THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47th St., New York, N.Y. 10017

Printed in U.S.A.

94-GT-350

A UNIQUE TEST FACILITY TO MEASURE PARTICLE RESTITUTION AND FRAGMENTATION

S. C. Tan, P. K. Harris, and R. L. Elder
School of Mechanical Engineering
Cranfield University
Bedford, United Kingdom

ABSTRACT

This paper describes an experimental test facility for measuring particle restitution ratio and particle fragmentation where the turbulent effect of air has been minimised. The restitution ratios, which relate the particle rebound characteristics to the impact velocity (and angle), are used in a trajectory code so that rebound conditions can be calculated after a particle has collided with a wall surface. Trajectory calculations are often used to predict the separation performance of inertial particle separators in a design cycle without resorting to the expensive 'cut and try' method. A 'coanda' particle injector is used to separate particles from the airstream which then relies on its own inertia to collide with a target plate. Particle rebound occurred in an quiescent condition in a target chamber which has been isolated from the surroundings. The particle rebound velocity (and angle) is measured with a two-spot transit anemometer operating in the backscattered mode. Measurements are taken at about 1.0-1.5 mm from the target plate surface. The overall dimension of the test facility is relatively small (1.0 x 0.5 x 0.5 m) compared to a windtunnel facility due to the absence of an airflow. Some results are presented for certain materials showings the effect of impact velocity, angle and particle size.

INTRODUCTION

Gas turbine engines operating in a sandy environment often ingest solid particles such as sand, which could erodes engine components and reduces their performance, reliability and life if left unprotected. Helicopters (Mann [1989]), for example, often have inertial particle separator which depends on the combination of the particle 'ballistics' and the separator's geometrical shape to deflect particles into the scavenge section of the engine thus avoiding the erosive damage to the compressor. The areas most vulnerable to erosion, however, can be predicted using a particle trajectory model (Tan [1984]) which can simulate trajectories of particles, and calculate the amount of material removed.This enables the effectiveness of erosion resistant materials to be measured and consequently overall engine performance and lifespan. The trajectory model, however, relies on the particle rebound characteristics, or restitution ratios (Grant [1975], Tabakoff [1987]), in order that computation can be continued after a particle has collided with a solid surface. These ratios can vary with particle sizes, impact velocity and angle, target and particle material composition. Available information on the restitution ratios is very limited and the current test facility has been designed to gather these data. Traditional methods (Grant [1975], Tabakoff [1987]), of obtaining these ratios involved measuring particle rebounds on a target plate mounted in a windtunnel but these measurements suffer from the aerodynamic effects caused by the flow around the plate. The trajectory of the smaller particles, for example, are particularly susceptible to the aerodynamic forces and measurement taken at a distance from the surface may not reflect the actual rebound event.

The current test facility overcomes these problems by employing the 'coanda' effect to separate the particles from the airstream. Under these conditions the particle impact with a target material takes place in a quiescent condition which has been isolated from the surroundings. The absence of the airflow has resulted in a smaller test rig compared to the windtunnel type facility. In addition, the current facility has been designed to minimise secondary effects on the restitution ratios due to particle rebound on 'worn' or 'rippled' surfaces by ensuring that measurements are carried out on a 'smooth' surface.

The particle velocity and angle are measured with a laser transit (two-spot) anemometer (Tan [1989]) and particle restitution ratios

Presented at the International Gas Turbine and Aeroengine Congress and Exposition
The Hague, Netherlands — June 13–16, 1994

formulated from these measurements.

EXPERIMENTAL TEST FACILITY

Figure 1 shows the experimental rig used for measuring particle rebound characteristics at different impact velocity, angle and particle size. It consists of a dust feeder system, and an accelerator and target chambers which are separated by a pinhole. Particles were injected at a target plate and a laser anemometer was used to measure the rebound velocity and angle in the target chamber. The dust particles which accumulated in this chamber were collected and weighed. Both chambers were isolated from the surroundings but the target chamber has an optical access made from perspex material for laser measurement.

