The Effect of Processing Parameters on the Propensity for Central Fracturing in Piercing

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Successful competition in the seamless tubular products market demands improvements in surface and dimensional quality in products from seamless pipe mills. It is reported that pass design, piercer setup and operating parameters have critical effects on both dimensional and surface quality. Defects which form during the piercing process are the result of these mechanical parameters (which control the localized stress states) in combination with metallurgical factors (which determine the material's resistance to fracture by aggravating stresses). Understanding the detrimental effects of inclusions led to the development of cleaner materials, but economically feasible operations in this direction have been exhausted. Because of this, attention is directed to improvement of deformation limits by control of mechanical processing factors, such as piercer setup and point/pass design. Control of these parameters leads to an optimum pass design that produces conditions favorable not only for enhanced deformation before fracture, but also for energy and power requirements.

In this experimental work the aim was to give more understanding about the relationship between surface quality and processing parameters and their influence on the quality of the shells. As a result, determination of basic causes for occurrence of central fracture was investigated and protection from these undesirable effects was discussed in detail.

INTRODUCTION

The rotary piercing process is the first forming operation in the conversion of a solid circular billet into a seamless tube. It consists of two barrel-shaped rolls with their axes parallel to the vertical plane and angular to the horizontal plane. These rolls rotate in the same direction and are so placed in relation to each other that the heated billet is squeezed between the largest diameters of the rolls. Since the rolls are at an angle to the work piece, the longitudinal component of the force of the rolls pulls the billet forward. As the billet travels along the pass, it meets the piercing point (plug) located between the rolls, and held in place by a mandrel and it is free to rotate. Figure 1 illustrates both the longitudinal and transverse sections of the two-roll rotary piercing operation. When the billet meets the piercing point, the grip of the rolls is sufficient to continue the advance of the work piece against the retarding effect imposed by the piercing point. The piercing point acts like an internal roll and can be considered like two sheet rolling rolls, one on each side of the point, between the point and the roll. It is evident that the forward motion of the billet is caused by the inclination of the axes of the rolls. As the billet travels from initial contact (with the rolls) to the gorge (the shortest distance between the rolls), the diameter of the billet is reduced and the billet section is changed from a circle to an oval with a long diameter in the vertical position, and this is partly corrected by the provision of the adjustable guides. Because of the rotation, the central portion of the billet is subjected to all of the stresses which

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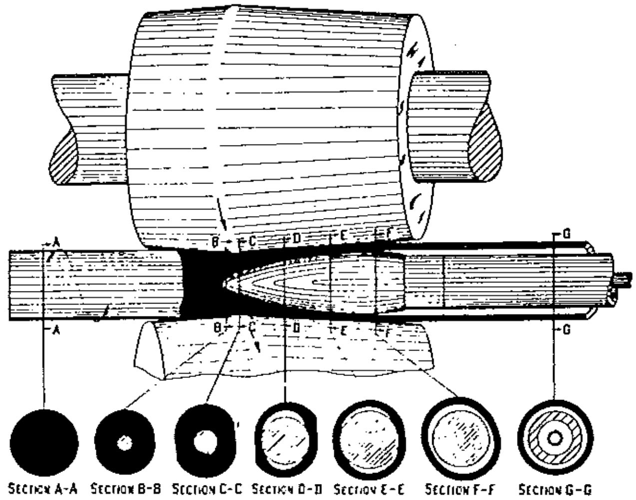


Fig. 1 — Illustrating Action of Rotary-Piercing Mill on the Round Billet.

are applied around its circumference during successive contacts between the billet and rolls. With a sufficient reduction, a cavity will be formed in the center of the billet even without the presence of the piercing point[1]. Because the specimen is rotating, the secondary tensile stress induced at the center, normal to the compressive load line, effectively rotates with respect to a given point in the billet. This means that the regions at the billet center which are in a plastic state, are subjected to a cyclic stressing from tension to compression (Figure 2). This rotating tensile stress state, in combination with the plastic state of the material in the central region, is the mechanism by which internal rupture or void coalescence takes place. In practice, this cavity is not permitted to form in front of the piercing point, since the rough surface of the self-formed cavity might not permit the inner surface of the shell to be subsequently rolled smooth by the action of the point. Because of this, the piercer point is positioned in advance of the gorge so that it will actually effect the opening in the billet, being assisted in its function by the cross-rolling action.

CONCEPT OF THE CENTRAL FRACTURE

The two-roll rotary piercing technology for the production of seamless tubes was developed by the Mannesmann brothers in Germany by 1886. During straightening of the round bars in the two-roll reeler with skew mounted rolls, they noticed that cracks were formed in the center of the bars resulting in a high percentage of scrap. They also noticed that occurrence of the cracks resulted from the alternating stress state in the center of the bars as it rotated between the rolls. The Mannesmann brothers took advantage of this opening-up tendency and pierced the bars with a suitable plug to produce seamless tubes[1].

Despite this advantageous feature of the two-roll rotary machine, there is a tendency for the processed billet to tear apart at the center during the operation. This leads to internal surface defects in the finished product. Pipes with internal defects are rejectable, and they substantially reduce the yield and production rate of the mill. Because of this, any small improvement in this respect can result in significant cost advantages. Therefore, this process imposes severe restrictions on the use of the machine depending on the steel grade. Figure 2 indicates the cross section of the two-roll rotary piercing in front of the piercer point. As seen, the billet undergoes compressive stresses by the rolls as its diameter is reduced with resultant secondary tensile stresses induced at the center. The result is a tendency for cavitation at the center.

Even though the reasons for the occurrence of central fracture are not clear, it is generally agreed that it occurs in the feed region where intensive cross rolling takes place. Since 1886, central fracture has received a great deal of experimental and theoretical attention and various interpretations. Its occurrence at the central region of the billet was observed by many investigators in industry, as well as at research centers and universities. Although some agreements were reached among investigators, there are still controversies in the interpretation of the mechanical behavior of the pierced material that is subjected to failure during piercing.

The oldest theory, based on shear fracture, may still have some validity among investigators[2]. According to this theory, when a steel billet is subjected to the rotary piercing operation, compressive stress is generated in the direction of the external forces. Because the pierced material is rotating, secondary tensile stresses are induced at the center normal to the compressive load line and, as a result, a strong shear stress acts in a continuously changing direction, which finally causes the pierced material to fracture[2].

