Experimental Evaluation of a Mineral Exposure Model for Crushed Copper Ores

D. Garcia,* C.L. Lin,* and J.D. Miller*

ABSTRACT

Copper mineral inclusions dispersed in crushed ore particles have a certain size distribution (grain-size distribution). For efficient heap leaching processes, the crushing plant should be designed and operated to crush the ore to an appropriate particle-size distribution so that copper mineral grains are exposed and can be leached. In this regard, based on the approach of Hsih, Wen, and Kuan (1995), a mineral exposure model has been evaluated to describe the extent of grain exposure as a function of particle size. Experimental evaluation of the mineral exposure model for different copper ores has been accomplished by 3D analysis of crushed ore particles using cone beam x-ray microtomography. The model evaluation with micro-CT data suggests that the extent of preferential grain boundary breakage varies both with ore type and with particle size for a given ore type.

INTRODUCTION

In the copper heap leaching process, inclusions of copper mineral grains (copper-bearing minerals) are to be dissolved from ore particles. The copper-bearing minerals have some unknown grain-size distribution, texture/exposure, and spatial distribution in the ore particles. The procedure is to crush the ore so that the copper mineral grains are exposed and can be dissolved during the heap leaching process. If the relationship between the percentage of the exposed copper mineral grains and the particle size for a given ore type can be determined, then the practical recovery in the heap leaching process can be predicted for a specific particle-size distribution. It is, therefore, extremely important to determine the percentage of exposed copper mineral grains for a given ore as a function of particle size. X-ray microtomography (XMT) is currently the only direct measurement technique available for such mineral exposure analysis. In this regard, XMT has been used to determine the copper mineral grain-size distribution and extent of exposure for a given particle-size distribution.

For the approach used in traditional mineral processing, comminuted particles can be classified as either free particles or locked particles. In the case of hydrometallurgy, the fraction of grain exposure determines the extent of leaching. Thus, both liberated and exposed grains will respond to chemical attack during leaching. The unexposed grains that remain as inclusions in the gangue particles are not dissolved easily during the leaching operation.

* Department of Metallurgical Engineering, University of Utah, Salt Lake City, Utah

According to generally accepted terms, "grain" pertains to the crystalline and intimately mixed mineral phases with well-defined boundaries, composed of distinctive crystal chemistry and microstructure, whereas "particle" refers to crushed single and multiphase particles, generally composed of heterogeneous crystal chemistry and texture/structure. "Free particles" are particles of ore consisting of a single mineral. "Locked particles" are particles of ore consisting of two or more minerals. "Degree of liberation" is the fraction of a specific mineral in the form of free particles relative to that of both free and locked particles. "Exposed grains" are grains exposed at the surface of locked particles, whereas "unexposed grains" are grains enclosed within other host mineral, the gangue. The ratio of the volume of exposed valuable grains to the total volume of both exposed and unexposed grains in the comminuted particle is defined as "the degree of exposure" and is analogous to "the degree of liberation" for comminuted particles as used in particle separation processes. Thus, as the degree of liberation defines the limits to recovery in particle separation processes, so the degree of exposure defines the extent of leaching that may be expected in a reasonable time.

THEORY

The concept of Hsih, Wen, and Kuan's (HWK's; 1995) exposure model is based on a liberation theory developed by Gaudin (1939). In this model, the mineral grain-size distribution is related to the crushed particle-size distribution, using an intergranular fracturing factor, P. The intergranular fracturing factor is primarily controlled by the mineralogical characteristics of the particular feed material ($P = 1$ for pure intergranular fracture, preferential grain boundary fracture, and $P = 0$ for pure transgranular fracture).