Accelerator Chamber

The accelerator chamber consists of the 'coanda' particle injector which is mounted on a table slide, and connected to separate pressure and dust feed lines. The dust particles are fed into the injector via a hopper which was kept at the pressure of the injector. Particles are separated from the air by a combination of the coanda effect and the particle's inertia as shown in figure 2. The injector emits a 'conical ' shaped dust distribution which was filtered by a pinhole to give a narrow stream of particles. Early tests had already confirmed that this particle stream has a consistent concentration needed for laser measurements. The pinholed plate was made from tungsten carbide material which is highly resistant to sand erosion. The pinhole was aligned with the particle injector and the laser anemometer. The chamber also has a removable pot which collects dust particles which have been filtered by the pinhole.The injector pressure is monitored with a digital transducer and controlled by a simple valve located in a control room.

'Coanda' Particle Injector

The basis of the rig involves the acceleration of particles of known size by an airstream and then the separation of the airstream from the particle 'stream' using the 'coanda' effect as shown in figure 2. The basic principle behind the 'coanda' effect (Yee [1983], Levinsky [1972]), lies in the ability of the boundary layer to maintain stability at high flow turning angle. Early tests, carried out without particles, had shown that the main airstream tends to adhere to the curvature of the injector deflecting the main airstream by several degrees. The injector is operated by compressed air, therefore a range of particle velocity could be attained. As the injector pressure increases, however, the boundary layer becomes unstable (and flow separation occurs) and the main airstream begins to 'level-out' until it behaves like an ordinary jet. Measurements under these conditions had shown that the particle velocity (and angle) could vary by as much as ±20 % from the mean, which is unacceptable in the current study. As a result, precautions were taken to ensure that the particle's trajectories are not affected by the airstream. Firstly, measurements were carried out in the target chamber (fig.1) which is separated from the accelerator chamber (where the injector is mounted) by a wall except for a small pinhole. Secondly, to ensure adequate deflection of the airstream when taking measurements at high injector pressure (greater particle velocity) so that it has minimal effect on the particle's trajectories. The measured particle velocity in the current arrangement varies by about ±5%, and the particle trajectory angle (measured over a range of velocity) varies by about ±3% as shown in figure 3.

Target Chamber

The target chamber consists of a rotatable plate holder and is attached to a three-axis linear traverse mechanism via a cantilevered rod. The floor of the chamber has a removable pan which collects dust particles after each test. These were later used for fragmentation analysis by comparing with the initial dust sizes.The target plate is held in position by a backing plate and an adjustable swivel screw. The backing plate ensures that the target material is kept flushed throughout the test. The traverse mechanism, controlled by a computer, helps to ensure that particle rebound measurements are always carried out on a 'smooth' surface so that secondary rebound effects caused by 'worn' or 'rippled' surface do not affect the results. It also helps to maintain a fixed distance between the measurement position and the injector exit because particle trajectory will start to deviate from the level flight beyond this distance.

Measurements of the particle velocity (angle) were taken at about 1.0 and 1.5 mm normal to the target plate surface so that actual rebound phenomenon is recorded. This separation is adjustable by the computer because at certain obscured positions, light scattered from the particles (necessary for laser anemometer measurements) can be blocked by the plate preventing measurement to be taken.

The chamber is isolated from the surroundings except for an optical access made from perspex material for laser measurements.

Dust Feeder System

The feeder system consists of two dust hoppers, one is connected to the injector by a feedline and the other acts as a refill.Dust particles are fed into the jet directly upstream of the injector as shown in figure 1. A mechanical exciter (operated by pressure) is attached to the hopper and is controlled by adjusting the frequency of the mechanical vibration and a feed screw in the hopper which sets the aperture. Both the injector and hoppers were kept pressurised at the same pressure supply hence particle seeding (into the injector) is entirely due to gravitational effects.

Laser and Data Acquisition System

Particle rebound characteristics were measured using a 35mW He-Ne laser transit (two-spot) anemometer operating in the backscatter mode (Gill [1981], Agha [1982]). The principle behind the technique is the measurement of the time of flight of particles as they passed across a probe volume as shown in figure 4. The volume consists of two collimated beams of light emitted by a laser source which are focused into two intense spots separated by a small distance. When a particle passes through the first focal spot, the backscattered optical pulse triggers a high speed clock which is stopped by the passage through the second spot resulting in the time of flight measurement. By automatically rotating the probe volume, a number of time-of-flight histograms can be build up at different angular positions which can be resolved to give the mean flow velocity and direction. The scattered light from the particles are captured by two photomultiplier tubes (PMT) and the signal processed by a 50 nanosecond correlator. Data reduction was carried out in-situ with a desktop computer and stored for later postprocessing.