Another stress approach was put forward by Siebel[3,4]. He assumed that central fracture occurs before the pierced billet reaches the piercer point, so that the presence of the point has no effect on the occurrence of fracture. Qualitatively, the stress distribution in a round which undergoes the compressive load is shown in Figure 3. As seen, the volume element (shaded area) undergoes the compressive stress, σ_1, and tensile stress, σ_2, normal to

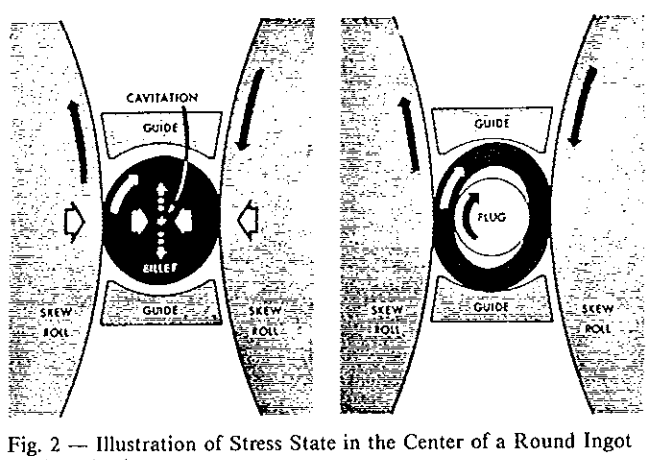


Fig. 2 — Illustration of Stress State in the Center of a Round Ingot During Piercing.

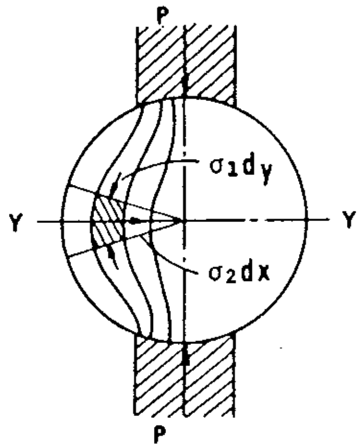


Fig. 3 — Compressive Stress Distribution in a Round.

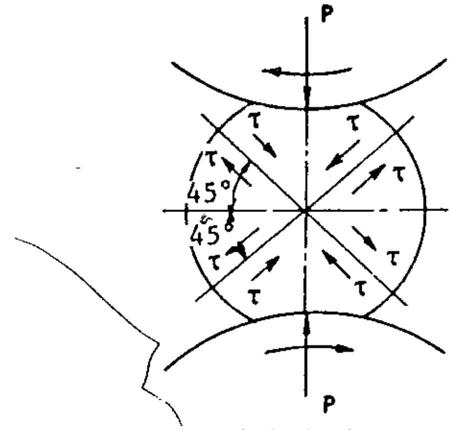


Fig. 4 — Shear Stress Distribution in a Round Ingot Subjected Compressive Load.

the compressive line. In this case, the elastic stress distribution at the center can be shown to be

$$\sigma_1 = -\frac{6P}{\pi D_b \ell} \qquad (1)$$

$$\sigma_2 = +\frac{2P}{\pi D_b \ell} \qquad (2)$$

As the loads are increased, the stress distribution changes and plastic deformation starts to penetrate to the center of the round. The stress difference (σ_2 - σ_1) increases, and it reaches its maximum value at the center. The section of the round becomes approximately an ellipse. When a billet is subjected to this kind of loading by being deformed between two rolls (Figure 4), the surface layer of the billet undergoes plastic deformation only when it comes underneath of the rolls for loading, but the middle part is always subjected to heavy shear stresses, combined with a tensile stress (σ_2) which will appear in the center and will cause central fracture[3]. This theory assumes that the whole length of the billet is loaded simultaneously. In practice, however, only the portion in the deformation zone undergoes loading, the unloaded part of the billet probably changing the stress system in the deformation zone.

In contrast to these theories, another concept was an analogy between transverse forging and piercing[5]. That theory implies that in rotary forging, because of the non-uniform deformation in a billet triaxial tension is generated and the center part of the billet undergoes no plastic deformation, so that cleavage fracture takes place. Transverse forging is a forging process where compressive load is introduced continuously to a round which rotates around its axis (Figure 5). First, radial stresses are generated in the billet by applying the compressive load, then, tensile stresses are introduced as a result of periodical blows. During transverse forging, the outer layer of the piece receives more work and, as a result, takes an ellipsoidal shape more than any inner layers. This, in turn, causes an increase in the diameter of the outer layers (Figure 6).

Because of this action, tensile and compressive stresses are generated in the inner and outer parts of the billet, respectively (curve σ_z). In addition to this, the outer layer also tends to extend in the tangential direction, and tensile stress is generated in the center while compressive stress is generated in the outer layer in the same direction (curve σ_θ). Thus, tensile stresses begin to take place in every main direction and the material has a completely non-uniform state of tension. When the values of these tensile stresses approach one another, plastic deformation will not take place with even large values of tension.

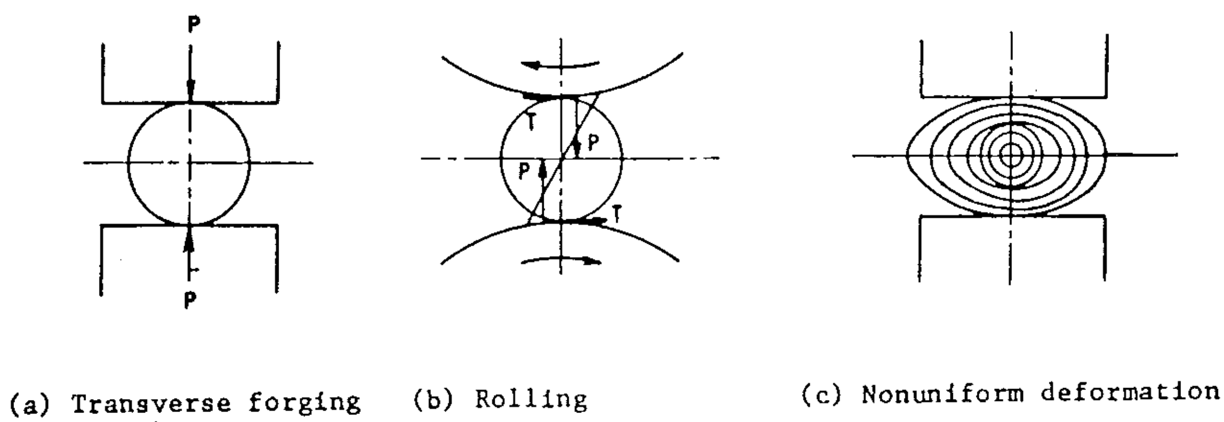


Fig. 5 — Illustrations of Various Stress States in a) Transverse Forging, b) Rolling and c) Nonuniform Deformation.

