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Conclusion

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XXVIII. Conclusion

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Basic studies show that the measured impact pressure can be accounted for by assuming compressible deformation of the liquid drop in the first stages of impact. The distribution of pressure under a drop produces a shallow indentation in the surface of ductile solids and a ring fracture in brittle materials. The flow of liquid across the surface from under the drop leads to erosive shearing along the edges of the deformed area. Although in theory erosion due to surface flow would not occur on perfectly smooth surfaces, ideal conditions of this kind are impracticable. The smallest discontinuities (step heights down to about 1000 Å) have been shown to act as nuclei for erosion pits. The short duration of the peak load during drop impact gives the impact an explosive character. In brittle materials the reflexion and interference of stress waves can cause extensive fracture in regions remote from the initial impact area. Spalling of the rear surface of a thin plate due to drop impact on the front surface could be an important mechanism in the failure of ceramic radomes in high speed aircraft and missiles. To some extent the strength of brittle solids can be improved by treatments which alter the size or number of surface flaws.

An interesting feature of the basic studies is that when a spherical drop strikes against a plane surface the initial velocity of the outward flowing liquid is very much higher than the impact velocity. This effect has also been observed for the normal impact of a jet with an inclined front surface; the flow velocity from under the inclined surface is again greater than the impact velocity. This behaviour has been explained using Birkhoff and Taylor's theory for the shaped charge (Munroe) effect. Other examples of this mechanism occur in the collapse of a concave liquid surface and in the coalescence of liquid drops; in this case a high velocity jet is produced between the approaching curved surfaces.

A related effect has been considered in Sir Geoffrey Taylor's paper; his analysis of the pressure exerted by a jet impinging on a plane surface indicates the possibility of very high pressures. These are predicted for conditions where the jet strikes obliquely and the impact surface moves normal to itself toward the jet.

Impact pressures have been measured by piezoelectric transducers, and more recently by a dislocation etch technique. Both methods give results which agree with the theoretical values. The dislocation etch method in transparent crystals has also been used to illustrate the extent of deformation of the crystal. This work has shown that appreciable dislocation movement can occur at stresses too small to cause detectable surface damage. Dislocation movements of this kind may be important in the initiation of fatigue failure at low stress levels.

The mechanism of damage due to multiple impact is more complex than that in the single impact process. Basic studies on repeated impact show that damage can occur in metals at average impact pressures which are below the yield stress of the material. Yielding occurs initially in small areas which are of the order of 1 μm in diameter. Local yielding of this kind is characteristic of hydrodynamic loading. The liquid under pressure seeks out and causes yielding at surface weaknesses, which would not necessarily develop under, for example, solid/solid loading conditions. Surface depressions formed in this way are then eroded by the shearing action of the surface flow to form pits. In very ductile metals the pits are further deformed by ductile tearing. In metals which have a tendency to brittle failure, for example iron-base alloys, fractures propagate from the bottom of surface pits. Fracturing of this kind accounts for most of the metal removed during erosion. In high strength Co–Cr alloys persistent slip bands and intrusions suggest that a fatigue mechanism is operating and is in part responsible for failure.

There have been a number of investigations which have attempted to correlate erosion damage with mechanical properties. It has been known for a long time that hardness is important in determining erosion resistance. It is worth noting, though, that some of the most erosion resistant materials are the stellites; this is a little surprising since their hardness is low compared with other erosion resistant materials such as, for example, ausformed steel. It is possible that the structure of the stellites, consisting of a hard phase distributed in a tougher matrix is the important factor. Recently studies on the rain erosion resistance of materials have shown that the elastic moduli and notch toughness also have an important bearing on erosion. It should be born in mind in any discussion of material properties pertinent to the liquid impact problem that the appropriate values are those obtained under dynamic conditions.

The importance of the angle of impingement has been demonstrated. The impact pressure is reduced according to the cosine of the angle of impact. The damage generally decreases with angle, but there are important exceptions. One example occurs in hard plastic materials where the subsurface damage and ring crack damage coincide for an angle of impact of about 15°. At this angle the 'total' damage is greater than for normal incidence. When the drop impacts at an angle the flow of liquid is increased in the direction of impact, there may also be a further increase in velocity due to jetting if the geometry is suitable; considerable local failure will then occur so that the 'total' amount of damage remains high.

In the practical problem of aircraft and missiles surfaces will in general be angled, however, these surfaces can have localized regions standing normal to the impact direction. This is likely to occur, for example, where two components join, at welds and at rivet heads. The discontinuity in surface height may be small, but laboratory experiments have shown that discontinuities of submicron dimension are susceptible to erosion.

In supersonic flight a detached shockwave can markedly reduce the damage by breaking up the drops into a fine mist before they strike the surface. However, this breakup process takes a finite time, and for a given situation only drops up to a certain diameter will be disintegrated completely. A part theoretical part experimental relation has been developed which predicts, with some success, the degree of protection offered by the shockwave for given flight conditions.

It is difficult to give a precise figure for the speed at which erosion becomes important since this will clearly depend on the size of the rain droplets and the intensity of rain, but laboratory and flight tests show that most materials if subjected to 'repeated' impact exhibit measurable damage for velocities in excess of about 200 mi./h. As the velocity increases the amount of damage increases at a much faster rate, and in the region of

Mach 1 to 2 a 'single' impact causes serious deformation. The obvious solution to this problem is to avoid flying at very high speed through rain, and this is in fact what happens with many aircraft in that they fly relatively slowly up through the rain, and achieve their highest speeds above the rain level. The altitude limit for rain is usually quoted as about 30000 ft., although it is admitted that, if vigorous convection currents develop, droplets can be carried even higher. Cloud tops up to 55000 ft. have been reported.

