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STRESS ANALYSIS OF CATHODE BOTTOM BLOCKS

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A 2-dimensional finite element model, which makes it possible to study the thermal stresses in cathode bottom blocks formed due to thermomechanical interactions between the current collector bar and the carbon block, has been developed. The model computes the stresses in a vertical cross sectional area of the bottom block, *i.e.* the stresses which are responsible for wing cracks and other longitudinal (block) cracks from the slot to the top of the bottom block. This paper concerns the thermomechanical stresses formed in cathode bottom blocks with ramming paste sealed collector bars.

INTRODUCTION

The service lives of aluminium cell cathodes depend on the lining practices, workmanship, materials and pot construction, but also strongly on the procedures followed during preheating, start and operation of the cell. Improper materials as well as poor execution of any relining or operational procedure may result in materials failures that can have serious consequences for the lining. Cracking of bottom blocks and early penetration of bath and metal may result in faster heaving of the bottom carbon pane, followed by extensive lining deterioration and deformation of the shell until the cell is finally shut down when the liquid aluminium gets contaminated by large amounts of dissolved iron from the current collector bars. Another important matter is that the cathodic voltage drop and the electrical power consumption in the cathode are increased as a result of the high electrical resistivity across a crack in the current path.

The preheating and starting procedures are always critical for crack formations. If the sealing of the collector bar to the carbon block is done by cast iron, the stresses may get very high due to the severe thermal shock, and cracks may be formed. These cracks are, however, visually detectable in a short period after casting, making it possible to prevent that a block with cracks is installed in the cathode. Previous works by Letizia *et al.* [1] and Michard [2] on the thermal stresses formed in cathode bottom blocks during cast iron sealing gave interesting results on how to minimize these critical stresses.

Other methods often applied in order to seal the current collector bar to the carbon block is by using a ramming paste or a carbon glue. The paste or glue is applied at ambient temperature and thermal shock during sealing is avoided. Nominally failure-free blocks are therefore installed. However, interactions between block, collector bar and baked paste/glue during preheating, start and operation will lead to formation of stresses that may crack the carbon. These cracks are usually not detectable and may adversably influence cell performance as well as pot life.

In order to reduce the probability for crack formation in the carbon block, a finite element model has been developed. The model is based on bottom blocks with collector bars sealed by carbon ramming paste, and a thermomechanical approach is used to analyse the stresses and crack formations. The model has been used to study the following parameters which will be discussed in the paper:

- Bar slot geometry.
- Elasticity of ramming paste between carbon bottom blocks.
- Chrushable or rigid endwall lining.
- Friction between collector bar and carbon block.
- Carbon block geometry.

The model has made it possible to propose favourable alterations in the block and slot geometry, collector bar installation, and cathode lining procedures.

THE FINITE ELEMENT MODEL

The 2-dimensional model is based upon a vertical cross section of the bottom carbon pane including the collector bars, a layer of graphite powder in the bottom of the slot, and ramming paste as collector bar sealant and in the joints between the blocks (Figure 1).

Due to the repetitive and symmetrical nature of the bottom lining, it is possible to simplify the model by choosing only a part of it, or more precisely; half a block with its surroundings. The actual geometry of the block, slot and collector bar is taken from cathodes at Mosal Aluminium's Mosjøen plant in Norway.

The high shear stresses formed at the interface between bar and block may give rise to a vertical displacement between the bar and the block. To account for this, the model includes gap elements, elements with properties simulating the gap or the interface between the two materials, also including friction. The gap elements may be imagined as steel springs. All other elements are isotropic and linear elastic shell elements with materials properties determined experimentally on cathode lining materials.

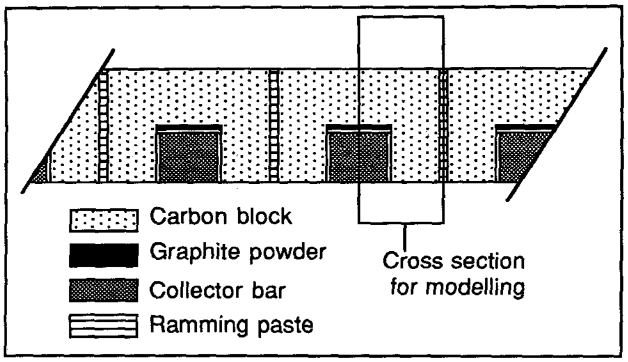

Figure 1. Cross section of part of the carbon bottom pane shows the selected part for modelling.