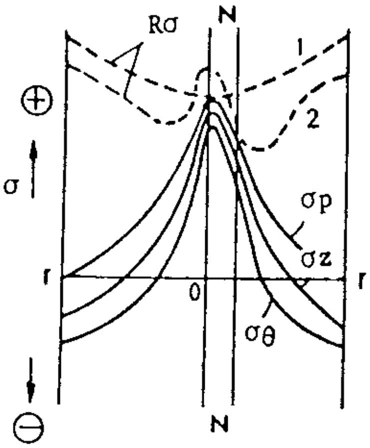


Fig. 6 — Illustration of Stress Distribution in Transverse Forging.

Then plastic deformation continues depending on the effect of the tensile stresses produced at the center. It continues until the largest tensile stress reaches the fracture resistance, R_σ, and a cleavage type of fracture then appears along the rotational axes of the billet. Despite its similarities, the question of whether the behavior of the material in the transverse forging represents the actual case, in rotary piercing (Figure 5), is questionable. There are differences in processing speed, applied force and tangential force.

Although general agreement was reached among the investigators who supported the stress point of view for the cause of the central fracture, practical experience indicates that the problem is not so simple. In fact, it is more complex and understanding the incidence of fracture requires consideration of the deformation involved in the feed region where an extensive amount of cross rolling takes place. Russian work(6) by Teterin implies that, reducing the amount of deformation in front of the plug and reducing the rate of deformation by decreasing the number of turns of the billet, minimizes the possibility of central fracture. Another investigation of the effects of redundant deformation on the efficiency of the process, carried out by Blaznyski and Cole(7), showed that in addition to essential straining of the material, longitudinal, twisting and circumferential shear strains would be introduced and aggravate the severe conditions in the pass. Later, Blazynski used internally marked wax billets to find out the effect of redundant deformation on the occurrence of the cavitation. The most important observation made from this work was that the level of redundant deformation in front of the plug is negligible. It was also observed that the position of the piercer point plays an important role. Since the axial force exerted by the piercer point on the billet is compressive, its (lead) increase will tend to inhibit central fracture. Thus, a large plug advance is shown to have the desirable tendency of inhibiting the incidence of central fracture. This work verified earlier Russian work on the same subject(8). An increase in plug advance, however, has its negative effect in that occurrence of wall laminations is likely. Therefore, the increase in lead must be carefully balanced with the tendency to laminate. Finally, they came to the conclusion that stress concentration and high strain rate in front of the piercer point were mainly responsible for the occurrence of central fracture.

Now it is clear and generally agreed that the magnitudes of stresses and deformations, and also any lack of uniformity in them, depend upon the point/pass design of piercing mills. This in turn, effects the occurrence of the central fracture. Thus, the necessary conditions for developing a theoretical approach to the problem of pass design, the effect of point/pass geometry, roll geometry and process variables on the quality of the finished tubes, should be investigated. They have received a great deal of attention in the past, however, no systematic study has been conducted to determine the effects of processing parameters on the formation of internal cracks.

Effects of the reduction in front of the piercer point, roll inclination angle, ovalization and temperature on the occurrence of internal fracture were investigated under actual conditions(9). In those experiments, the reduction in front of the piercer point was varied from 2.9 to 12.4%. It was shown that increasing the reduction from 3 to 8% has practically no effect on the occurrence of central fracture. On the other hand, increasing the reduction beyond 8% leads to an increase in the number of tubes with central fractures. The effect of the angle of the inclination of the rolls and ovalization on the occurrence of internal fracture was also investigated. In this experiment, reductions in the gorge and in front of the point were 11.5 to 14% and 3.0 to 5.5%, respectively. It was shown that the inclination angle of the rolls and ovalization have practically no effect on the occurrence of internal fracture with these particular setting parameters.

To investigate the effect of temperature, experiments were made on four heats of steel grades. Each heat was divided into three portions, which were rolled at normal temperature (group A), 30-35°C above the top limit (group B) and 30-35°C below the minimum permitted temperature (group C). It was observed that with increased heating temperature, the number of tubes with internal fractures increased(9). That effect can be attributed to the fact that, before the billet reaches the piercer point, the heat input to the billet not only consists of furnace heating (and for this experiment, overheating which produced a soft localized mushy surface) but also of heating caused by redundant mechanical and friction work in the feed region. Thus, surface temperatures were in excess of 1370°C, so that cracking could be directly attributed to the loss in hot ductility.

To summarize, it can be said that there are two distinct types of fracture that take place at the center of the billet during deformation. It either occurs before the leading end of the billet reaches the piercer point or it takes place just at the nose of the piercer point as a result of the presence of the point. As discussed, there is no definite agreement about their occurrence. However, mechanical factors which disturb the stress and strain history of the system are mainly responsible for their appearance.

These mechanical factors (which control the localized stress state) in combination with metallurgical factors (which determine the material's resistance to fracture by aggravating stresses) cause this detrimental result. Combination of these factors can be categorized into three groups: (a) material parameters, (b) process parameters and (3) geometric parameters. The first group involves material properties such as composition (steel grade) of the pierced material, piercing temperature and the structure of the material. The second group results from the process itself, namely, tangential and axial slip, piercing speed, feed efficiency*, stich-zahl** and feed angle, and the third group involves the design variables of the setup and point. Now it is clear that control of these parameters can lead to an optimum mill design which would give the best quality products, free from every kind of imperfections.

EXPERIMENTAL PROCEDURE

To investigate the influence of the processing variables on the propensity for central fracture in piercing, round ingots were pierced into larger diameter shells with an expanding pass design. For the experiments, the design of the piercer points was based on a schedule aimed to obtain a uniform wall reduction. Figure 7 illustrates the shape of experimental points, 1 (dashed) and 2 which give 30-35% wall reduction per successive turn. All the points were specially designed to determine the influence of the deformation rate, point shape, heavier and/or lighter wall reduction schedule on the occurrence of central fracture. For example, the piercer points shown in Figures 8 and 9 provided higher uniform wall reductions (40-45%) in each successive turn of the billet through the pass. In this respect, different setups were employed during the experiments. The setups included the current lead and gorge and both an increase and decrease in the lead with corresponding corrections in the gorge to produce the same proposed shell size. These two most important processing parameters, roll gorge and point lead, were systematically varied to determine their effect on the occurrence of central fracture.

