cut with different shapes.

Figure 3. Transverse cut of billets with coarse central crack [2].

Curiously, shear cuts were less prone to end splitting tan with sawn cuts. Results of a metallographic study suggested that the reason was that in shear cur region, sulfides were not aligned longitudinally: they had a 45^{o} angle with respect to the rolling address, what inhibited the initiation and propagation of cracks in the bar end.

Figure 4. Classification of billet cut from the point of view end splitting trend. Left: Unacceptable cut, with tendency to end splitting, generally associated to the presence of a central crack as that observed in figure 3. Middle: Intermediate cut, with some tendency to splitting. Right: Cut of good quality, with low tendency to end splitting [2].

Figure 5. Billets with artificial mid cracks, cut with oxygen burner (left) and bars with split ends, obtained during rolling of the billets with artificial cracks. [2].

Regarding shaped cuts, bars with 45^o end and those with rounded ends completed the rolling sequence without opening, while those cut with saw or with the end cut to 20^o opened in the sixth pass (see figure 6). This has been explained by the fact that while the first resists the formation of a concave end, a tension concentrator, preventing crack initiation and propagation.

These tests, although not having practical application (introducing a not plane cut and not with oxygen would complicate operations), demonstrate that the type and shape of the cut have an influence on end splitting. It is also verified that sulfide alignment plays a role.

It has often been reported that large central cracks are a factor in cut quality and end splitting. This is a solidification defect, occasioned by mechanical and/or thermal stresses that overcome the material strength, in two opposed faces, corresponding in this case to inner and outer radii of the caster, propagating to the billet center (figure 3). Solidification cracks are usually in interdendritic positions, usually refilled with manganese sulfides.

Other coarse cracks formed during solidification, whose presence has been associated with split ends, are the diagonal cracks, see figure 7. These diagonal cracks may occur associated with pronounced rhomboidity [4].

Bar End Profile Dimensions in mm	Sulphur Content, %	Initial Rolling Temps., °C	No. of Passes to Splitting
68	0.38	1060	6
68, 56, 20°	0.38	1082	6
68, 34, 45°	0.38	1105	15*
68, 45°	0.38	1076	15*
68, 34 rad.	0.38	1077	15*

* Completed the maximum number of passes without splitting

Figure 6. Tests in pilot rolling mill, with free cutting steel bars. Bar end rounded, straight or machines with different shapes [3].

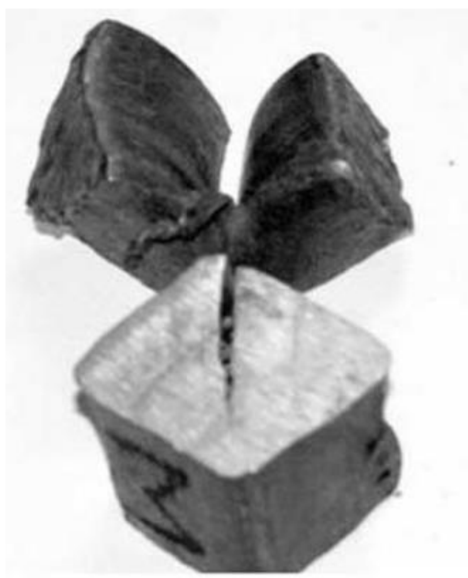


Figure 7. Split end related to a diagonal crack in the former billet [1].

End splitting occurs always in the plane of the roll gap. This suggest that in the pass where splitting starts, there must be a coincidence although partially, between the crack plane and the roll gap (see figure 8, left).

It is important to mention that in a number of cases it is not possible to associate end splitting with coarse defects in the billet. In figure 8 two transverse cuts of a split leaded free cutting steel bar. The one on the left was cut where the crack started; the other, on the right, cut closed to the previous one, which has no defect.

