AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 1

THE FUNDAMENTAL MECHANISMS OF MATERIAL REMOVAL BY FLUIDJET MACHINING

Sang-Wook Kang
Thomas Reitter
Gustav Carlson

June 1994

ABSTRACT

The fundamental mechanisms of material removal by fluidjet machining have been theoretically and experimentally investigated as a potential method for dismantling nuclear weapons with efficiency and safety. Preliminary experiments and analyses have revealed that at small standoff distances between the nozzle exit and the target workpiece there is no mass removal from the workpiece, but that far from the nozzle there exists an optimum standoff distance at which the jet impact removes mass from the workpiece at a maximum rate. Such results suggest a mass-removal process due to the droplets and ligaments impinging on the material that cause sudden pressure increases in the impact regions.

This proposed material-removal mechanism has been addressed theoretically by considering a series of multiple droplet impacts on a material. The calculated results display a series of pressure peaks at the target surface as each of these droplets strikes the material, supporting the plausibility of the proposed mass-removal scenario at the optimum standoff distance. Although plausible further experiments and analyses are needed to verify the proposed jet-induced mass removal mechanism.

1. INTRODUCTION

Our objective is to determine whether high-velocity (velocities greater than 200 m/s) waterjets offer an efficient and safe method for the dismantlement of nuclear weapons. High-velocity liquid jets, especially non-abrasive waterjets, may be suitable for cutting the high explosives, because the jet machining does not involve solid-to-solid interface contacts, yet provides a medium for transporting the machining chips and the generated heat. The safety aspect of waterjet machining needs to be addressed. A survey of literature reveals a paucity of work on the application of high-velocity waterjets to the dismantlement of high explosives.

The research projects include both the experimental and theoretical approaches [Ref. 1]. The theoretical analyses are performed to understand the nature of the transient material response to a liquid impact on its surface. The CALE code at LLNL has been used extensively for this purpose [Ref. 2]. The tests were performed both to determine the ranges of dominant parameters involved in the most efficient mass removal operations, and to validate the theoretical predictions. We discuss the present status of these experimental and theoretical approaches here.

2. ANALYSIS

2.1. Experiments

Measurements were made of the removal rate of aluminum vs. the standoff distance for various nozzle designs and pressure conditions. Aluminum was selected as an initial benchmark material because of the comprehensive data available for its material properties, including the stress-strain relationships under dynamic (high-strain rate) conditions. Although tests have been also performed with some high explosive materials, such as PBX-9404, we discuss here the aluminum tests, as they provide a glimpse into the basic material-response processes.

Figure 1 shows the material removal rate as a function of the standoff distance between the nozzle exit and the target workpiece. The liquid is water; the reservoir pressure is 276 MPa (40,000 psi); the nozzle exit diameter is 0.356 mm (0.014 in.); the target material is 6061-T0 aluminum.

We observe no material removal when the standoff distance is less than about 10 mm. The cutting rate increases with standoff distance until it reaches a maximum. This optimum standoff distance is at about 170 mm, or about 480 nozzle diameters. Different pressures and different nozzle diameters yield the same behavior, i.e., (a) there is no material cutting at close range, and (b) there is an optimum standoff distance for maximum material removal, typically on the order of 300 to 500 nozzle diameters.

At large distances liquid jets eventually disintegrate into ligaments and droplets (see Figure 2, taken from Ref.3). The figure shows varying jet breakup lengths depending on the stagnation pressure, or equivalently, the Reynolds number. At the first peak of the curve the jet is laminar; the higher Reynold number produces a jet in the transition regime and finally a turbulent jet forms at high Reynolds numbers. The present test results are in the turbulent flow range, the Reynold numbers being from 1-2 (10^5), where the jet breakup (that is, intact) length is about 70 nozzle diameters from the exit.

Therefore, at the optimum standoff distance the jet is no longer intact, but rather has disintegrated into ligaments and droplets, and these droplets cause cutting of the solid material.

We envision the physical processes taking place at the optimum standoff distance as follows. The numerous droplets that broke up from the jet continue to travel at high velocities toward and impinge on the target workpiece. These multiple droplet impacts cause local water-hammer-like pressures (stresses) at the material surface; and their magnitudes are greater than the fatigue limit of the material, and sometimes even exceed the ultimate yield strength. Repeated impacts on the material then bring about material removal.

The proposed jet cutting processes apply only to the case where the standoff distance is optimum, and that other processes may be taking place at other distances. Since we are concerned about the mechanisms involved in the maximum removal of energetic materials, we have concentrated on analysis of the jet cutting phenomena at the optimum standoff distance.

In what follows we discuss the theoretical approaches taken to addresses the problem of solid-material responses to repeated jet droplet impacts, and the preliminary results obtained from these analyses.

2.2. Numerical Simulations

We have investigated a number of parameters for high-velocity waterjets into Aluminum, PETN and PBX-9404 disk targets using the CALE code. This is a 2-D, compressible, inviscid hydrodynamic code that allows for arbitrary Lagrangian or Eulerian treatment of all or part of the mesh.

We present two typical numerical simulation results for PETN and Aluminum (6061-T6) being impacted by a series of water droplets with a velocity of 1,000 m/s. These two materials are chosen to each represent brittle and ductile response characteristics.

The initial flow-field is shown in Figure 3. The droplet spacing for the calculations was prescribed such that the droplets would impinge on the material one after another one-microsecond apart. While this timing is somewhat arbitrary, results from such a scenario provide physical insights into the material-deformation behavior when repeatedly impacted by a series of droplets.