To investigate the effect of point shape with the combination of processing parameters, special machined piercer points were employed. Figures 10 and 11 show point and blunt-nose point, respectively. In the non-machined condition, shown by the dashed lines, these points would have some lead. The set-up parameters for the short and blunt-nose points, however, have zero lead, with the same gorge value. During experimentation, these setups provided intensive amounts of work in the center of the billet and in the feed region of the mill pass.

*"Feed efficiency" is the ratio of the delivery speed of the pierced shell to the axial component of the peripheral speed of the rolls at the gorge.

**"Stich-zahl" is the number of revolutions of a planar section of the round in the feed region of the piercer setup.

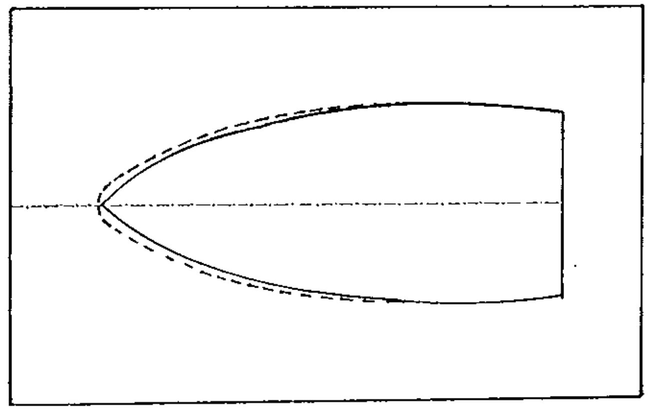


Fig. 7 — Illustration of the Point Profiles 1 (dashed) and 2 (solid).

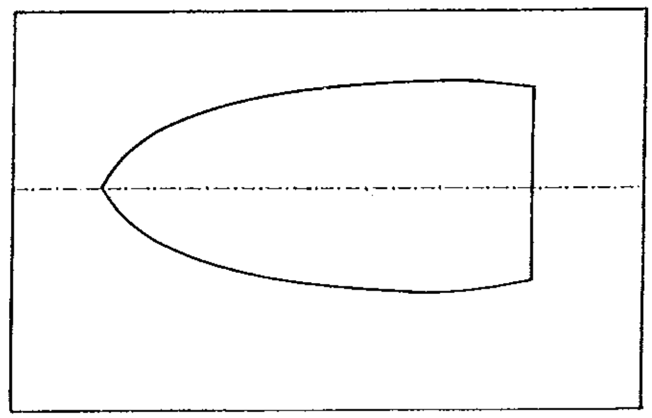


Fig. 8 — Illustration of the Experimental Point Profile 3 with Heavier Uniform Wall Reduction and Shorter Point Working Length.

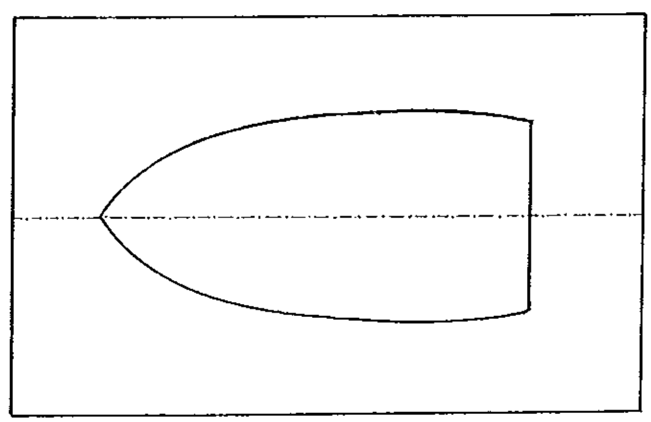


Fig. 9 — Illustration of the Experimental Point Profile 4 with Heavier Uniform Wall Reduction and Shorter Point Working Length.

Thus, these special profiled points were supposed to change the deformation history from that occurring in normal processing conditions. Round ingots were pierced using these specially designed point profiles under various processing conditions. After the experimentations, for comprehensive inspection, piercer stickers were taken from these setups, and they were sectioned for assessment of the deformation characteristics of the piercer points with the combination of setup variables.

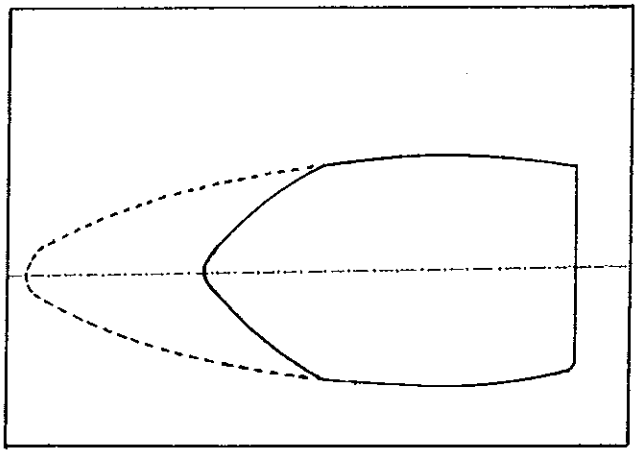


Fig. 10 — Illustration of the Short Point Profile.

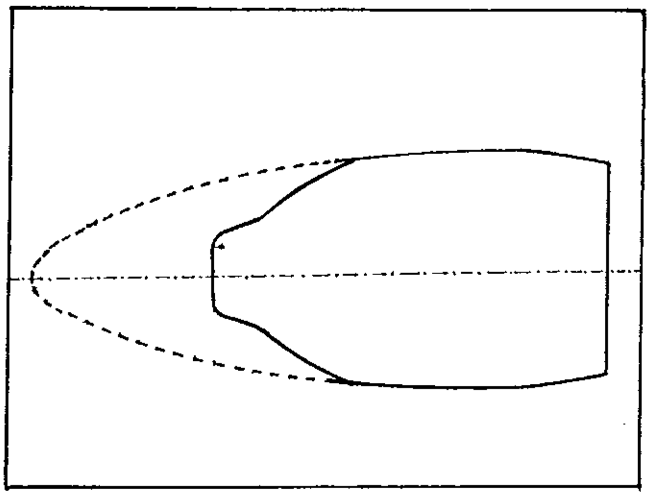


Fig. 11 — Illustration of the Blunt-Nose Point Profile.