The elements for calculation and the planes of symmetry and constraint are shown in Figure 2. The gap elements show approximately zero stiffness to tensile stresses, but infinitely high stiffness by compression. Sliding is described by a coefficient of friction. It is assumed that no forces are acting on the block or the bar from the lining beneath. This is reasonably because the 2-dimensional model only considers the interaction between the block and bar, and not the mechanisms resulting in block heaving. The elements simulating the ramming paste between the blocks are constrained in horizontal direction, except for Case 5 where the effect of chrusable lining is studied.

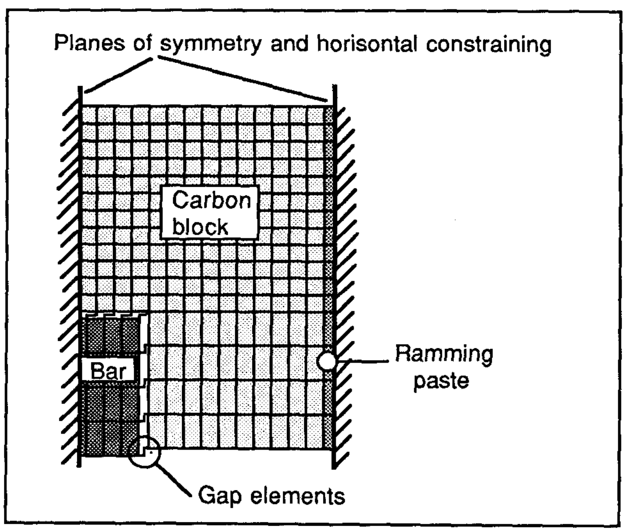

Figure 2. The 2-dimensional model for stress analysis.

STRESS MECHANISMS AND FRACTURE CRITERIA

Temperatures and thermal stresses in the carbon block show the largest variations during preheating, start-up and early operation of the cell. The ramming paste sealant between the block and the collector bar remains plastic up to about 500°C and only marginal stresses will occur below this temperature. At higher temperatures, when the paste is baked, the stresses will vary mainly due to differences in thermal dilation between carbon and steel. These differences are caused by some paste shrinkage, a continuous thermal expansion of the block, and a temporary shrinkage of the steel bar caused by a phase transformation (α-Fe $\rightarrow$ γ-Fe), starting at about 700°C. The highest stresses appear shortly before this phase transformation and at the highest temperatures when the difference in thermal expansion between the bar and the block is at its highest (Figure 3). Hence, these are the most critical states for crack formation and the conditions at 950°C have been chosen for the calculations. The thin layer of baked paste sealant between the current collector bar and the prebaked block is regarded as a part of the block in these calculations.

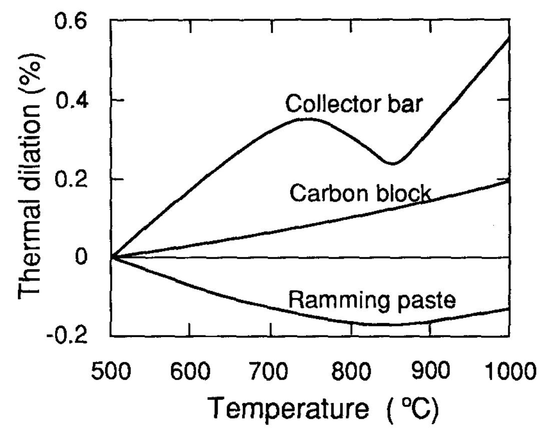

Figure 3. Thermal dilation of current collector bar, carbon block and ramming paste in the temperature range between paste baking (≈500°C) and cell operating temperature.

Thermal stresses formed in the block due to forces acting between the vertical slot faces and the current collector bar result in concentration of compressive stresses in the wings and tensile stresses in the carbon block above the bottom, *e.g.* upper part, of the slot (Figure 4). The criterion for tensile fracture is simply the tensile strength, a fracture will appear when the tensile stress exceeds the tensile strength of the material.