Unique Features of the Test Facility

The 'coanda' technique of accelerating particle trajectories had resulted in a simple test facility compared to the windtunnel used by other researchers (Grant [1975], Tabakoff [1987]). One of the main features of the facility is that it is small (compared to a windtunnel) with dimension of only about 1.0 metre long, 0.5 metre wide and 0.5 metre high thus saving on costs and space.

The most important feature in the current test facility, however, is that the measurement of the particle rebounds is carried out in a quiescent condition where the aerodynamic effects had been minimised.The 'coanda' effect separates the particle from the airstream and particle then relies on its own inertia to maintain its trajectory. Since there is no flow distribution near the target plate, particle impact angle very close to the plate is not affected by the boundary layer. In windtunnel, however, the flow near the plate can alter the particle impact angle, especially with smaller particles because they are more susceptible to aerodynamic forces. The absence of the boundary layer in the target chamber enabled measurement to be taken very close to the plate (about 1.0-1.5 mm) so that actual rebound events are recorded. Similar measurement in a windtunnel would have to take into account the boundary layer effects.

In addition, to alter the particle velocity in the current facility simply involves adjusting the injector pressure with no aerodynamic effects similar to those caused by changes in the flow distribution (and possibly the particle trajectory) around the target plate in a windtunnel. Similar effects can also arise when the angle of attack (impact angle, β_1) is altered. The current facility does not suffer from these difficulties because of the absence of the airflow around the target plate.

The other important feature of the design is that secondary effects on the particle rebound characteristics caused by 'worn','rippled' or 'spoiled' surfaces had been minimised. The mechanism of particle rebounds on these type of surface are not well understood therefore precautions have been taken to ensure measurements are carried on 'smooth' surface with the aid of the three-axis linear drive mechanism. A number of discrete 'impact' positions at each impact angle had been pre-programmed into the computer which controls the traverse mechanism. During the test, the traverse gear will automatically moved from one position to another after a set duration while maintaining a fixed distance (the particle trajectory can deviate from the level flight due to the drag and gravitational forces) from the injector exit. The duration of each position is user-adjustable but it is usually set to between 3 and 5 minutes. The changing of the positions, after each duration, ensures that a 'smooth' surface on the plate is used for restitution measurements.

Measurement Technique

The particle velocity restitution ratio, V_2/V_1, is defined as the ratio of the rebound velocity to the impact velocity (Tabakoff [1987]). Similarly, the directional restitution ratio, β_2/β_1, is defined as the ratio of the rebound angle to the impact angle as shown in figure 5.

Early tests had already established the relation between the particle impact velocity, V_1, and the injector pressure.The impact angle,β_1, is defined as the angle between the plate and the horizontal. The measurement of the particle rebound velocity, V_2, and angle, β_2, was carried out at about 1.0 - 1.5 mm from the target plate surface using the laser anemometer. The particle restitution ratio is then formulated from these measurements.

Specially graded quartz particles with a fine distribution of ± 10 % were used in tests. Figures 6 and 7 show the particle restitution ratios plotted against the impact angle for two target materials. They also include the effect of impact velocity, angle and particle sizes.

The particle fragmentation characteristics were assessed by comparing initial dust size distribution to the dust which have collided the target material. The analysis of the dust distribution was carried with a Malvern Particle Sample Analyser. Figures 8 and 9 show the fragmentation characteristics and the effect of impact velocity on the amount of fragmented particles.

The experimental data was curve fitted with the power series type of polynomial functions of the third order. These functions could be used in a trajectory calculation to predict the separation efficiency of inertial particle separators and erosion in components exposed to sand particles material.

DISCUSSIONS

The restitution result for aluminium material, figure 6, also include Tabakoff's data (Grant [1975]) which was carried out at the following conditions;

Target material - 2024 Aluminium
Particle material - Quartz
Particle mean diameter - 200.0 micron
Impact velocity - 76.2 m/s

Effects of Impact Angle and Velocity

Figure 6 shows that the aluminium material has three distinct rebound characteristics. The directional coefficient, β_2/β_1, measured at impact velocity of 50 m/s shows agreement with Tabakoff's result but a higher rebound angles were obtained at greater impact velocities. This means that, at low impact angle but high impact velocity, the rebound angle will also be higher and vice-versa at higher impact angles. In contrast, at low impact angles but high impact velocity, the velocity restitution ratios obtained are smaller. The velocity restitution result shows that agreement with Tabakoff's data was found only at high impact angles.