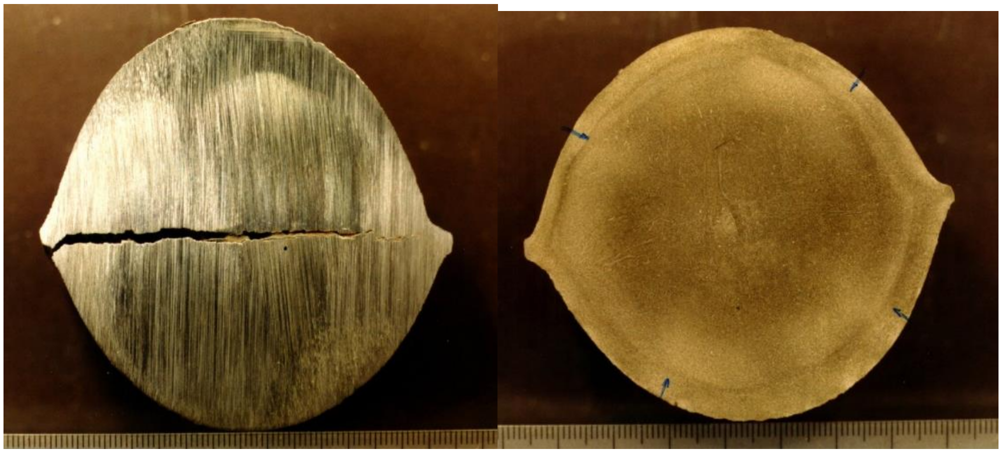


Figure 8. Leaded free cutting steel bar, 70 mm diameter, presenting split end. The crack is formed in the symmetry plane of the roll gap. Left: transverse cut in splitting start zone. Right: Transverse cut closet to crack start, polished and etched with Oberhoffer reagent. The macrostructure remaining from solidification is observed, including the chill layer. There is no coarse defects that could be precursors of the splitting. Blue marks point to the original corners of the billet, detected by the change of direction of the columnar grains.

ROLLING PROCESS

In this paragraph, hot ductility as a relevant factor for end splitting is analyzed, as well as four factors that have an influence: sulfur content, temperature control, pass design, and guiding problems.

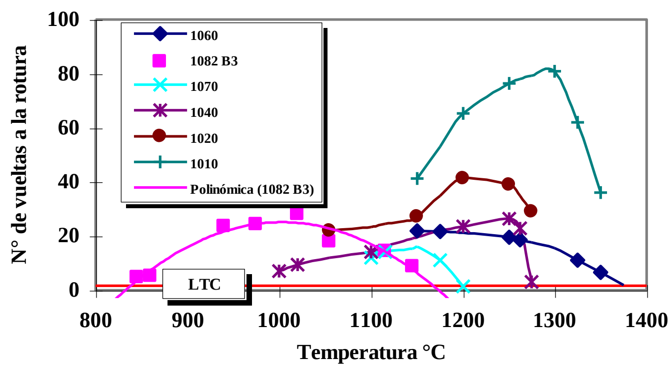
Hot ductility

It is generally admitted that the occurrence of end splitting and central bursting depends on if the material withstands the efforts to which it is submitted in the rolling mill. In this sense, if less inner cracks are present, it is easier for the material to withstand the stress during rolling. Conversely, the lower are the stresses in the rolling mill, the less the risk of splitting will be.

The capacity to withstand stress may be define don the basis of hot ductility, as measured by hot torsion, tension or compression testing. As an example, in figure 8 hot ductility curves for different steel grades are shown, based on torsion test. Under torsion, ductility is evaluated as the number of turns till sample rupture. The test is carried out at a defined deformation speed, varying according to the part of the rolling mill to be simulated: roughing, intermediate or finishing mill.

According to figure 9 (top), standard low carbon steels show very high ductility, within a wide temperature range, extended to temperatures higher than those used in rolling. Because of this those steels do not present ductility-related defects, under normal conditions. High carbon steel, instead, present a lower maximum ductility, within a smaller temperature range.

Low carbon free cutting steels (figure 9, bottom) are usually barely above the hot workability limit, considered to be 1.7 turns till rupture, and generally to a high temperature.



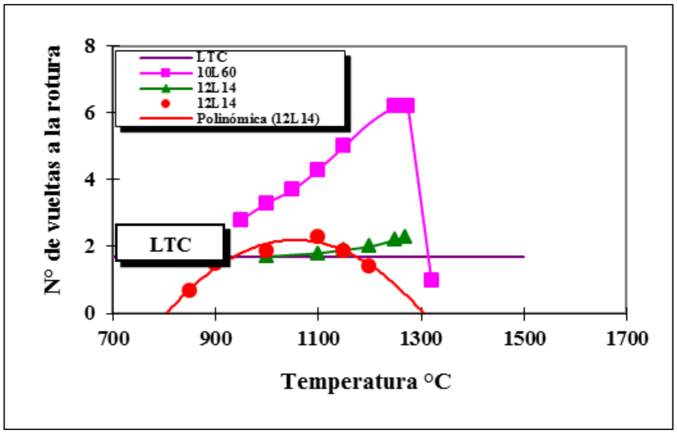


Figure 9. Hot ductility curves, measured by the number of turns till rupture, during torsion tests at different temperatures, for a given deformation speed. Top: carbon steels. Bottom: free cutting steels [5].