Recent photographic observations of events inside an operating turbine have done much to clarify the sources of damage, and suggest possible design modifications to alleviate the problem. It appears that the water which does the damage collects on the fixed nozzles after condensation on the nozzles or walls of the turbine and is then pulled by the steam drag into the path of the moving blades. The water frequently leaves the fixed nozzles as large drops (up to about 1400 μm diameter), but the evidence is that these drops soon start to break up into smaller, and hence less damaging, drops. This suggests that the damage on the moving blades could be reduced by increasing the separation between the fixed and moving blades. This has in fact been tried with some success.

Another apparent solution to the problem would be in the complete extraction of the water from the system. This, however, would be technically difficult since the condensation occurs at such high rates in the body of the turbine. Attempts have been made though to remove the pools of water which collect on the fixed blades either by 'sucking' them off or else slotting the blades so that the water can travel to an outlet. These attempts have all met with some success but have not eliminated the erosion damage.

Cavitation collapse can also give rise to pressures capable of deforming the strongest solids. When the collapse occurs on the surface of a solid the deformation is usually attributed to the stress waves generated by the collapse. However, recent studies have shown that a further mechanism may operate in this situation: the collapsing cavity may produce a high speed liquid jet by involution of the far side of the cavity. Photographic evidence shows that this jet then passes through the cavity and can strike the solid surface. Although it has yet to be demonstrated experimentally it seems likely that this jet formation could be an important factor in cavitation damage. The mechanism of jet formation has similarities with that mentioned earlier for the other jets; both forms of microjets can travel at high velocity and are possibly important factors in the erosion process.

Cavitation damage consists usually of single-event symmetrical craters and of irregular fatigue type failures. Experiment supports the view that cavitation and droplet impact are closely related; the form of damage is often very similar and if materials are classified in order of their resistance to cavitation the same order is closely followed by their erosion resistance. For this reason the drop impact test is frequently used for quantitative evaluation of the cavitation resistance of materials. The results of cavitation experiments in a laboratory show that the damage is very sensitive to specimen geometry and minor flow perturbations. In this respect there are still difficulties in extending results from models to the practical situation.

It is pleasing to note that, in addition to the problems it causes, high speed liquid impact can have useful applications. High speed liquid jets have been applied with some success to wood cutting, and the possibilities of cutting rock and coal are at present being investigated. If this form of cutting proved feasible it would have the advantage over more conventional coal cutting appliances in that, in the absence of frictional heating, the possibility of ignition of methane gas would be reduced. Continuous jet velocities of about 3000 ft./s (900 m/s) have been produced, and at these velocities the jets cut coal and most forms of rock.

It has been reported several times during the course of the Discussion that erosion damage increases very rapidly with impact velocity. In metals damage varies as the second, third or even higher powers of the velocity, and in ceramics and glasses the dependence may be as large as six or seven. This may seem surprising since the impact pressure varies linearly with velocity (for very high pressures the variation will be somewhat larger due to the increase in the sound speed). The difference, of course, is connected with the fact that erosion damage involves several different deformation mechanisms. This also means that it is not possible to relate impact pressure and erosion damage in any simple way. In ceramics, for example, the large dependence on impact velocity is connected with the fact that failure is a sudden process occurring at a critical stress level: above this level a brittle material will rapidly disintegrate. In metals, on the other hand, failure occurs by yielding, work-hardening and finally fracture. This is a much slower process in terms of weight loss.

For particular materials under particular conditions velocity relationships are of great value in predicting behaviour over a velocity range. Attempts to generalize these relationships for all materials or even over a class of materials is, however, not advisable. The type of failure can change so completely with a change of material or with an alteration in erosion conditons that it becomes impossible to predict the amount of damage.

Several papers have given figures for the velocities and pressures found in the droplet impact, rain erosion, turbine erosion, and cavitation. Table 1 summarizes some of these results. It is apparent that similar high pressures are developed in all these processes.

TABLE 1. VELOCITIES AND PRESSURES INVOLVED IN LIQUID IMPACT

condition of impact	velocity (m/s)	pressure (Kg/mm^2)	
single impact with 2 mm drops	305 1140	63 363	measured and calculated
steam turbine blade erosion	up to 600	up to 150	calculated
rain erosion	91 335 670	16 70 200	calculated
cavitation erosion	—	up to 100	calculated
rock cutting with liquid jets (steady pressure)	1000	50	measured

It is clear that there are areas where further research is needed in the immediate future. A study of the impact and cavitation behaviour of materials over a range of temperatures and in varying states of stress would clearly be relevant to practical situations. Further, in the case of aircraft and missiles there is evidence that failure often occurs initially where components are joined; further research both on the structure itself and on realistic models will be necessary if the design engineers are to reach the best solutions.

There are indications that in some applications multiphase materials have the greatest resistance to erosion. The development of new multiphase solids and composite materials and the study of their behaviour will require considerable effort, although the task should be easier now that many of the basic deformation mechanisms are understood. Since the pressures induced by high speed liquid impact and cavitation are so high materials exhibiting their highest strength values under dynamic loading are needed. This strength is ultimately controlled by the defects present in the solid. Research on defects is made difficult by their submicroscopic size, but the gap between theoretical and practical strengths is such that the rewards offered are great. Further there would be a clear advantage if the energy of the impact could be distributed throughout a large volume solid. The production of materials with low elastic moduli but high tensile strength would be of value.

Many of the results presented in this discussion have emphasized the close links between droplet impact and cavitation. It seems probable therefore that if materials can be developed that provide a solution to one of the problems that they will also be applicable to the other.