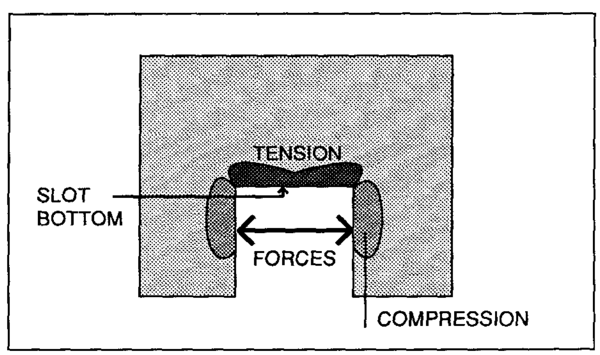

Figure 4. Stress zones caused by the forces acting between the collector bar and the carbon block.

The highest shear stresses appear in areas where the largest differences between tensile and compressive stresses are found. These areas are near the slot corners where both tensile and compressive stresses are high.

The Coulomb criterion for fracture in brittle materials may be used for the shear fracture in a plane [3]:

$$|\tau| + \mu\sigma = S_o \quad (1)$$

where μ is a coefficient of internal friction, σ and τ are the normal and shear stresses across the plane and S_o is an inherent shear strength. An important consequence of this equation is that the shear strength is dependent on the normal stress across the plane. The Coulomb criterion may also be written as:

$$\sigma_2 = -\sigma_- + q\sigma_1 \quad (2)$$

where q is given by:

$$q = [\sqrt{\mu^2+1} + \mu]^2 \quad (3)$$

σ_1 (tension) and σ_2 (compression) are the major and minor principal stresses, respectively, while σ_- is the uniaxial compressive strength. For amorphous cathode carbon blocks the internal coefficient of friction is approximately 0.75, giving the value $q \approx 4$. Together with the tensile strength, σ_+, we have the final criteria for tensile failure and shear failure:

$$\sigma_1 > \sigma_+ \quad (4)$$

$$\sigma_2 > -\sigma_- + 4\sigma_1 \quad (5)$$

Another important consequence can be deduced from the Coulomb criterion. The tensile failure will appear in the plane with the highest tension while the shear failure will appear in a plane different from the plane with the highest shear stress. The most critical plane for shear failure can be found by solving Equation (1) with regard to the principal stresses and the angle between the critical plane and the principal stress:

$$\left|\frac{\sigma_1 - \sigma_2}{2}\sin 2\phi\right| + \mu\frac{\sigma_1 + \sigma_2}{2} + \frac{\sigma_1 - \sigma_2}{2}\mu\cos 2\phi = S_o \quad (6)$$

where ϕ is the angle between σ_2 and the plane with the shear stress τ. The angle for the plane with the most critical shear stress is then found by solving $dS_o/d\phi = 0$:

$$\phi = \frac{1}{2}\tan^{-1}\left(\frac{1}{\mu}\right) \quad (7)$$

With the internal coefficient of friction equal to 0.75, Equation (7) results in $\phi \approx 27°$, which is the angle between the axis with the lowest principal stress (compression) and the plane with the most critical shear stress. This angle agrees well with failures observed during uniaxial compression tests of cathode carbon specimens.

The consequence of this result is that the angle between a tension and a shear failure is only 27°, in contrast to 45° which is the angle between the planes with the highest tensile and shear stresses. This should be in mind when bottom block failures are studied during cathode autopsies.

The mode of failure is important when the stresses are related to the probability of fracture. Increased overall compressive stress in the block increases the risk of shear fracture, while the risk for tensile failure are almost unaffected. Increased tension makes the probability for both tensile and shear fracture higher.

THE BAR SLOT GEOMETRY.

Prior to sealing the collector bar in the slot, a layer of ramming paste or graphite powder is usually spread out in the slot bottom. The model shows that the thickness of this layer is important with regard to the magnitude of the tensile stresses near the inside slot corners. By increasing the thickness from zero to 2.5 cm, the highest tensile stresses are reduced by 60 % (Figure 5), which means a considerably lower probability for tensile failure.

According to the criterion for shear failure (Equation (5)) a lowered tensile stress should allow higher compressive stresses before fracture. However, the areas with the most critical tensile and shear stresses are not the same, stressing the fact that both tensile and compressive stresses should be considered at a given position in the block. By using the Coulomb criterion, the value 25 MPa for the uniaxial compressive strength, and the principal stresses found in Figures 5 and 6, it is found that the change in shear failure probability for a point close to the slot bottom corner is slightly increased, but the magnitude of the compressive stress is still lower than the shear failure limit (Table 1). The elasticity (Young's modulus) of the baked ramming paste joint was set equal to 1.0 GPa.