The derivation of the exposure model follows the approach used by Gaudin. In the case of a fixed grain size (d), the fractional exposure (F_E) is given for a specific particle size (D) as follows:

$$F_E(K) = P\left[\frac{K^3 - (K-2)^3}{K^3}\right] + (1-P)\left[\frac{K^3 - (K-1)^3}{K^3}\right] \qquad K = \frac{D}{d}$$

In order to derive the model, the following assumptions are made:

- The ore consists of a scarce phase of valuable mineral and an abundant phase of gangue.
- Both mineral and gangue have the same uniform size of cubic grains d.
- The grains are aligned in the ore so that the grain surfaces form continuous planes.
- Grains of the two species are randomly located throughout the ore.
- The ore is broken into uniformly sized particles D, according to a cubic fracture lattice either randomly or nonrandomly superimposed on the ore parallel to the grain surfaces.
- P is the probability of fractures occurring at the grain boundary, which is a real number between 0 and 1; $(1 - P)$ is the probability of fracture occurring as random, transgranular breakage events during which event interfacial area is conserved.
- The crushed particle is invariably larger than the size of the grain.

Although these assumptions represent no actual conditions, they provide a reasonable foundation for initial study.

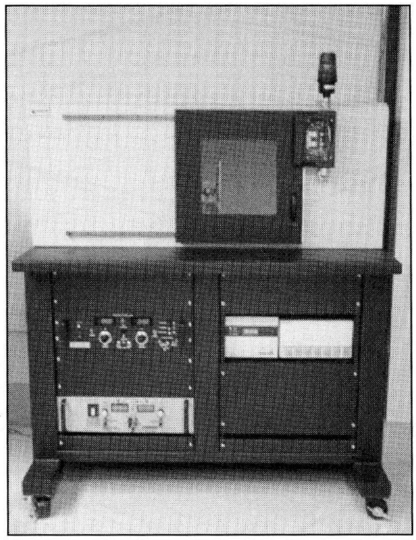


FIGURE 1 The cone beam XMT system at the University of Utah

MINERAL EXPOSURE ANALYSIS

The advanced XMT system at the University of Utah was designed and assembled to obtain 2,048 × 2,048 pixel reconstruction over a 10-mm diameter, while allowing for the 3D imaging of somewhat larger (40 mm) objects (Lin and Miller 2002). Specifically, the specimen-positioning stage system can be manually mounted at one of three different locations, providing system magnifications of 5, 2, or 1.25, and spheres of reconstruction with respective diameters of 10, 25, or 40 mm. Also, the system has been designed to be capable of handling high-density materials, even materials having a density as high as 8.0 g/cm^3. A photograph of the cone beam XMT system is shown in Figure 1.

Particle-Size Distribution for Heap Leaching

Copper mineral inclusions have a certain size distribution (grain-size distribution), N(X), where N is the weight fraction of grains for particle size X (Miller et al. 2003). The heap leaching process should be designed to crush the ore so that the copper mineral grains are exposed and can be leached. Figures 2 to 4 present the grain-size distribution for various particle size classes for Composite 2 (rhyolite/sulfide), Composite 4 (andesite/sulfide), and Composite 6 (andesite/oxide) samples. In this regard, a 3D connected components labeling technique was used to label and classify each individual grain volume (number of volume elements, voxels). In this way, then, the grain size is defined as the cube root of the grain volume. There is evidence that the copper mineral grain-size distribution is bimodal for particle sizes greater than 1.7 mm, as revealed in the grain-sizes distribution presented in Figures 2, 3, and 4.

RESULTS AND DISCUSSION

In the case of Composites 2 and 6 (Figures 5 and 6, respectively) it seems that for particles greater than 10 mm in size the predominant mechanism of breakage is intergranular fracture. In contrast, for Composite 4 (Figure 7), the predominant mechanism of breakage appears to be transgranular fracture for particles greater than 10 mm in size. One possible explanation for this behavior, in the case of Composite 4, is that the grain sizes