Sulfur effect
The large difference in hot ductility of standard low carbon steel and free cutting steels reveals the role of sulfur in hot ductility. Sulfur is dissolved in liquid steel, and manganese sulfides do not precipitate before solidification. This is because the MnS solubility product in liquid steel is large; so, the high concentration of Mn and S necessary for MnS precipitation are achieved only in the interdendritic liquid, enriched in solute.

$$\log [\%Mn] [\%S] = - 8{,}194/T + 4.96$$

If Mn content is not enough, oxysulfides and iron sulfide may precipitate; they, due to their low melting point (1190 ^{o}C) bring about hot shortness. Mn/S ratio required to avoid such oxysulfides and iron sulfides is smaller for larger S content (see figure 10).

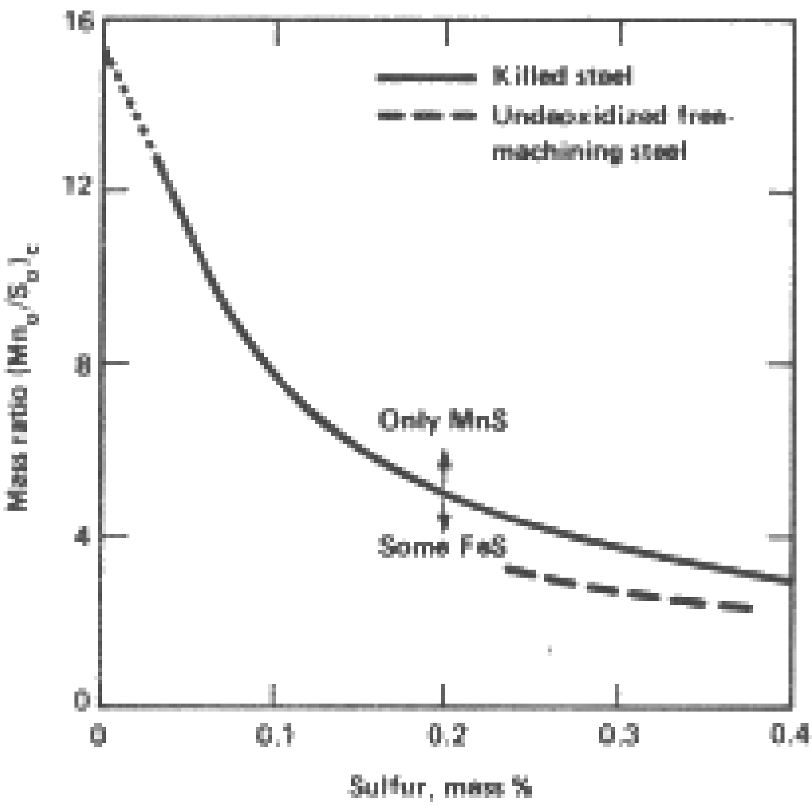


Figure 10. Influence of sulfur content on Mn/S ratio necessary to avoid iron sulfide formation [6].

Even in the case of no occurrence of oxysulfides or FeS, MnS may diminish hot ductility. The shape adopted by manganese sulfides during solidification is influenced by oxygen activity in liquid steel. They are classified as type I, II and III (figure 11). If oxygen

content is high, type I sulfides are formed, also called globular sulfides. They have a large size, and are generally located in the interdendritic space, accompanied sometimes by manganese oxide. These globular sulfides are desirable for free cutting steel, for high machinability. With an intermediate oxygen content, type II sulfides are formed as a network in grain boundaries. Because of this they are also called intergranular sulfides. Type III sulfides arise if the level of dissolved oxygen is low, as in aluminum killed steels.
The presence of type II sulfides (present as aligned sulfide stringers in rolled products) has been related to end splitting [8]. Nevertheless, they are difficult to avoid under standard solidification conditions of silicon manganese killed steels used for civil construction

