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Statistical analysis of fracture characteristics of industrial iron ore pellets

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ABSTRACT

The fracture load of iron ore pellets in the 12.5 to 16-mm size range is routinely measured in pellet plants following the ISO 4700 standard. The analysis of such data, however, seldom goes beyond averages and standard deviations of the load required for fracturing each pellet. Iron ore pellets are produced in the range from approximately 8 to 19 mm, so the entire distribution of fracture strengths over the range of sizes produced is relevant. This study analyzed in great detail the variability and the size-scale effect on the strength of five industrial iron ore pellets. The fracture strength data of pellets contained in five size ranges were analyzed on the basis of 12 probability distributions, as well as different parameter estimation methods. Further, other measures collected from compression tests, that is, pellet stiffness and specific pellet fracture energy, were also analyzed as a function of pellet size. Results show that the Weibull distribution provided comparably good fitting to pellet strength data. Fracture energy data could be described well using the normal distribution with square root transformation, although the Gumbel distribution was identified as the best fit-for-purpose distribution describing the data. The maximum likelihood parameter estimation method was demonstrated to be marginally more capable of fitting the data than the least-squares technique. It was also shown that the fracture strength of pellets increases with a reduction in pellet size. This size effect on strength was found to be more pronounced than that predicted using Weibull theory on the basis of variability in pellet strengths.

1. Introduction

Pellets compete with lump and iron ore sinters in the oxide charge of both direct reduction and blast furnace processes, which are the main routes in ironmaking. They offer advantages over their contenders regarding some important parameters, i.e., more regular particle size distribution and uniform chemical composition, as well as good reducibility [1]. One additional advantage of pellets that is particularly attractive when compared to their competitors is their superior resistance to physical degradation during both handling and reduction. These advantages help improve not only the operational stability but also the efficiency of the reduction process, which translates into higher productivity.

In spite of their greater resistance to mechanical degradation, pellets can break during transportation and handling, generating fines or coarse fragments. Although generated in smaller proportions than with lump ore and sinter, such debris is also undesirable. Particles smaller than, typically, 5 to 8 mm (fines) can be removed by screening and be reused in the sintering process at integrated steel mills. Alternatively, whenever steel plants do not have sintering units, they can be sold only at marginal prices [2]. Fragments with sizes coarser than 5 to 8 mm may also be generated during handling. However, these are not removed by screening, because they fall within the pellet specification size. As such, these fragments are fed to the furnace and may contribute to the formation of clusters in direct reduction shaft reactors [3]. The presence of such clusters in these reactors is detrimental to the permeability of gases through the oxide charge, negatively affecting the efficiency of the reduction process [4].

Given the importance of mechanical strength, the fracture load of iron ore pellets is routinely measured in pelletizing plants following the ISO 4700 crushing strength test, through which pellets contained in the size range 12.5–16 mm are fractured one by one. This information is routinely used in quality control in pelletizing plants [1], being also an important part of commercial contracts between pelletizers and their customers [5]. However, data is seldom analyzed beyond simple averages and standard deviations. Furthermore, pellets are produced in the size range from 8 to 19 mm; characterizing their crushing strength in this entire range of sizes, and identifying any size effect on the strength of pellets, are also relevant analyses.

Iron ore pellets are nearly spherical and highly porous solids that exhibit brittle behavior. Their response to compression has attracted the interest of researchers in both experimental and simulation studies. For instance, an active group of researchers from Luleå University of Technology (Sweden) used simulation techniques, namely smoothed particle hydrodynamics [6] and the multi-particle finite element method [7], to predict the mechanical response of iron ore pellets, with good agreement to experiments. They also obtained detailed material parameters for an elastic-plastic constitutive model of pellets produced in the laboratory [8]. Recently, they compared impact strength to slow compressive strength and demonstrated that impact strength was approximately 30% higher [9].

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Table 1
Probability distributions analyzed in the present work.