The effect of the impact velocity for the duralumin material, figure 7, is less well defined compared to aluminium material but similar characteristics were also found.

In general, impact velocity has an effect on the restitution ratios of aluminium and duralumin materials.

Fragmentation Characteristics

Figures 8 and 9 show the effect of impact velocity and particle sizes on the amount of fragmented dust. They generally show that as particle impact velocity and size increase, the amount of fragmented dust also increases. For larger particles, figure 8, fragmentation takes place mostly at lower end of the dust size spectrum but for smaller particles, figure 9, this occurs across the whole size bandwidth.

CONCLUDING REMARKS

A unique test facility which employed the 'coanda' effect has been designed for measuring particle rebound characteristics and fragmentation in a quiescent condition. The technique allows accurate measurement of the particle rebound characteristics. The secondary effect on the rebound phenomenon due to a 'worn' or 'rippled' surface has also been minimised by ensuring 'smooth' surfaces were used for measurements. The simplicity of the facility has greatly reduced its overall size compared to a windtunnel.

Particle velocity and angle were measured using the laser anemometry technique, and variation from the means was found to be only about ± 5 %. Particle restitution ratios and the effects due to impact velocity, angle and particle sizes have been presented for two sample materials.

REFERENCES

Mann,D.L., Tan,S.C., "A Theoretical Approach to Particle Separator Design", ISABE 1989.

Tan,S.C.,"A Computer Code to predict Particle Trajectories in a Three Dimensional Gas Turbine Intake", Cranfield Institute of Technology, MSc Thesis, August 1984.

GRANT,G. and TABAKOFF W., "Erosion Prediction in Turbomachinery Resulting from Environmental Solid Particles," Journal of Aircraft, Vol. 12, No. 5, May 1975, pp. 471-478.

TABAKOFF,W., MALAK,M.F. and HAMED, A., "Laser Measurements of Solid Particle Rebound Parameters Impacting on 2024 Aluminium and 6Al-4V Titanium Alloys," AIAA Journal, Vol. 25, No. 5, May 1987, pp. 721-726.

TAN,S.C., MANN,D.L., ELDER,R.L. and THORN,R.L., "A Study of Particle Trajectories in a Gas Turbine Intake,", ISABE 1989.

Yee,K.H., Shayley,P.J. and Collings,N., "Erosion of Metals by Flyash Particles", Wear 91 (1983) 161-170

Levinsky,E.S.,"Analytical and Experimental Investigation of Circulation Control by means of Turbulent Coanda Jet", NASA CR2114,1972

Gill,M.E.,"Description of a programme for analysis of data arising from a two-spot laser anemometer", Report,Cranfield Institute of Technology,Nov 1981,

Agha-Seied-Mirzbozorg,M.,"Multi-Channel Analysis for the analysis of laser Anemometry (L2F) signals",PhD thesis, Cranfield Institute of Technology,1982

ACKNOWLEDGEMENTS

The authors would like to express gratitude to Rolls-Royce plc, the Department of Trade and Industry and the Ministry of Defence for granting permission to publish this paper.