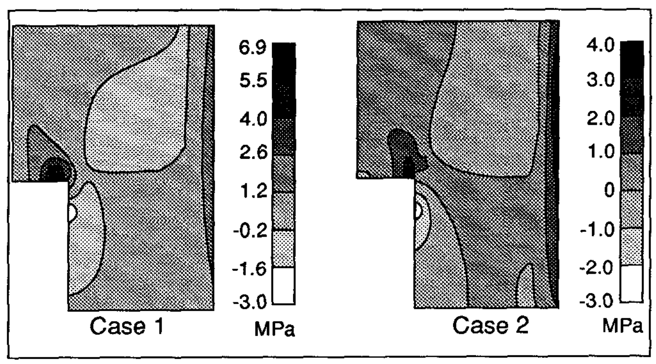

Figure 5. Tensile stresses in the bottom block without (Case 1) and with a 2.5 cm (Case 2) layer of graphite powder between the bar and the slot bottom.

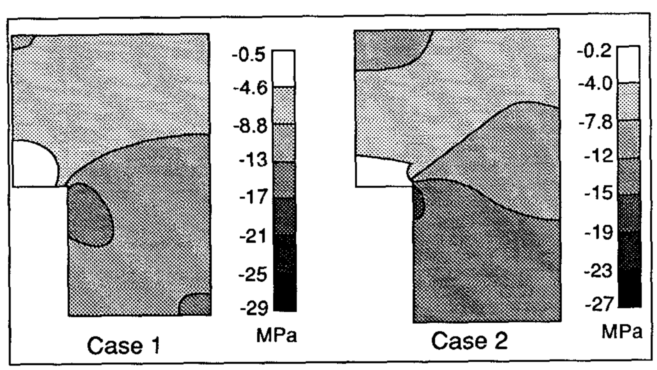

Figure 6. Compressive stresses in the bottom block without (Case 1) and with a 2.5 cm (Case 2) layer of graphite powder between the bar and the slot bottom.

Table 1. Shear failure probability based on the Coulomb criterion. All values are given in MPa.

	Tension σ_1	Compr. σ_2	$\sigma_{2c} = -25 + 4\sigma_1$	σ_2/σ_{2c}
Case 1	1	-13	- 21	0.62
Case 2	1	-15	- 21	0.71

Another consequence is that a thicker layer of graphite powder has not resulted in a lower overall pressure at the vertical face between the collector bar and the carbon block. This is important in order to keep the electrical contact resistivity as low as possible, avoiding overheating and increased cathodic voltage drop and power consumption.

RAMMING PASTE ELASTICITY

The stresses in the cathode block may be influenced by the compaction level of the paste rammed into the joints between the carbon blocks. It has been found that considerable vertical density gradients can occur in the baked joints [4]. This is assumed to be a result of improper lining procedures. In order to determine the effect this may have on the stresses in the block, two cases (Cases 3 and 4) have been studied. The baked paste elasticity in Case 3 is set to 1.5 GPa, while the elasticity in Case 4 is 1.5 GPa in the upper half and 0.5 GPa (poor compaction) in the lower half of the joint.

The difference in the critical tensile stresses in the two cases is insignificant (Figures 7 and 8). With regard to compression it is possible to observe overall reduced compressive stresses in Case 4, but the difference is small.

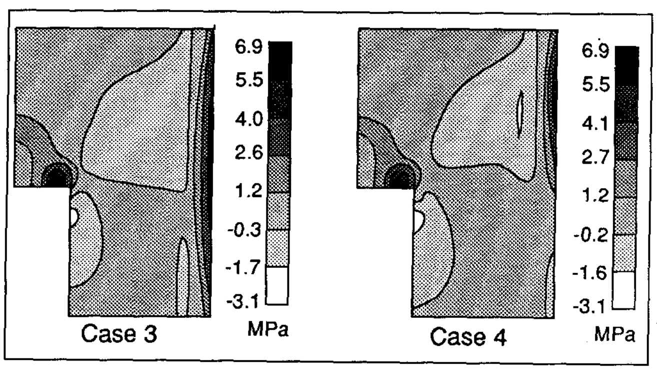

Figure 7. Tensile stresses with and without density gradient in the baked joint. Case 3: Uniform ramming paste density. Case 4: Uneven density in rammed joint.