Response of PETN to Droplet Impacts.

The numerical results for the PETN response to droplet impacts are given in Figures 4 and 5. Owing to the axisymmetry of the problem only the top portion of the field is shown in these figures. The water droplet diameter for this case is 0.4 mm, and the failure strain magnitude for a PETN material is set at 20 per cent, a typical value for brittle materials.

The deformation of the PETN material at $t = 2$ microseconds is shown in Figure 4. At this time two droplets have already impinged on the material, and the third droplet is seen to be approaching the material. Note that after only two impacts the PETN material has undergone considerable deformation, including a piece of PETN that has come off from the surface, designated A in the figure.

Another result of interest is the pressure history of the material due to repeated droplet impacts. The induced-pressure history in the interior of the material is shown in Figure 5. The zone selected is half way between the material front and the back face, so as to take into account the behavior of the stress waves that travel in both the axial and the radial directions. Note that there are two peaks in the pressure history at this interior location, corresponding to the waves that were generated after each droplet impact. Such pressure peaks in the material would cause deformation and possibly an eventual failure of the material.

Response of Aluminum to Droplet Impacts.

The numerical results for the response of a 6061-T6 Aluminum to droplet impacts are given in Figures 6 and 7. Again, owing to the axisymmetry of the problem only the top portion of the field is shown in these figures. The water droplet diameter for this case is 0.063 mm, and the failure strain magnitude for an Al-T6 material is set at 150 per cent, which is considered reasonable for ductile materials.

The deformation of the Aluminum material at $t = 2.9$ microseconds is shown in Figure 6. At this time three droplets have already impinged on the material. Note the material geometry at this time, especially near the impact zone, where the aluminum has undergone considerable deformation as a result of the droplet impacts.

The induced-pressure history of the material near the impact point is shown in Figure 7. After each droplet impact the pressure reaches a high value for a short time and then decreases when the waves travel inside (axially) and laterally (radially) in the material. These peaks are analogous to those caused by the well-known water-hammer effects [Ref. 4], and their magnitudes often are greater than the fatigue limit of the material, sometimes exceeding even the ultimate yield strength. In such cases the material would lose strength and some portions would eventually spall off from the material.

3. CONCLUDING REMARKS

We have investigated the material removal phenomena caused by high-velocity waterjet impacts. Preliminary experiments show that material removal is optimum at a certain standoff distance between the nozzle exit and the target workpiece, and that this optimum distance is typically on the order of several hundred nozzle-exit diameters. At these great distances the jet is likely to have disintegrated into ligaments and droplets. A material removal mechanism is proposed: at the optimum standoff distances the material is removed mainly due to the multiple impacts of these droplets.

Numerical simulations for the response history of various materials following a series of droplet impacts show considerable material deformations and spallations. Various materials have been studied for their response characteristics, both brittle (high explosive types), and ductile materials, e.g., aluminum. Both materials display considerable deformations due to droplet impacts, but the brittle material such as PETN undergoes greater deformations than the ductile material (aluminum T6). The effects of the droplet impacts include high pressure peaks in the material, and these magnitudes are sizable, sometimes exceeding the material yield strength.

While plausible, the proposed mass-removal mechanism needs to be further investigated to put it on a firmer foundation through additional theoretical and experimental efforts.

ACKNOWLEDGMENTS

The cooperation of B. Do, J. Crutchmer, D. Garrett, and P. Cramer of Hanger and Mason, Pantex Plant, Amarillo, Texas, especially the capable assistance of B. Do during the course of this project is gratefully acknowledged. Thanks are also due to T. Ursic of A.M. Gatti, Inc., Trenton, New Jersey, for making his newly-patented efficient nozzles available for research use, both at Pantex and at LLNL.

REFERENCES

1. Kang, S-W, Reitter, T., Carlson, G., Crutchmer, J., Garrett, D., Kramer, P., and Do, B., "Target Responses to the Impact of High-Velocity, Non-Abrasive Water Jets," Proc. 7th American Water Jet Technology Conf., Seattle, WA, 28-31 August 1993.
2. Tipton, B., "CALE User's Manual," Lawrence Livermore National Laboratory Technical Report (1992).
3. Tikhomirov, R., et al., High Pressure Cutting, ASME, New York (1992).
4. Reitter, T., and Kang, S-W, "Analysis of Maximum Pressure Attainable by Water Jet Impact," Lawrence Livermore National Laboratory Technical Report UCRL-ID-114273 (May 1993).

Figure 1. 6061-T0 Al removal rate as a function of stand-off distance for 0.356-mm nozzle at 276 MPa

d_N : Nozzle diameter

ℓ : Jet intact length

v_j : Jet velocity

p : Stagnation pressure, $\rho_j v_j^2 / 2$

Figure 2. Sample Jet Intact Length vs. Stagnation Pressure [Ref. 2].

Figure 3. Multiple Droplet Impacts on a Material (Schematic).

Figure 5. Pressure History at an Interior Zone of PETN

Figure 4. Calculated Material Deformation for PETN at $t=2 \mu s$. (Droplet diameter = 0.4 mm; Droplet velocity = 1 km/s)

Figure 6. Calculated Material Deformation for Al-T6 at $t = 2.9 \mu s$.
(Droplet diameter = 0.06 mm; Droplet velocity = 1 km/s)

Figure 7. Pressure History at an Interior Zone of Al 6061-T6.

**DATE
FILMED**

9 / 15 / 94

END