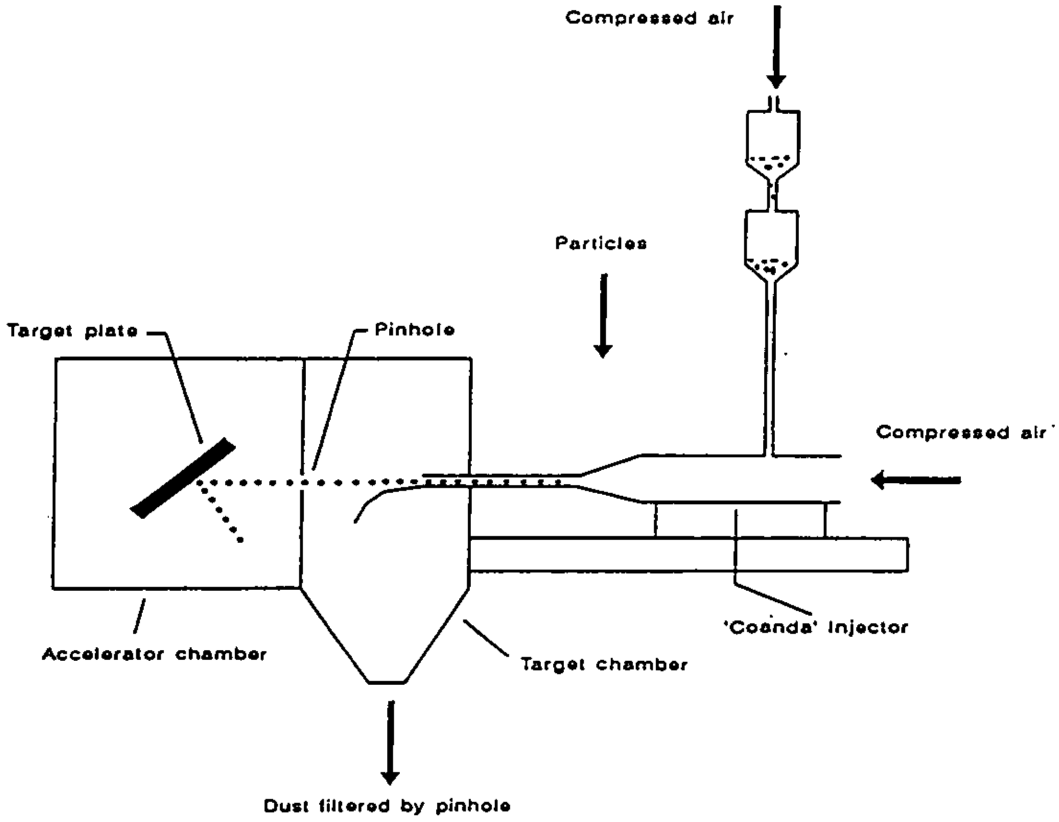

FIGURE 1 SCHEMATIC TEST FACILITY

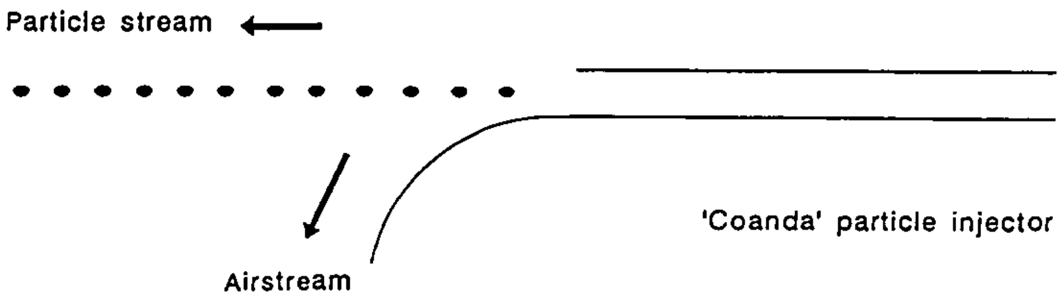

FIGURE 2 PARTICLES SEPARATED BY 'COANDA' EFFECT

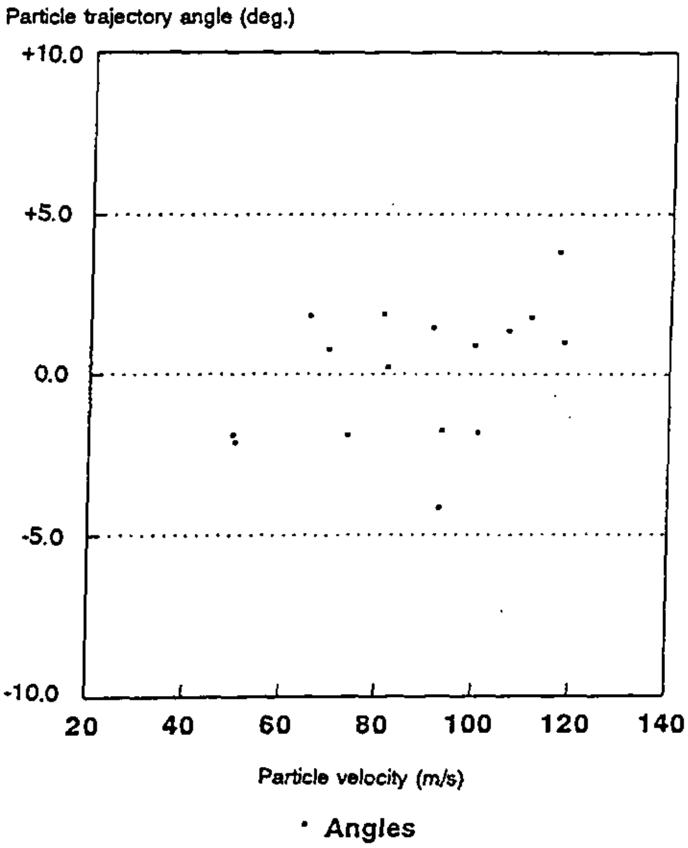

FIGURE 3 DEVIATION IN THE PARTICLE'S TRAJECTORY ANGLE FROM THE HORIZONTAL FLIGHT (0 DEG.)