Metallographic studies were also concentrated on the deformed and non-deformed specimens to determine the metallurgical center integrity of the billets where the initiation of central cavitation would take place.

DISCUSSION

To analyze the surface quality, the two most important variables, the feed efficiency and stich-zahl values, were computed and results were evaluated. Surface quality is related to the feed efficiency which is an important factor that controls the production rate and effective working volume that undergoes a relatively large amount of cross rolling in the feed region, with the potential danger of incurring fractures in the center of the billet. This performance variable varies quantitatively with the tooling surface condition of the rolls, billet material, piercing temperature, strain rate, roll speed and, more importantly, piercing setup. By its definition, a higher feed efficiency means a higher production rate through the piercer, while a small feed efficiency describes a small advance per revolution of a planar section of the billet through the feed region. Figure 12 illustrates the helical advance of the billet in four functional regions. In this work a mathematical expression which describes the feed efficiency quantitatively, was developed and given by:

$$\eta = \frac{\nu_0}{\pi D_g n \sin\theta} \; 100\,(\%) \qquad (3)$$

In regard to surface quality, the number of revolutions of the billet (stich-zahl) in the feed region were calculated. Stich-zahl is also an extremely important factor that controls the quality of the pierced shells. It is important because the work done on the round in the feed region is related to the numbers of the turns from roll contact to the nose of the point, In this study, another mathematical expression was developed to describe the number of turns in the feed regions, given by:

$$N = \frac{D_b\, L_f}{4A_c\, \eta\theta} \qquad (4)$$

With regard to cracking, sectioned stickers were examined, and two of these stickers, which were pierced with heavy-wall-reduction schedules with shorter point working length, exhibited fractures that occur in the porous central regions of the round just ahead of the nose of the points. Figures 13 and 14 illustrate the cracking at the nose of the points. Conversely, other stickers produced with a pass design with a lower stich-zahl and lighter average-wall-reduction schedules, exhibited no axial center fracturing.

Examination of the stickers showed that the occurrence of fracture ahead of the points under the aforementioned circumstances is a function of the point working length and point shape while stich-zahl, in this case, is secondary. The working length determines the rate of reduction from solid to tube, that is, the conversion from solid billet to a hollow shell is controlled by the length of the piercer point. The shorter the point length means the quicker the conversion from billet into a hollow shell, so that it provides conditions which give either higher or lower deformation rates. This working length is controlled by the length of the outlet of the rolls as the tube must produce in the mill with a required shell wall thickness. Therefore, the occurrence of central fracture is

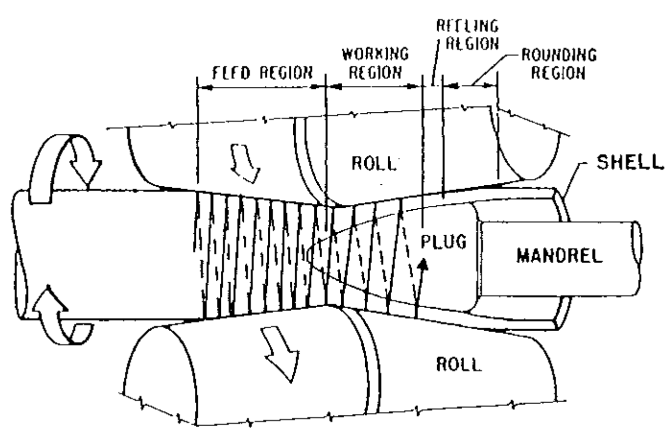


Fig. 12 — Illustration of the Helical Advance of a Billet in four Functional Regions.

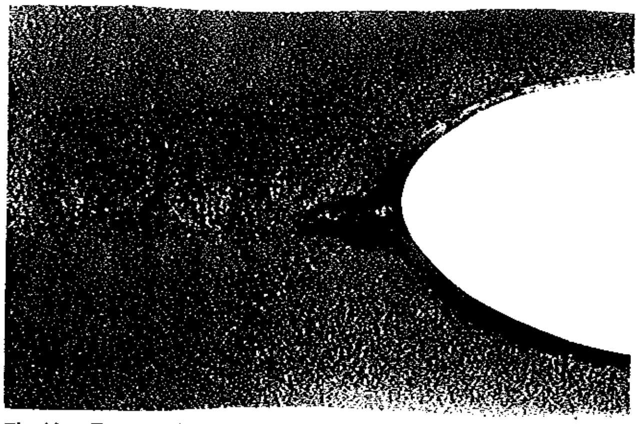


Fig. 13 — Fracture Appearance at the Nose of the Experimental Point 3 with Heavier Uniform Wall Reduction.

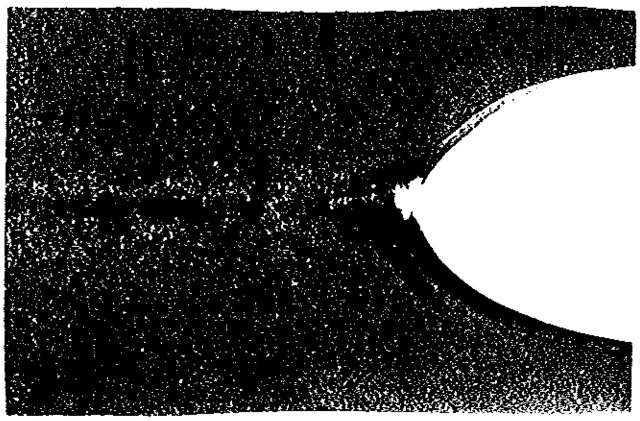


Fig. 14 — Fracture Appearance at the Nose of the Experimental Point 4 with Heavier Uniform Wall Reduction.

directly related to the working length (high reduction schedule) and the shape of these new designed experimental piercer points.