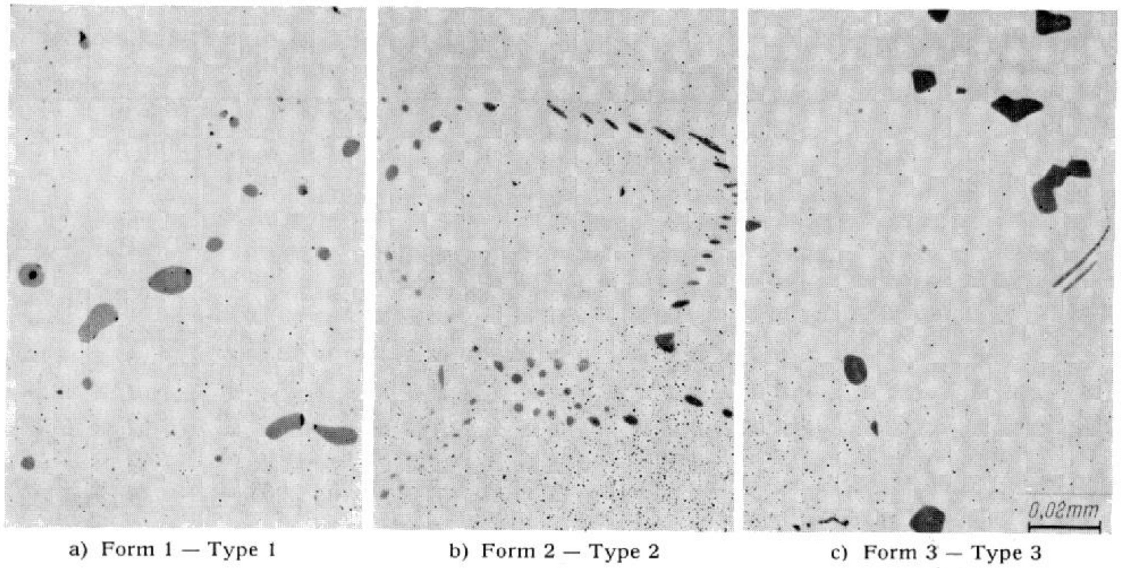


Figure 11. Type I sulfides (left), type II (middle) and type III (right), according to Sims classification [7].

The effect of sulfur on end splitting was clearly present in the aforementioned pilot rolling research, see figure 12. As sulfur is higher, the number of passes till sample rupture is smaller [3].

Temperature control
Hot ductility curves show the need to work within a definite temperature range for each steel type, and particularly for those of low ductility. Results of tests in the pilot rolling mill are also expressive (see figure 13). Just those bars rolled at the higher temperature did not presented open ends.
It must be highlighted that besides the specification and achievement of a suitable reheating temperature for the type of steel being rolled, it is important to take into account that temperature loss should not be too high for a given pass, by influence (for instance) of a displaced roll cooling device. Recently, this was the case in a Latin American plant, with split ends as the result.

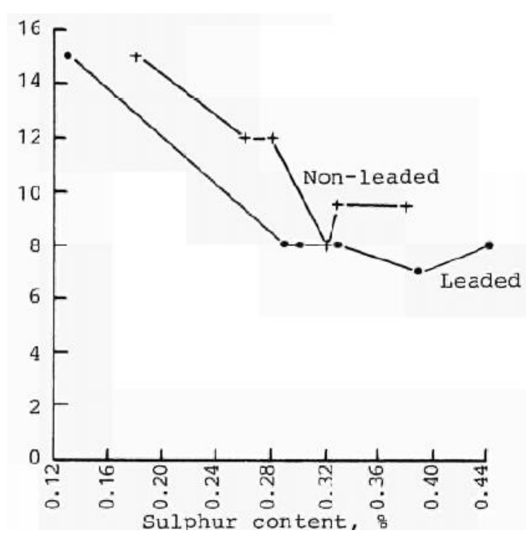


Figure 12. Influence of sulfur content on mean quantity of passes without end splitting in pilot trolling mil, for steel bars with and without lead [3].

Another feature highlighting the incidence of end temperature is the fact that in some cases, an auxiliary burner has been adopted to heat the end, or electromagnetic inductors have been introduced in intermediate locations within the rolling mill.