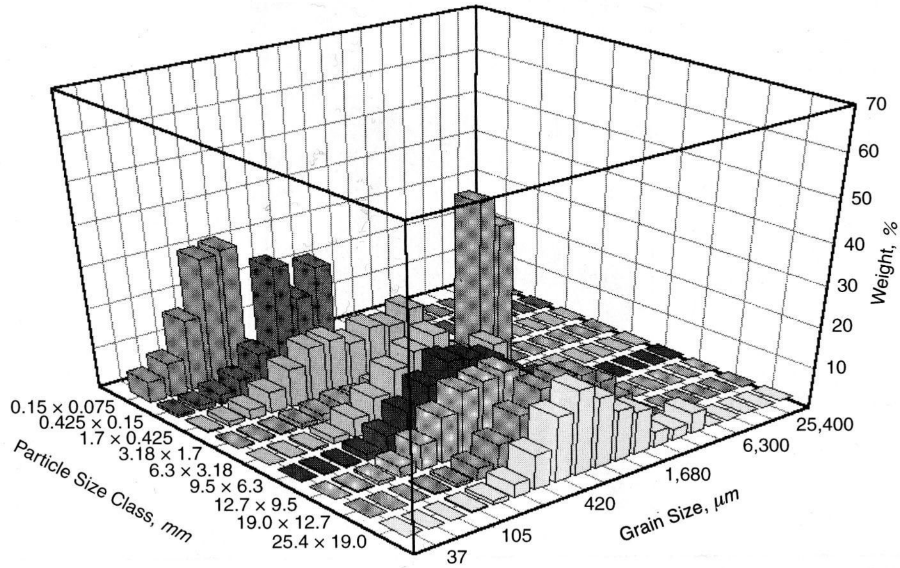


FIGURE 2 Overall grain-size distributions of Composite 2 for different particle size classes

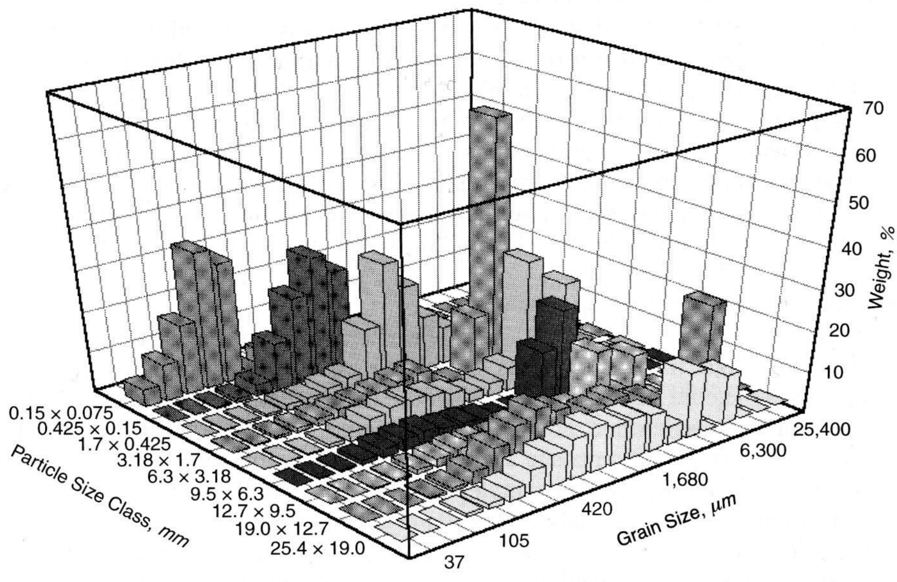


FIGURE 3 Overall grain-size distributions of Composite 4 for different particle size classes

are much larger than the grain sizes for Composites 2 and 6, hence a possible difference in fracture mechanism.

