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UNIVERSALITY CLASS OF THE FRAGMENTATION OF PLASTIC MATERIALS
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G. Timár*, J. Blömer†, F. Kun* and H. J. Herrmann‡

*Department of Theoretical Physics University of Debrecen
H-4010 Debrecen, P.O.Box:5, Hungary
e-mail: feri@dtp.atomki.hu

†Spezialwerkstoffe, Fraunhofer UMSICHT
Osterfelder Str. 3, 46047 Oberhausen, Germany
e-mail: jan.bloemer@umsicht.fraunhofer.de

‡Computational Physics IfB, HIF, ETH
Hönggerberg, 8093 Zürich, Switzerland
e-mail:hans@ifb.baug.ethz.ch

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Abstract. An experimental and theoretical study of the fragmentation of plastic materials is presented. In the experiments polyxymethylen particles of spherical shape were fragmented by impacting them against a hard wall. The experiments revealed a power law distribution of fragment masses similar to heterogeneous brittle materials, however, with a significantly lower exponent. To understand the experimental findings a three dimensional discrete element model is introduced. The model discretizes the sample in terms of randomly sized spheres which are connected by elastic beams. To capture the effect of plasticity a novel type of failure criterion is introduced complemented by a healing mechanism of broken particle contacts under compression. Computer simulations show a good quality agreement with the experimental findings.

1 INTRODUCTION

Fragmentation of heterogeneous materials is a very complex scientific problem with an enormous technological importance[1,2]. From the usage of explosives in mining through the comminution of minerals to the liberation of grains in particle composites fragmentation processes play a crucial role which calls for a thorough understanding. During the last decade research efforts have been concentrated on the breakup of heterogeneous brittle materials which is by now fairly understood[1,2,3,4,5,6,7]. Experimental and theoretical investigations have revealed that the energy imparted to the solid has to surpass a threshold value (critical energy) to achieve complete breakup[4,5,6,7]. In this fragmented state the mass (size) distribution of pieces follows a power law functional form with universal exponent depending mainly on the effective dimensionality of the system[1,3,4,6]. The branching-merging scenario of dynamically propagating cracks provided a qualitative physical picture underlying the universality[1].

Industrial processes require also the fragmentation of polymeric materials which exhibit ductile fracture. For polymers a complex deformation state may arise before breakup which leads to a more complicated crack initiation and propagation compared to brittle materials. In spite of its industrial relevance and scientific importance, the breakup of polymeric materials is still poorly understood. In the present project we carried out a detailed experimental and theoretical investigation of the impact fragmentation of polymers which revealed a broad spectrum of novel features.

2 RESULTS

We carried out experiments by impacting spherical particles made of Polyxymethylen (POM) against a hard wall. A single particle comminution device was used which accelerates the particles in a rotor up to the desired speed. Our device ensures normal impact on the wall in an evacuated environment. Particles of diameter $d = 5$ mm were fragmented varying the impact velocity v_0 in the range 30m/s - 180m/s. Experiments showed that to achieve breakup of the POM particle the impact velocity has to exceed a critical velocity v_c which was estimated to be $v_c \approx 60$m/s. Below v_c the particles suffered large permanent deformation with a few cracks opposite to the impact side, however, the sphere kept its integrity.

In the fragmented regime $v_0 > v_c$ we evaluated the mass distribution of fragments of the POM spheres by scanning the fragments with an open scanner. This way the fragment identification was reduced to searching white spots on a black background in a black-and-white digital image. Figure 1 shows that the measured mass distribution of fragments $F(m)$ has a power law functional form $F(m) \sim m^{-\tau}$ over three orders of magnitude followed by an exponential cutoff due to the finite particle size. The most interesting outcome of the experiment is that the exponent of the power law has a unique value $\tau = 1.15 \pm 0.04$ significantly smaller than the exponents obtained for brittle materials $\tau = 1.8 - 2.1$.