The sticker with point type 2 was the only one without fracture appearance. It was designed to achieve a lighter-wall reduction schedule (longer working length) and was machined from point type 1 (dashed line in Figure 7) to reduce the amount of deformation rate introduced at the nose of the point. As discussed before, the presence of the point substantially influences the stress and strain state of the materials at the head of the piercer point. Also, the sensitivity of the material to fracture reaches its maximum value at the head of the nose even though a very small disturbance of the metal flow from its uniform pattern causes a quick-tearing of this region. The tendency to fracture can be attributed to: a) loss of ductility due to the excess amount of heat generated in the center because of the high stich-zahl which introduces greater mechanical and frictional work, b) metallurgical defects (porous structure, segregation, etc.), and c) deformation rate (point working length). These factors accelerate occurrence of the fracture. Under a specific deformation condition, when the reaction stresses imposed by the piercer point against the material flow exceed the fracture strength of the billet material, failure will occur. The magnitude of these stresses imposed by the point greatly depends on the deformation rate, temperature and, more importantly, the shape of the continuously contacting portion of the piercer point*, and point length. Figure 15 illustrates the significance of the piercer nose shape with a deformation rate which is higher for point 1 than point 2 at the nose of the points. Another mathematical expression for the rate of deformation in terms of the point/pass geometry was developed, given by:

$$\dot{\epsilon} = \frac{\nu_o \theta \eta (D_b - D_g + D_p)}{D_b (D_b - D_g)} \qquad (5)$$

Thus, point design as well as setup parameters are very important factors to control the final quality of the shell. In the design of new piercer points, minimum resistance to metal flow with uniform wall reduction schedule, mimimum deformation rate, and roll contour with a good fit to the piercer points, should be provided.

Those stickers obtained from the setups that employed zero lead and heavier wall thickness exhibited fractures that took place at the center of the billet in the feed regions. Figure 16 illustrates the initiation of the fracture and its propogation in the feed region for the setup with the specially machined blunt nose piercer point. The fracture initiates just after the billet completes its first rotation at the beginning of feed region (Figure 16a). It gets larger and larger in the subsequent rotations and the largest pipe formation takes place just in front of the lead where ingot gets contact with the blunt nose point (Figure 16f). Examination of the stickers and analysis of the data

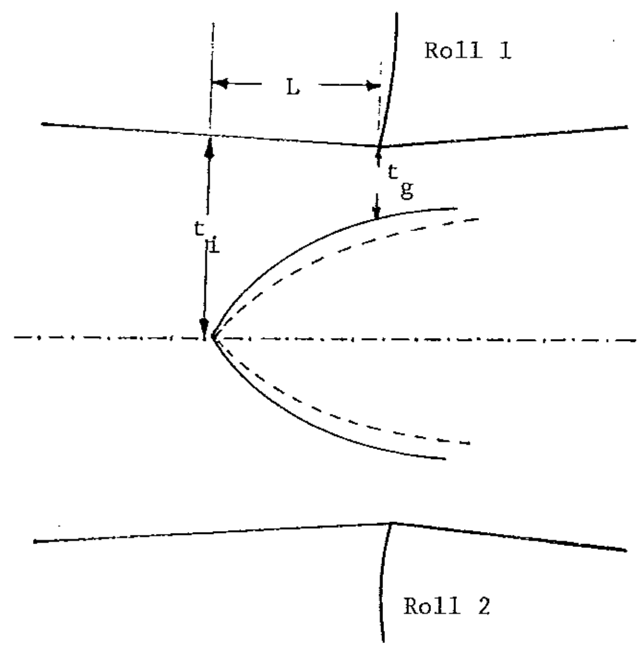
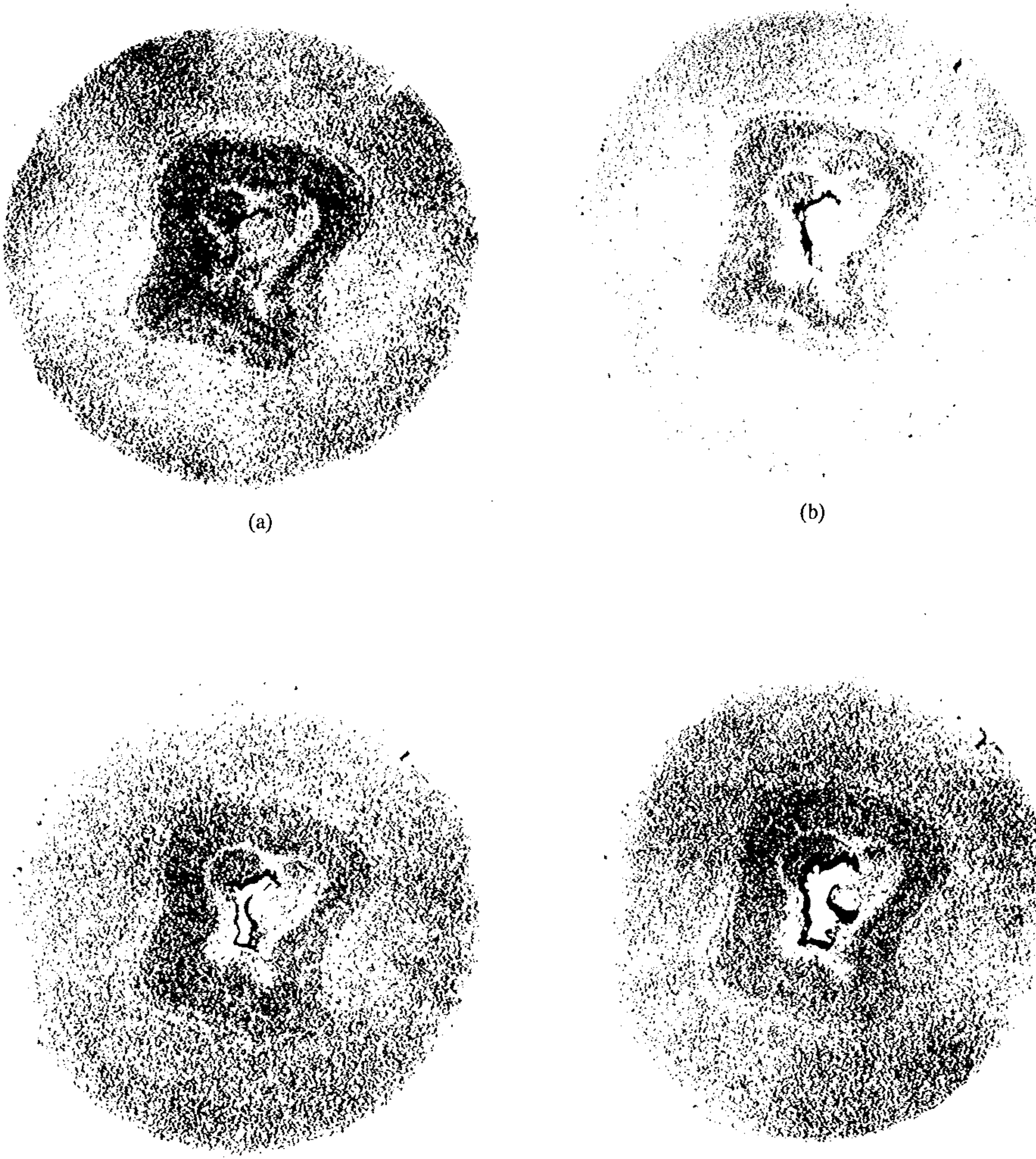