For particles smaller than 5 mm in size, there is no predominant mechanism of fracture for Composite 2; it appears that both transgranular and intergranular mechanisms are present. Composite 4 appears to exhibit mainly intergranular fracture and Composite 6 transgranular fracture. There is no evident explanation for this difference in behavior between these three samples. Analysis of the fracture mechanism requires more detailed

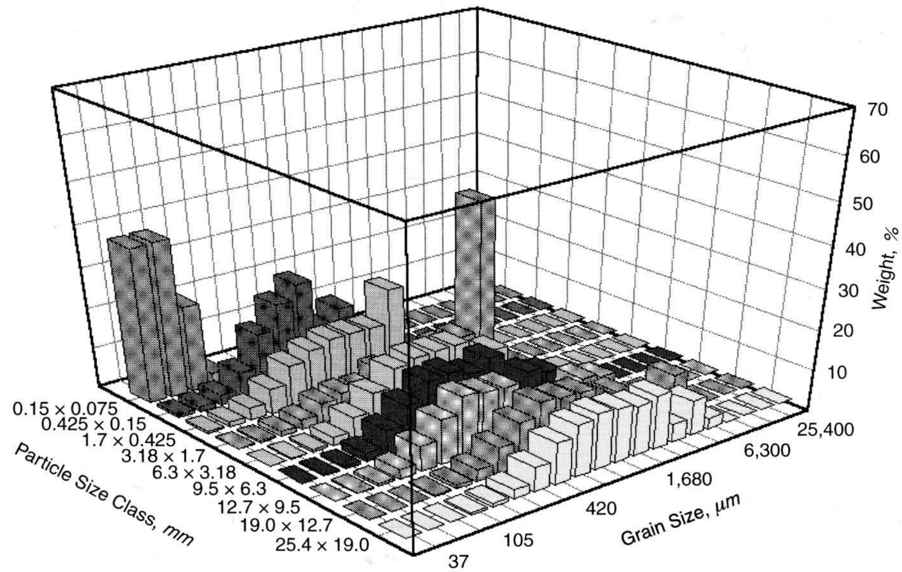


FIGURE 4 Overall grain-size distributions of Composite 6 for different particle size classes

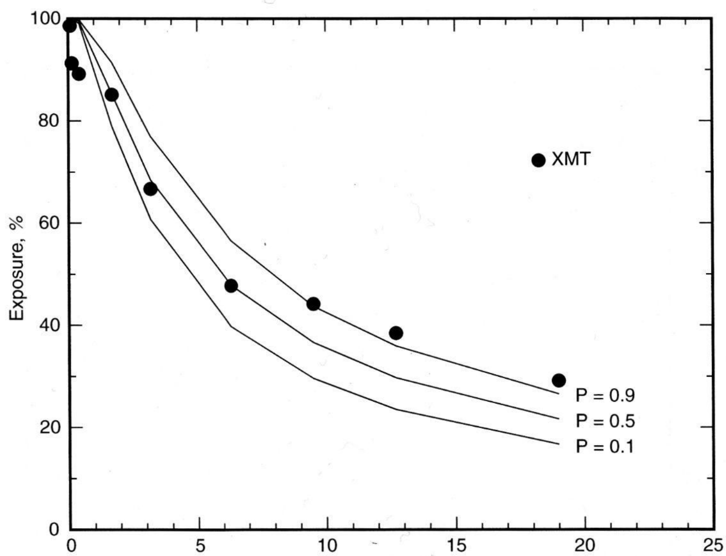


FIGURE 5 Exposure for Composite 2 given by XMT, model using P = 0.1 (mainly transgranular fracture), P = 0.9 (mainly intergranular fracture) and P = 0.5 (equal probability for transgranular and intergranular fracture)