In order to understand the physical mechanism which gives rise to the novel exponent, we carried out computer simulations of the impact process using a three-dimensional discrete element model. In the model the spherical sample is represented as a random packing of spheres connected by elastic beams. In 3D the total deformation of a beam is calculated by the superposition of elongation, torsion, as well as bending and shearing in two different planes. The unique deformation behavior and the fracture of plastic materials is captured by introducing two novel components in the model: The beams break when they get overs-tressed similarly to other DEM models, however, breaking is allowed also under compression due to shear deformation. Additionally, we assume

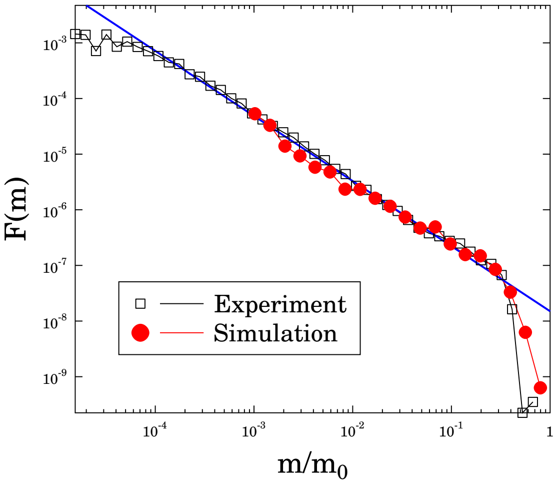

Figure 1: The mass distribution of fragments obtained in the experiments can be well fitted by a power law over three orders of magnitude. The slope of the straight line is $\tau = 1.1 \pm 0.05$. Computer simulations provide a reasonable agreement with the experimental findings.

that broken contacts can get reactivated when compressed over a sufficiently long time. This healing mechanism leads to plastic behavior of the material with the possibility of permanent deformation.

Final states of the impact process obtained by computer simulations are presented in Fig. 2 for two different impact velocities v_0 below and above the critical velocity of fragmentation v_c. It can be observed that below v_c (Fig. 2(a)) the impact induces a large permanent deformation of the particle, but no cracks appear. However, above v_c complete breakup is achieved into a large number of pieces (Fig. 2(b)). Plastic deformation implies that a large fraction of the imparted energy is dissipated which cannot contribute to fragmentation. It has the consequence that the fragments in Fig. 2(b) attain a surprisingly low speed by the end of the breakup process. The fragment mass distribution obtained by computer simulations are compared to the experimental findings in Fig. 1, where a nice agreement is evidenced.

3 CONCLUSIONS

1. We carried out experiments on the fragmentation of polymeric materials by impacting spherical particles made of Polyxymethylen against the hard wall. The experiments revealed a power law behavior of the mass distribution of plastic fragments with a unique exponents different from the one of heterogeneous brittle materials.

2. A 3D Discrete Element Model was used to obtain a deeper understanding of the fragmentation of plastic materials. The sample was discretized in terms of spherical particles connected by elastic beams. To capture the effect of plastic deformation a healing mechanism is introduced for beams at particle contacts under compression. The breaking rule of beams ensures the dominance of shear in crack formation.

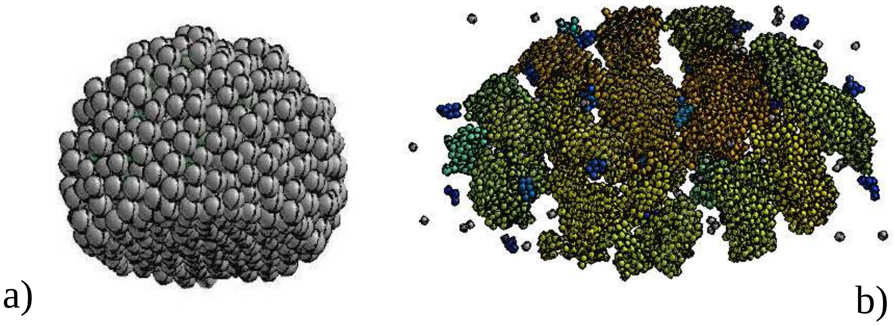

Figure 2: Final states of computer simulations of the impact process at different impact velocities. In (*a*) the impact velocity v_0 falls below the critical velocity of breakup $v_0 < v_c$ so that large permanent deformation remains without any apparent damage. (*b*) Above v_c fragmentation is achieved into a large number of pieces.

3. Computer simulations provide a good quality description of the experimental findings, i.e. at low impact velocities the sample suffers permanent deformation but does not break. Fragmentation is achieved at high enough velocities where the exponent of mass distribution has an excellent agreement with the measured value. Our experimental and theoretical work demonstrate that the fragmentation of plastic materials define a novel universality class of fragmentation phenomena.

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