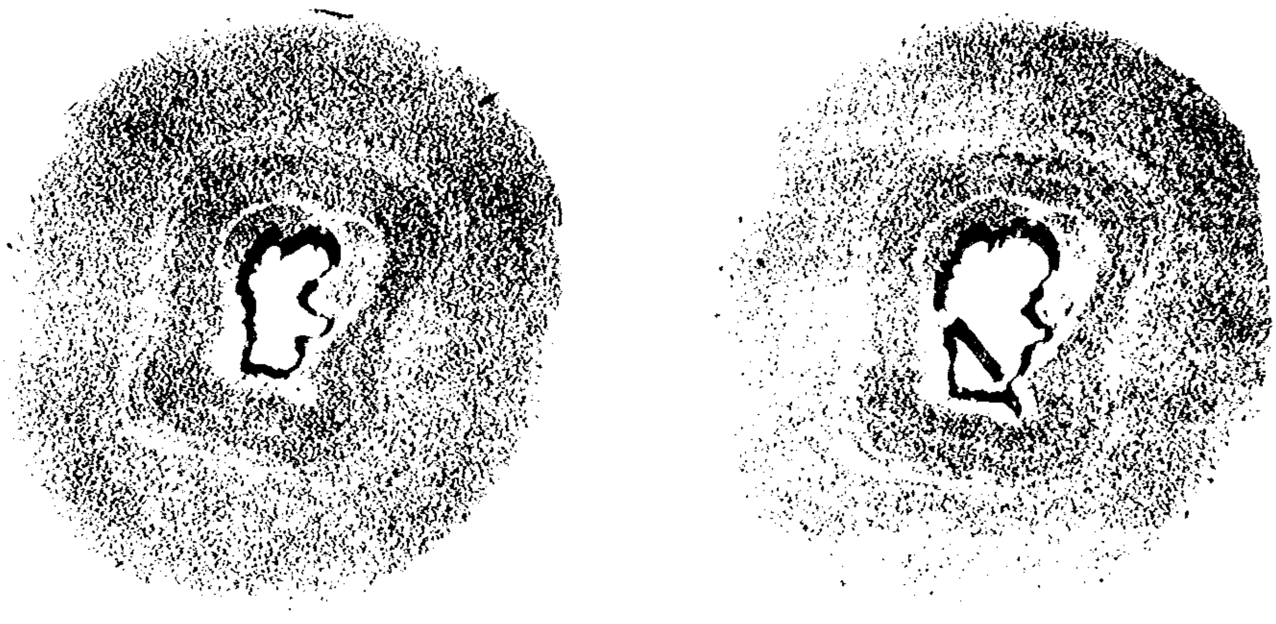
Fig. 15 — Illustration of the Differences between the Piercer Nose Shape of Point 1 and 2.

*Only a limited portion of the billet is continuously in contact with the material; the rest of the working length undergoes cyclic contact with the billet due to the ovalization.



(a) (b)

(c) (d)



(e) (f)

Fig. 16 — Illustration of the Initiation of the Fracture and its Propogation in the Feed Region for the Setup with Blunt Nose Piercer Point.

indicate that the occurrence of central fracture is directly related to the number of turns. This indicates that a relatively large amount of cross rolling occurs in the feed region.

Figures 17 illustrates the stress state in the transverse section of the round in the feed region during successive turns. As can be seen, compressive stresses (F1 and F2) act in the transverse direction while the roll tractive forces (T1 and T2) act in the tangential direction. The resultant components of these forces (P1 and P2) make a 45 degree angle with the applied compressive and tractive forces. The magnitude of these resultant stresses increases as they move deeper into the center of the billet. Finally, these separated ellipses become almost a flat line and the stresses, having shearing characteristics, reach their maximum value by producing a maximum amount of internal friction at the center of the billet. The value of the shear stress at this moment can be calculated from the expression given by:

$$T_{xy} = \frac{4P}{\pi D_b \ell} \tag{6}$$

These heavy shear stresses in combination with secondary tensile stresses cause failure of the processed billet at the center. Once it forms, an easy propagation mechanism immediately takes place. Figure 18 illustrates the propagation of the central fracture from where it initiates. As can be seen, because of the rotation, an already initiated fracture line undergoes a very heavy cyclic stress state, under the action of the aforementioned causes. Enlargement of the crack takes place when this radially orientated crack receives transverse compressive stresses from the rolls during the subsequent deformation

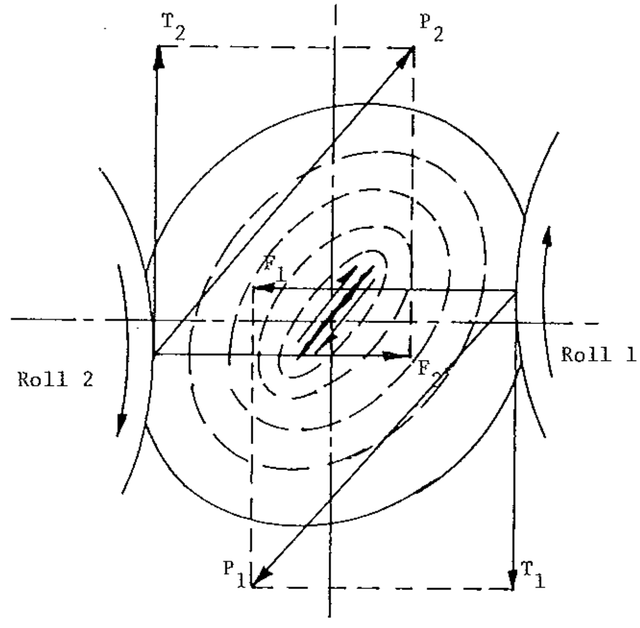


Fig. 17 — Illustration of the Stress State in the Transverse Section of a Round in the Feed Region.

process (Figure 18d). Propagation and enlargement of the fracture due to the stress state of the system reach their maxima with the combination of the increasing number of turns and the amount of cross rolling in this particular region. Finally the center of the billet looks like a pipe as illustrated in Figure 16. When the piercing operation is completed in this manner fractures in the inside surface appear as blisters and/or roughs as illustrated in Figure 19.