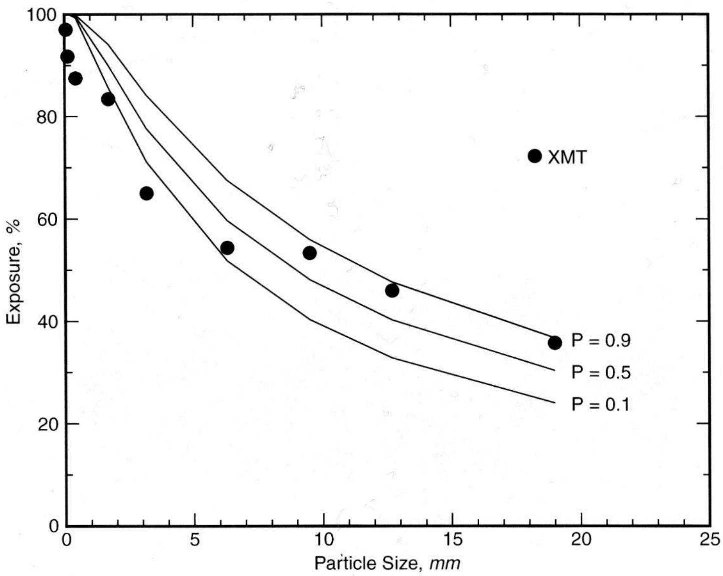


FIGURE 6 Exposure for Composite 6 given by XMT, model using P = 0.1 (mainly transgranular fracture), P = 0.9 (mainly intergranular fracture) and P = 0.5 (equal probability for transgranular and intergranular fracture)

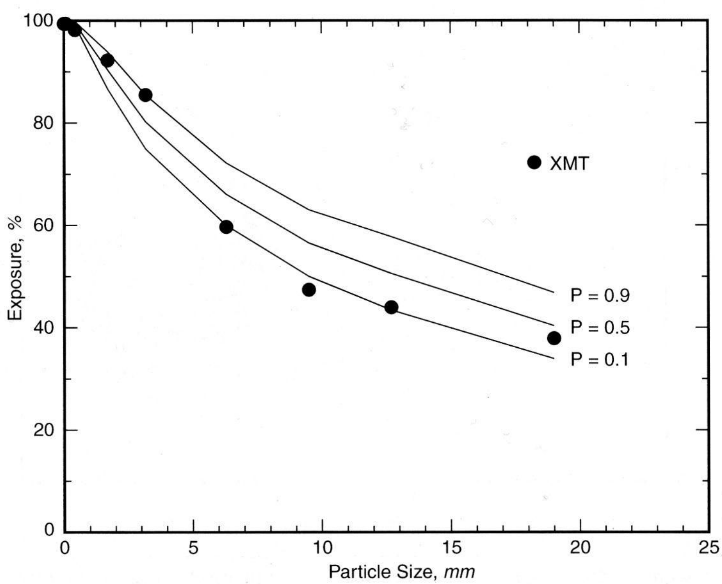
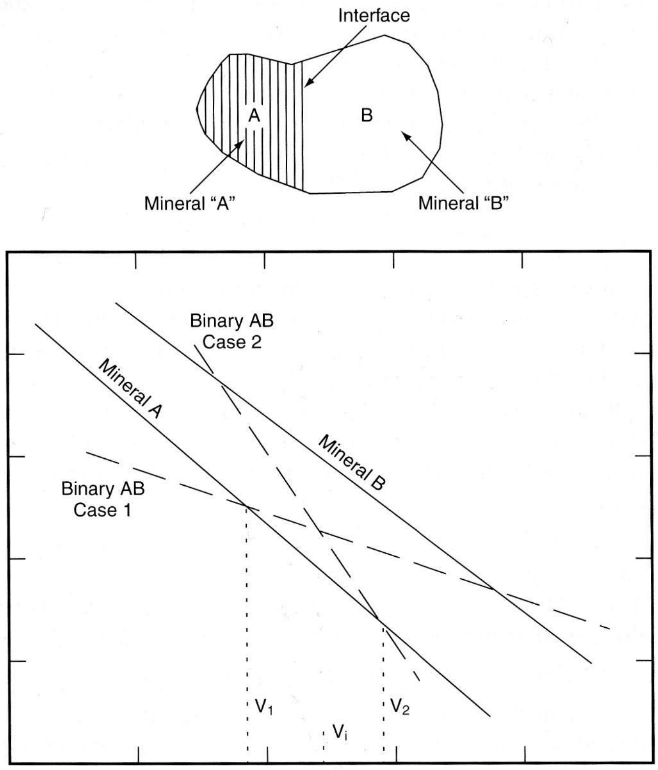