Pass design
In the already mentioned pilot rolling tests, the tendency to splitting was larger for high reduction, larger roll diameter and for more friction between rolling stock and roll.
Pass design less susceptible to splitting were:

Plane passes
Box-box
Square to round
Oval to round

Oval to square, instead, promoted end splitting.
These conclusions were based on the evenness of stress in the transverse section, and the existence of compression or tension stresses.

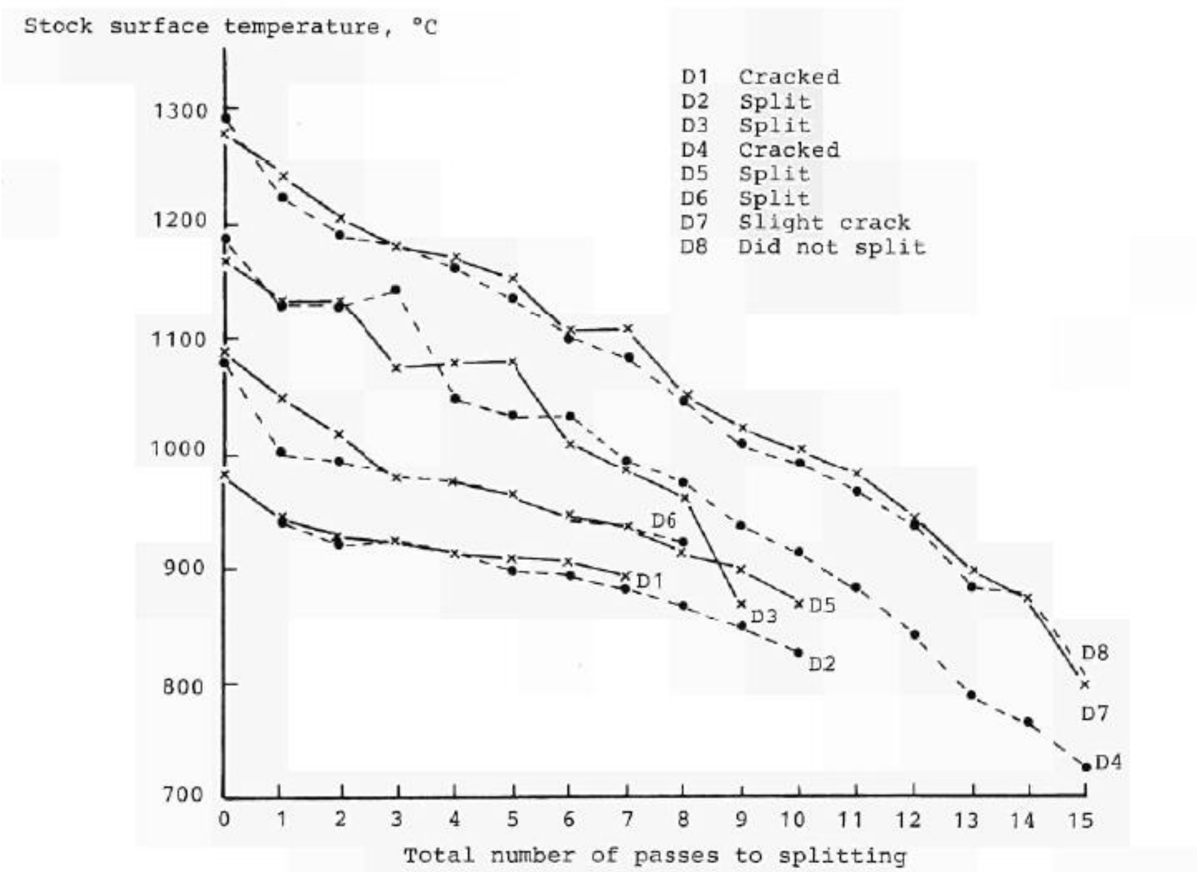


Figure 13. Influence of bar surface temperature on cracking or end splitting trend [3].

Another approach to the analysis of this problem is that of mathematical modeling analyzing end splitting and central burst in the rolling of flats. As an example, a graphic is presented, where the conditions for safe operation are determined, in dependence of pass design variables (figure 14).
The rage of conditions for central bursting to occur would be wider than for end splitting. The proclivity to splitting and central bursting is larger when roll diameter and reduction are smaller.
Other modeling exercises with similar fundamentals obtain coincidental results [9]. For instance, in figure 15 the zone of end splitting risk is presented, as a function of thickness reduction and the ratio between initial thickness and roll radius, for different roll diameter (left) and different friction coefficients between roll and bar stock (right).