Protection from the occurrence of the piping requires: (a) changing the existing stress state of the system by providing an optimum point/pass design, (b) reducing the number of revolutions of the billet at the beginning and through the rest of the deformation zone by providing an optimum lead, c) reducing the amount of cross rolling that takes place in the feed regions, by increasing the feed angle, increasing the gorge, increasing the inlet angle of the rolls and/or decreasing the draft depending on the design, and (d) increasing the hot ductility of the steel, which requires an optimum temperature for piercing.

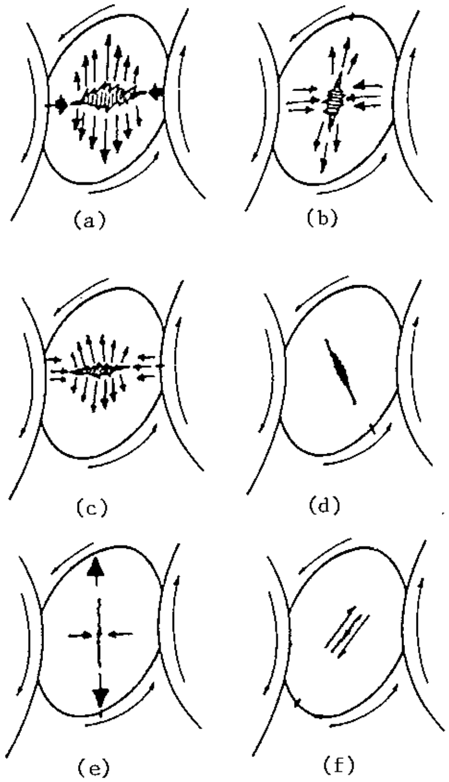


Fig. 18 — Illustration of the Formation of the Fracture and its Propogation in the Transverse Section of a Round in the Feed Region during Successive Turns.

CONCLUSION

Two types of fractures were considered in this study. In the first, in which the central fracture takes place at the head of the piercer point, occurrence of this fracture is related to the nose shape, the working length of the piercer point and high "stich-zahl". For protection from its occurrence, it is suggested that an optimum pass design schedule requires (a) a uniform wall reduction schedule which provides minimum deformation rate with a good fitting combination of the roll contour through-

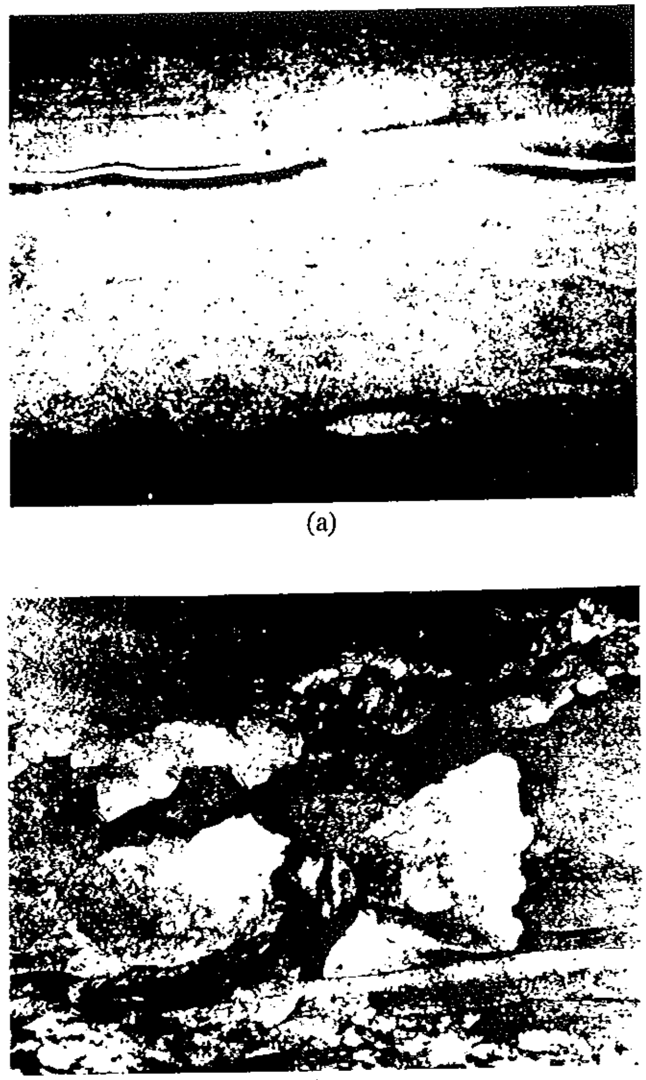


Fig. 19 — Illustration of the ID Surface Fracture Appear as (a) Blisters and (b) Roughs.

out the pass, (b) piercer points with minimum resistance to the metal flow, (c) lower stich-zahl.

In the second type of fracture, piping is caused by (a) improper pass design, (b) too many revolutions of the billet (too much cross rolling) and (c) loss of ductility (valid also for the first case). It can be avoided by providing an optimum mill design schedule. From these results, it is concluded that piercer setup and operating parameters have critical effects on the final quality of shells. Defects which form during the piercing process are the result of the aforementioned mechanical parameters which control the localized stress state, in combination with metallurgical factors which determine the material's resistance to fracture due to aggravating stresses.

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Symbol	Nomenclature	Units
σ_1	Compressive Stress	psi
σ_2	Tensile Stress	psi
D_b	Billet Diameter	inch
ℓ	Billet Length	inch
P	Pressure	psi
η	Feed Efficiency	%
ν_o	Axial Component of Roll Velocity	inch/sec
D_g	Roll Diameter at Gorge	inch
n	Roll Speed	rps
θ	Feed Angle	Rad.
N	Number or Revolutions	—
L_f	Length of Feed Region	inch
A_e	Shell Cross Sectional Area	$inch^2$
D_p	Point Radius at Gorge	inch
T_{xy}	Shear Stress	psi

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