FIGURE 7 Exposure for Composite 4 given by XMT, model using P = 0.1 (mainly transgranular fracture), P = 0.9 (mainly intergranular fracture) and P = 0.5 (equal probability for transgranular and intergranular fracture)



Source: Bradt et al. 1995.

FIGURE 8 Top: Schematic representation of binary mineral particle, AB; Bottom: Schematic representation of conditions for liberation by preferential interfacial breakage of a hypothetical binary particle

measurements of interfacial area to determine the extent of preferential breakage of multiphase particles for different sizes. With these data, further arguments can be developed regarding the breakage mechanism. Such research is now in progress.

Thus, the mineral exposure model is limited to a fixed fraction of grain boundary breakage independent of particle size. It seems from the results of these crushing experiments that the significance of grain boundary fracture (preferential breakage) varies not only with ore type but also with particle size. For example, in the case of Composites 2 and 6 (coarse grain-size distributions as described in Figures 2 and 4), the data best fit the model with a grain boundary fracture probability of 0.9 for coarse particle sizes. On the other hand at finer particle sizes, the data best fit the model with a grain boundary fracture probability of 0.1, indicating that random transgranular fracture predominates. These results are particularly interesting because they substantiate earlier research that suggested that for a given ore type, there may be a critical size at which the breakage mechanism for multiphase particles changes from transgranluar fracture to intergranular fracture (Bradt et al. 1995). Specifically, the previous results for the breakage of single, multiphase particles defined this critical size concept as revealed in Figure 8. This figure shows the case for which a pure particle of mineral B is stronger than a pure particle of mineral A for all sizes (volumes) considered. Both pure minerals increase in strength with decreasing particle size as observed by statistical analysis of experimental results from the fracture of brittle solids and as expected from Weibull fracture statistics.

In Figure 8, case 1, the strength of the interface of the binary particle is weaker than either of its components at a volume size (particle size) of less than V_1. As shown in Figure 7 for Composite 4, preferential fracture occurs for a particle size of less than 3.2 mm. On the other hand, for Composite 6 (Figure 6), most of the fracture mechanism is transgranular for a particle size of less than 6.3 mm.

SUMMARY

Based on XMT-measured grain-size distributions, the percentage of exposure was calculated from HWK's exposure model and the calculated results compared with experimental XMT exposure data. In general, the exposure measurements from XMT data can be explained from the HWK exposure model.

These results are particularly interesting because they substantiate earlier research that suggested that for a given ore type there may be a critical size at which the breakage mechanism for multiphase particles changes from transgranular fracture to intergranular fracture (Bradt et al. 1995).

REFERENCES

Bradt, R.C., C.L. Lin, J.D. Miller, and G. Chi. 1995. Interfacial fracture of multiphase particles and its influence on liberation phenomena. *Minerals Engineering* 8(4–5):359–366.

Gaudin, A.M. 1939. Pages 70–91 in *Principles of Mineral Dressing*. New York: McGraw-Hill.

Hsih, C.S., S.B. Wen, and C.C. Kuan. 1995. An exposure model for valuable components in comminuted particles. *International Journal of Mineral Processing* 43:145–165.

Lin, C.L., and J.D. Miller. 2002. Cone beam x-ray microtomography—a new facility for three-dimensional analysis of multiphase materials. *Minerals and Metallurgical Processing* 19:65–71.

Miller, J.D., C.L. Lin, C. Garcia, and H. Arias. 2003. Ultimate recovery in heap leaching operations as established from mineral exposure analysis by x-ray microtomography. *International Journal of Mineral Processing* 72:331–340.