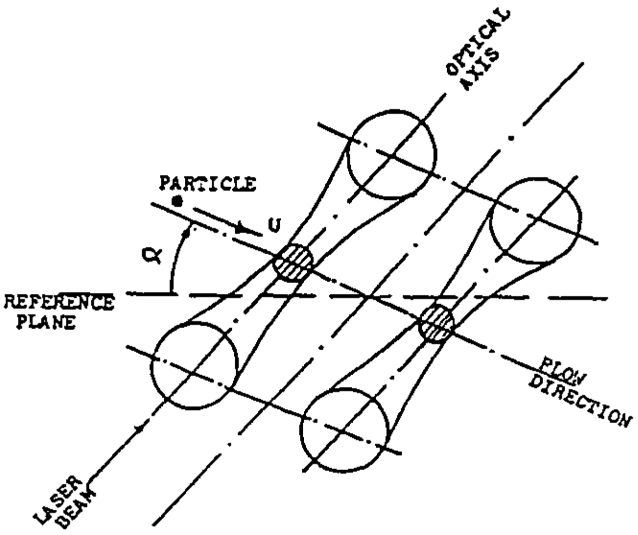

FIGURE 4 MEASURING VOLUME OF THE TWO-SPOT ANEMOMETER

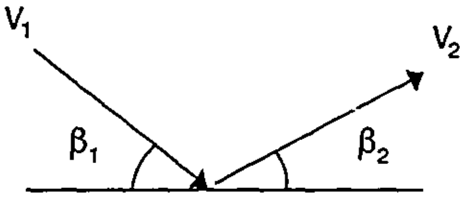

FIGURE 5 PARTICLE IMPACT AND REBOUND NOTATIONS