Distribution	Cumulative distribution function[a]	Reference
Normal (with Box—Cox transformation)	$t = x^{\lambda}$ for $\lambda \neq 0$ $P(t) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma t} \; exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right]dt$	[19]
Log-normal	$P(x) = \int_0^x \frac{1}{\sqrt{2\pi}\sigma x} \; exp\left[-\frac{(\ln x-\mu)^2}{2\sigma^2}\right]dt$	[10]
Weibull	$P(x) = 1- \exp\left[-(\frac{x}{\alpha})^{\beta}\right]$	[20]
Gumbel (Largest extreme value)	$P(x) = \exp\left[- \exp(\frac{\mu-x}{\sigma})\right]$	Minitab 17
Gamma	$P(x) = \int_0^x \frac{t^{\alpha-1} \; \exp-\left(\frac{t}{\beta}\right)}{\Gamma(\alpha)\,\beta^{\alpha}}dt$	Minitab 17
Logistic	$P(x) = \frac{1}{1+ \exp\left[-\frac{(x-\mu)}{\sigma}\right]}$	Minitab 17
Log-logistic	$P(x) = \frac{1}{1+ \exp\left[-\frac{(\ln x-\mu)}{\sigma}\right]}$	[21]
3-Parameter log-normal (upper truncation)	$P(x) = \frac{1}{\sqrt{2\pi}\sigma \; \ln\left(\frac{\lambda x}{\lambda-x}\right)} \; exp\left\{-\frac{\left[\ln\left(\frac{\lambda x}{\lambda-x}\right)-\mu\right]^2}{2\sigma^2}\right\}$	[22]
3-Parameter log-normal (lower truncation)	$P(x) = \frac{1}{\sqrt{2\pi}\sigma \; \ln(x-\lambda)} \; exp\left\{-\frac{\left[\ln(x-\lambda)-\mu\right]^2}{2\sigma^2}\right\}$	Minitab 17
3-Parameter Weibull	$P(x) = 1- \exp\left[-\left(\frac{x-\lambda}{\alpha}\right)^{\beta}\right]$	[23]
3-Parameter Gamma	$P(x) = \int_0^x \frac{(t-\gamma)^{\alpha-1}}{\Gamma(\alpha)\,\beta^{\alpha}}dt$	Minitab 17
3-Parameter log-logistic	$P(x) = \frac{1}{1+ \exp\left[-\frac{\ln(x-\lambda)-\mu}{\sigma}\right]}$	Minitab 17

[a] x is independent variable; t is transformed or integration variable; μ, σ, α, β and γ are model parameters.

In addition to fracture stress, the energy required for fracturing particles, called particle fracture energy [10], has also been recognized as an important measure. It occupies a central role in a model for predicting ore [11] and iron ore pellet [12] degradation during transportation and handling.

Not enough attention has been dedicated to the analysis of the variability of iron ore pellets over the range of sizes of interest in industrial practice. Analyzing their mechanical response using reliability tools, as is routinely done for other ceramic materials [13], is therefore relevant. The present work analyzed the variability of compressive fracture data of five industrial iron ore pellets over a wide range of sizes. Crushing strength, pellet fracture energy, and pellet stiffness data were analyzed on the basis of a variety of probability distributions, as well as parameter estimation methods.

2. Background

2.1. Pellet strength, stiffness and fracture energy

In order to limit the effect of particle size on the strength of iron ore pellets, it is more appropriate to use the peak stress than the fracture load. Gustafsson et al. [7] compared 3D finite element simulations of a model of an irregularly-shaped iron ore pellet with that of a spherical pellet. They showed that the equivalent effective stresses in the vicinity of the center of both model pellets were quite close, thus demonstrating the validity of modeling iron ore pellets as spheres.

Table 2
Summary of compressive strength of 12.5–16 mm (ISO4700), tumbling and abrasion indices (ISO3271) of the pellet samples studied.

Measure	Pellet sample				
	#1	#2	#3	#4	#5
Mean compression load (kgf)	357	326	322	300	260
Standard deviation of compression load (kgf)	107	126	118	124	85
Pellets with compression load <200 kgf (%)	17	20	16	21	45
Tumbling index (%)	93.8	93.4	93.6	92.3	92.2
Abrasion index (%)	5.5	5.7	5.7	5.9	6.6

Hiramatsu and Oka [14] analyzed the stresses of an elastic sphere subject to point-load compression. After simplifications, they obtained an expression for the tensile strength, given by

$$\sigma = \frac{2.8\,F_c}{\pi d^2} \qquad (1)$$

where σ is the tensile strength, herein called pellet strength, and F_c is the load responsible for fracture. d is the distance between the loading points, and is equal to the particle diameter in the case of spherical particles.

The validity of this expression was demonstrated by Hiramatsu and Oka [14] through comparison of its estimates from compression of irregularly shaped specimens and tensile strengths estimated using the Brazilian test, with good correspondence. Eq. (1) is particularly suited for calculating the strength of iron ore pellets, which present nearly spherical shapes [7].

Particle stiffness [10] is a convenient measure determined on the basis of the Hertzian contact theory [15]. The relationship between force and deformation for an elastic spherical particle compressed between flat platens presents an apparent work hardening behavior, given by

$$F(t) = \frac{K\,d^{\frac{1}{2}}}{3}\alpha(t)^{3/2} \qquad (2)$$