CRUSHABLE ENDWALL LINING

In all previous cases the model has been constrained horizontally in the plane of symmetry in the ramming paste joint. This simulates a state where the adjacent block or

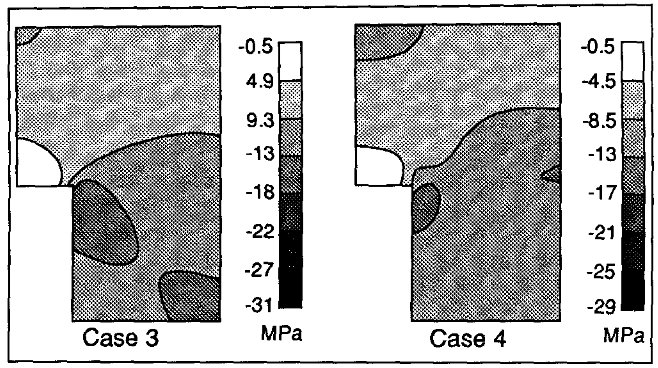

Figure 8. Compressive stresses with and without density gradient in the baked joint. Case 3: Uniform ramming paste density. Case 4: Uneven density in rammed joint.

endwall lining is completely rigid, and no horizontal displacement of the blocks can appear. This is not a true situation in a real cathode, as crushable insulation often are used in order to avoid excessive deformations of the pot shell [5]. Such lining principles will accommodate the horizontal thermal expansion of the cathode bottom pane and the overall compressive forces in the cathode will decrease. This state, with no or little resistance to horizontal displacement of the block, is modeled in Case 5.

The results (Figure 9) show that the overall compressive stresses in Case 5 are reduced to a negligible level compared to the state with rigid endwalls (Case 1, Figure 6). The highest compressive stress is less than 4 MPa and represents no hazard for shear fracture in the block. On the other hand, the tensile stresses are slightly increased due to the overall reduction of compressive forces. The probability of wing cracks due to tensile failures are thereby somewhat increased. It must, however, be stressed that the two models compared (Cases 1 and 5) are extremes with regard to the property of the endwall lining. Real cathode linings will have properties in between these two, resulting in a smaller difference in tensile stress and somewhat lower difference with regard to the probability of tensile failure. The difference is, however, real and a number of cathode autopsies have shown that the endwall blocks are more susceptible to wing crack failure than their neighbours.

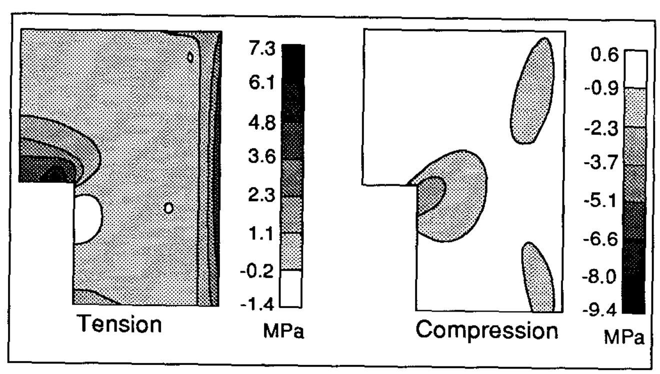

Figure 9. Stress fields in a block where the horizontal movement restrictions have been removed (Case 5).

FRICTION BETWEEN BAR AND CARBON BLOCK.

The roughness of the collector bar surface is crucial to the friction between the bar and the slot walls. In the model calculations so far the coefficient of friction has been neglected, which means there is no restriction to vertical collector bar displacement. In any real case there will be a certain steel/carbon friction and the rougher the bar surface becomes the higher will the friction coefficient be. The bar may thus not be free to slide in the slot and the stress fields may be considerably changed. An extreme case, in which the bar is completely constrained (Case 6), is studied by applying a model with an infinitely high bar/slot friction (Figure 10). Compared to the results in Case 1 (Figures 5 and 6) it is obvious that the tensile stresses in the material near the slot walls are considerable increased, while the tensile stresses near the slot bottom are decreased by only about 10 %. The compressive stresses are almost unchanged.