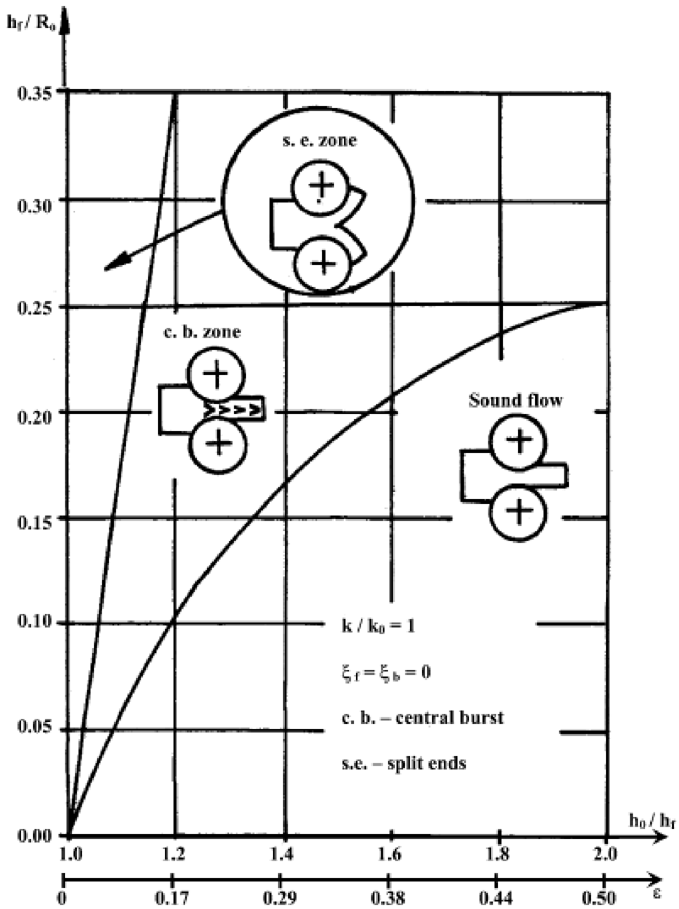


Figure 14. Risk zones for end splitting and central burst during rolling. h_0 y h_f: bar thickness at the entrance and exit of the stand; R_0: roll radii; ε: relative reduction; k: mean value of yield strength; ξf y ξb relative stress in exit and entrance [1].

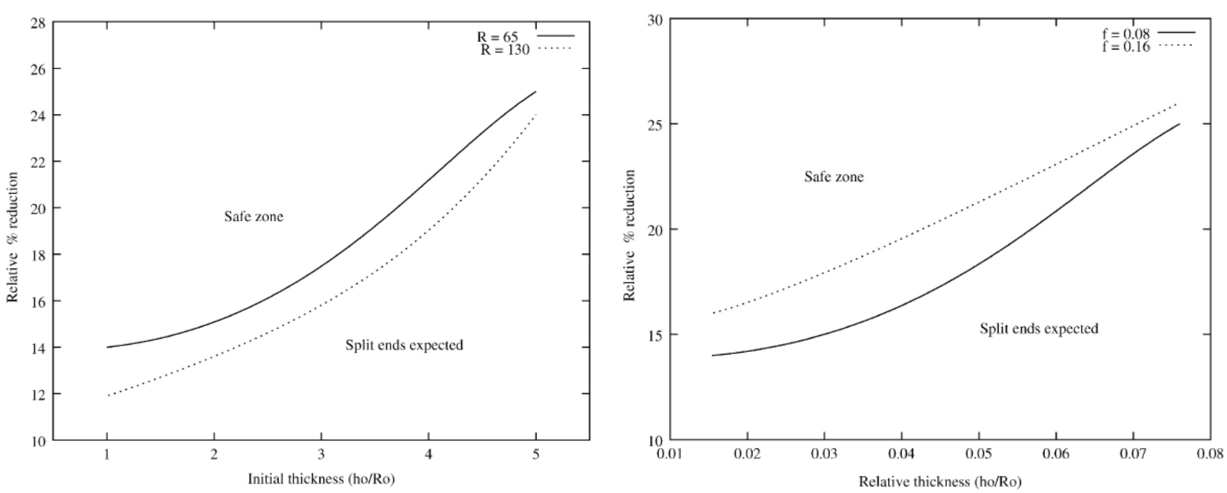


Figure 15. Left: Limit between safe and unsafe zone for different roll radii, using the hydrostatic pressure criteria for end splitting. SAE 1090 steel. Right: Idem for different friction conditions. Roll radii: 65 mm [9].