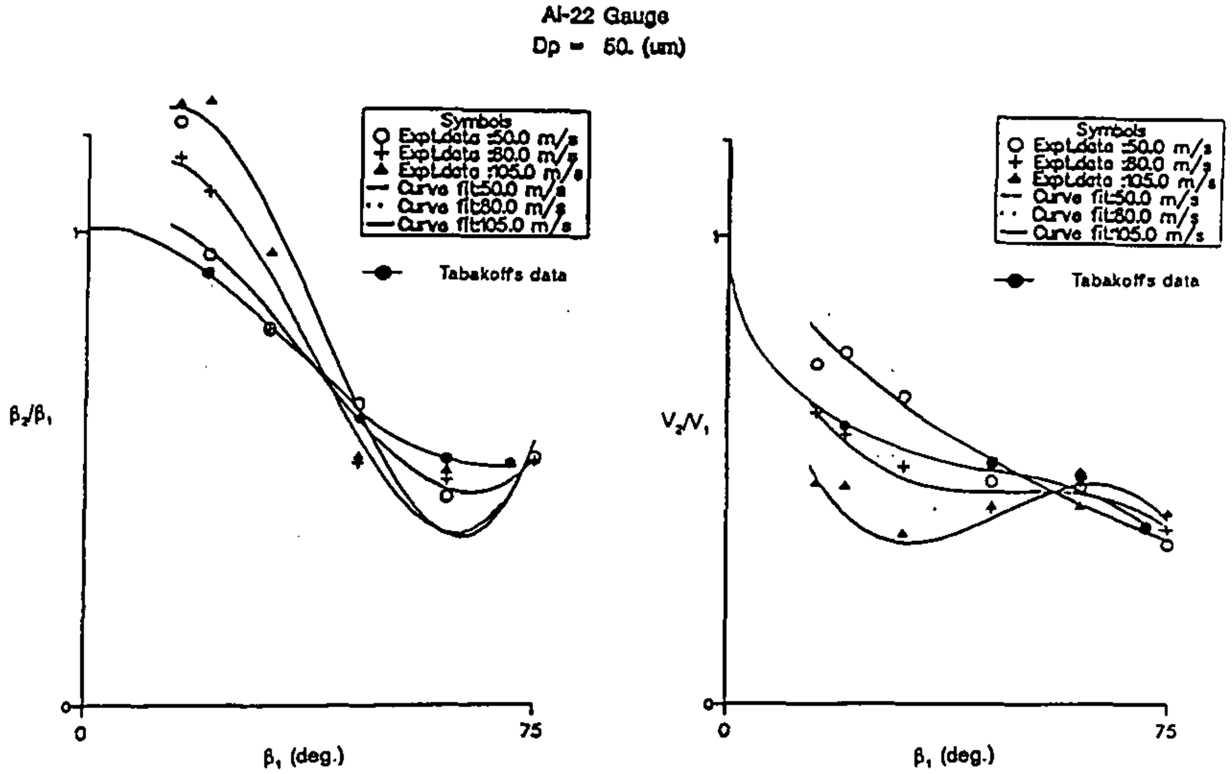

FIGURE 6 MEASURED RESTITUTION RATIO FOR ALUMINIUM MATERIAL

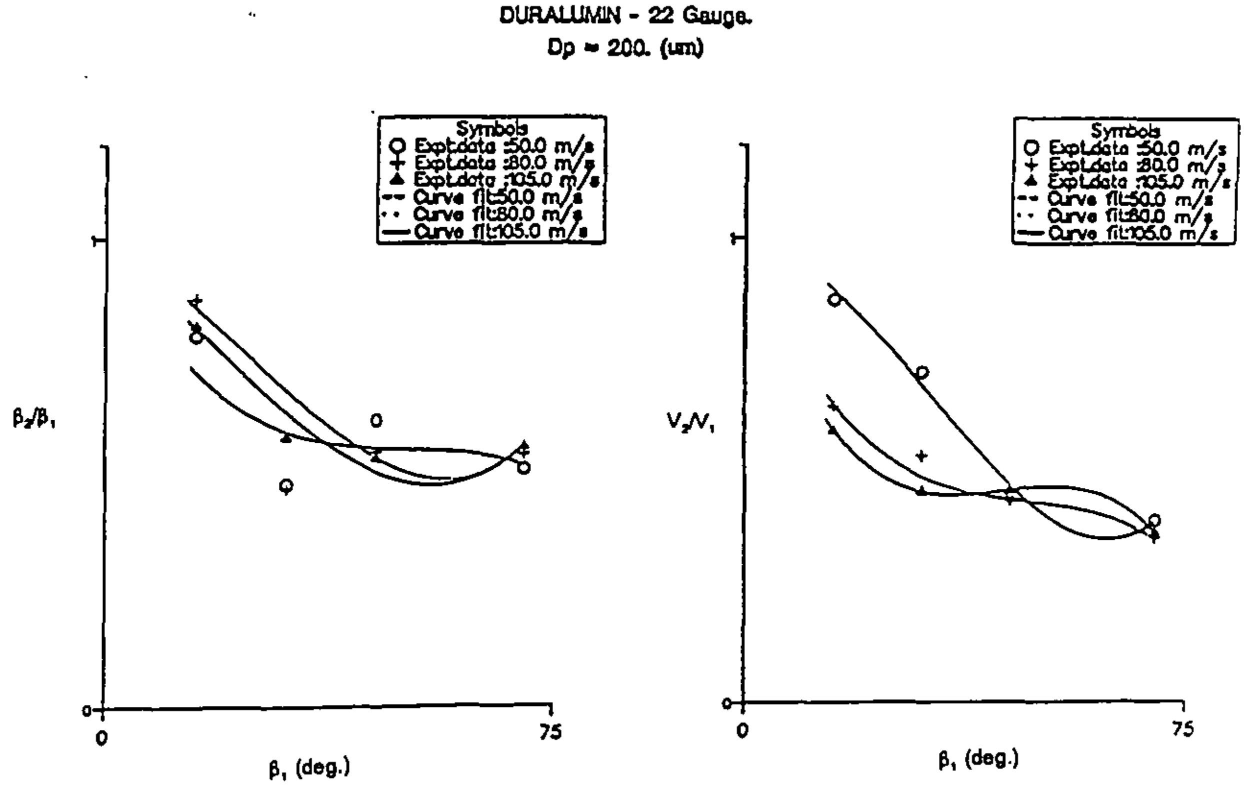

FIGURE 7 MEASURED RESTITUTION RATIO FOR DURALUMIN MATERIAL