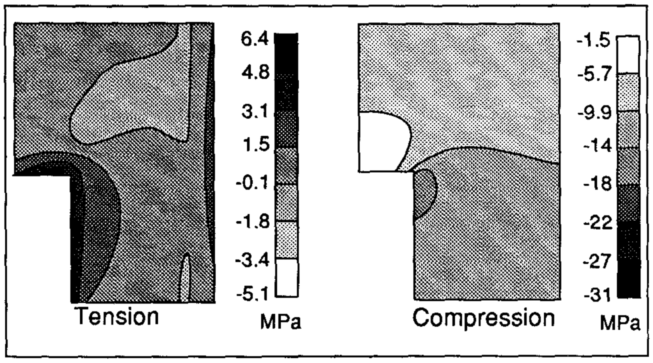

Figure 10. Stress fields caused by high friction between collector bar and carbon block (Case 6).

The increased friction has resulted in a radically increased shear fracture probability, while the stresses that may result in tensile fracture are nearly unchanged or slightly decreased. The risk for wing shear failure is strongly reduced by using collector bars with a smooth (low friction coefficient) surface.

CATHODE BLOCK GEOMETRY

The direction of a wing crack in a carbon block is dependent on the mode of failure, tensile or shear, and the directions of the stress axis. The stress directions are again highly dependent on the carbon block geometry. A study by Dumas [6] showed that by changing the ratio between the block and slot heights it was possible to develop cracks in controlled directions. A large block/slot height ratio was found to give angled cracks from the inside slot corners to the block side face, while a lowered ratio gave vertical cracks propagating from the slot bottom to the top surface of the block.

A somewhat simplified version of the model shown in Figure 2 was used to study this effect. The thermomechanical interactions between the bar and the block is substituted with a force acting on the vertical carbon slot walls. This model considers the block as a free-standing unit having no interaction with the rest of the cathode, *i.e.* no horizontal displacement restrictions.

The results from this modelling (Figure 11) agree with the experiments performed by Dumas. Decreased height of the carbon material above the slot results in a shift of the critical tensile stresses from the slot corners to the slot bottom.

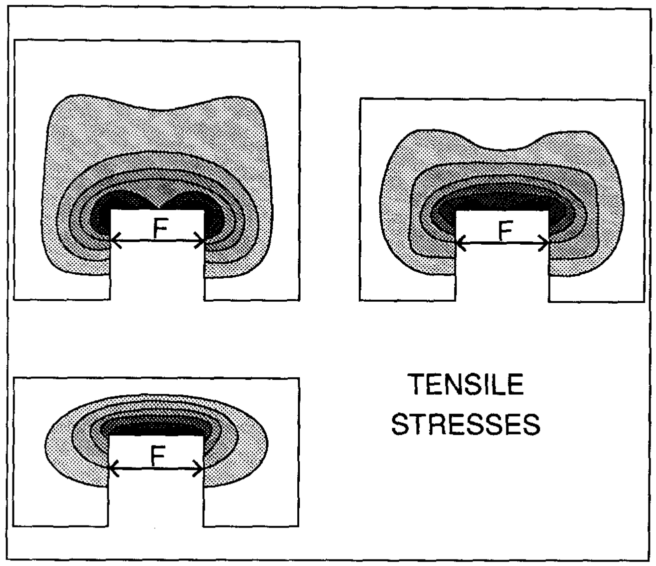

Figure 11. Shift in tensile stresses due to change in carbon block geometry. The darkest areas represent the highest stresses.

CONCLUSIONS

Both shear and tensile failures may appear in the vicinity of the inside slot corners. The angle between a shear and a tensile failure is less than the angle between the planes having the highest shear and tensile stresses, only about 27°.

The risk of wing crack formation can be reduced by increasing the distance between the collector bar and the bottom of the slot. This will not increase the electrical contact resistance through the vertical steel/carbon interface.

Density gradients in baked paste filling the joints between the bottom blocks caused by poor execution of ramming procedures do not seem to influence the crack forming stresses in the block.

Crushable endwall lining results in reduced overall compressive stresses. This reduces the probability for shear failures in the blocks, but the risk for tensile fractures are slightly increased.

High friction between the collector bar surface and carbon will slightly reduce the highest tensile stresses but will increase the risk for shear failure in the wings. By determining the mode of failure such model calculations may be used to determine the optimum bar surface roughness.

As the ratio of block height to slot height is decreased the direction of tensile crack propagation turns from an angled wing crack to a vertical fracture between the bottom of the slot and the top surface of the block.

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