In this case, it is observed that the smaller the roll diameter and the reduction percent, the larger the trend to splitting, too. Additionally, a higher friction coefficient between roll and bar increases the risk.

These conditions apparently contradict the results in [3]. Tests were carried out rolling plasticine, with a slit in the end. This was done with different roll diameter. After rolling, the dimension of the opening was measured. The result was that the larger the roll diameter, the larger the split opening (see figure 16).

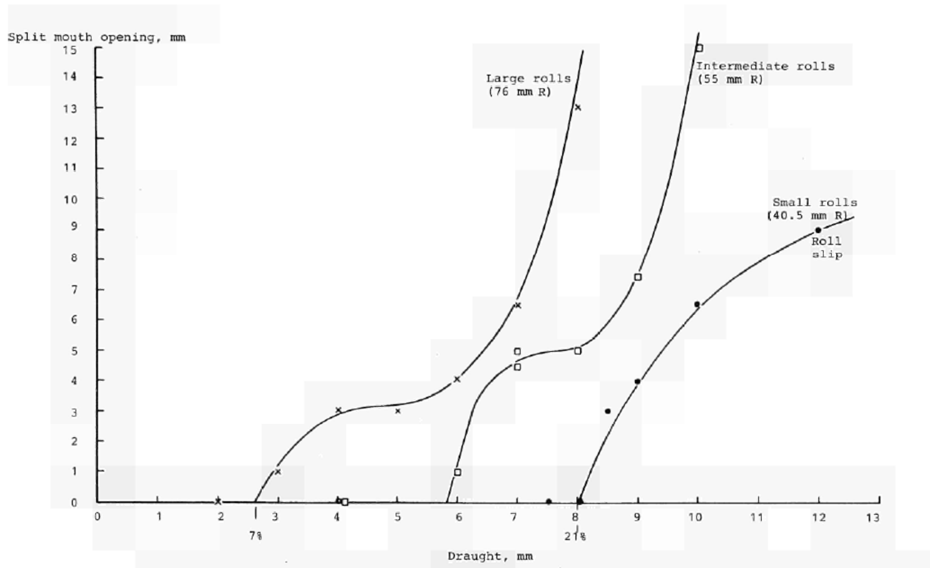


Figure 16. Split end in function of the difference between initial and final bar thickness for different roll diameter, in simulations with plasticine, with a 40 mm depth slit in the end [3].

The same occurs regarding reduction. While model results conclude that in rolling of flats risk is higher for smaller reduction, pilot testing shows the opposite result (figure 17).

Figure 17. Overfilling in box pass with 35% reduction and slip end in pilot rolling [3].

Guiding problems

In some rolling mills, Split ends occur in occasion of bar guiding problems. For instance, when a square pass enter into an oval gap, and the end does not enter in flat position but in diagonal, due to some trouble with the guide, the stress is higher, and after several passes splitting may arise [10].

CONCLUSIONS

End splitting occurs because the material being rolled has not enough ductility to withstand the stress to which it is submitted. This may happens for different reasons. Coarse cracks in the billet end, like central or diagonal cracks, weakens the end, particularly when the plane where are located coincides in part with the symmetry plane between rolls.

Hot ductility of Steel depends on the one hand of their intrinsic features, and on the other hand, on the temperature at which they suffer the stress, and its speed.

It is important to roll the steel within the range of higher ductility at a given deformation speed. This is more critical for steels with inherent low ductility as those containing high sulfur.

The role of MnS stringers is also clear; having S controlled at the lower level of the specification is favorable. Nevertheless it is worth to mention that if caster condition is proper and excessive thermal/mechanical stresses do not arise, very high Mn/S ratio is not necessary.

Bar ends loss temperature faster. Another factor is roll cooling, it has to be correctly oriented, not excessive and keeping the position along the processing time.

In other factors experimental and modeling results are apparently controversial. There is coincidence in the fact that more friction between bar and rolls promotes splitting, but not in factors like roll diameter and reduction.

On the basis of pilot rolling results, plane, box-box, square to round and oval to round passes are favorable to avoid splitting, while oval to square promotes splitting.

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