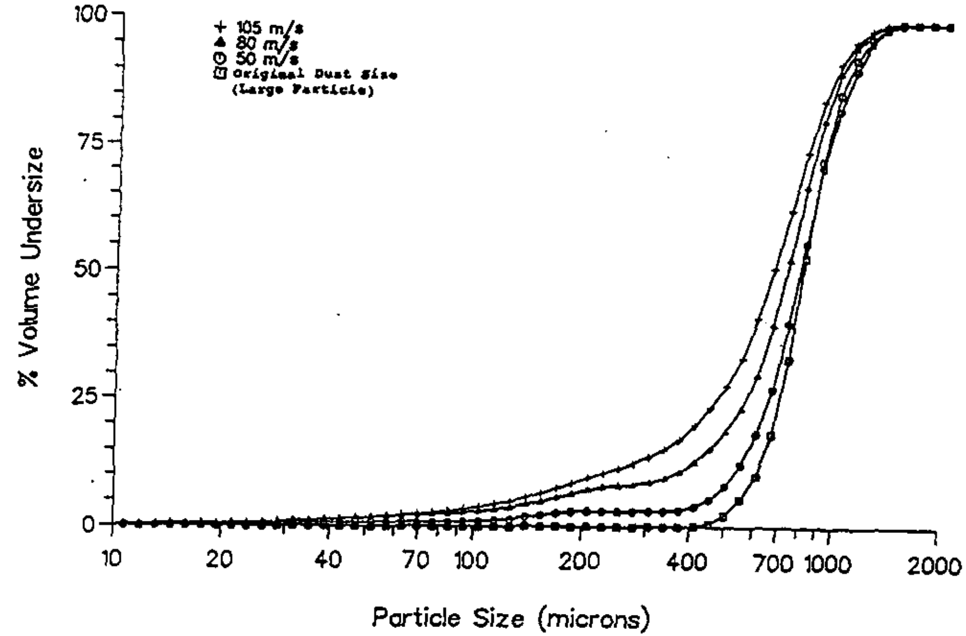

FIGURE 8 EFFECT OF IMPACT VELOCITY ON FRAGMENTATION (LARGE PARTICLES)

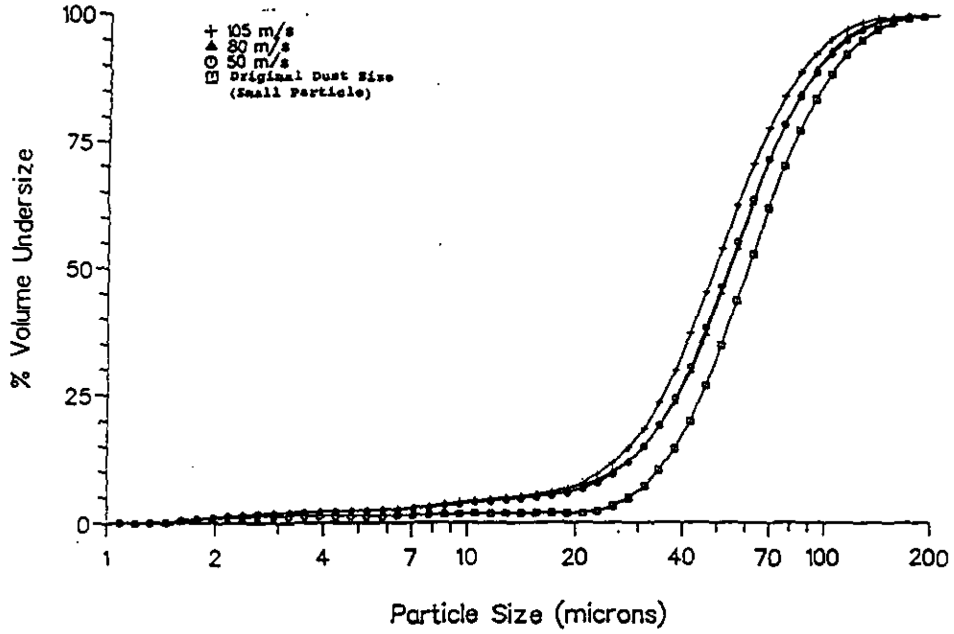

FIGURE 9 EFFECT OF IMPACT VELOCITY ON FRAGMENTATION (SMALL PARTICLES)