In an extensive series of investigations conducted by T.W. Barbee Jr., D.R. Curran, L. Seaman, D.A. Shockey and others at the Stanford Research Institute [72B1, 73S1, 73C8, 76S2, 77C2] it has been shown that cracks or voids are nucleated at a rate that increases exponentially with the excess of the tensile stress over a threshold value. The radius of each crack or void has been found to increase at a rate proportional to the product of its current value and the excess of the tension over a threshold value for growth. The parameters entering these rate equations are called nucleation and growth (NAG) parameters and work in which they have been measured is noted in table 3.6. The nucleation and growth laws have been inferred, on the basis of a number of assumptions, from the results of counting and measuring individual cracks or voids appearing on cross-sections of recovered samples [78S2]. The void growth results are in reasonable accord with continuum-mechanical models [71S1] and a microscopic model [72S2, 73S4]. The empirical conclusion that the same viscous growth law applies to the radius of penny-shaped cracks is rather surprising, as conventional continuum-mechanical analysis predicts that the crack boundary should move at constant velocity after a brief period of acceleration. DeRosset [73D2] has pointed out that one must expect some coalescence of cracks when they are present at the observed densities, and has shown that coalescence of cracks expanding at constant velocity leads to apparent exponential growth.

Because spall damage accumulates gradually and affects the stress field through its effect on the gross mechanical properties of the material, detailed analysis of spall phenomena requires combining rather complicated mechanical theories with detailed time-resolved wave profile

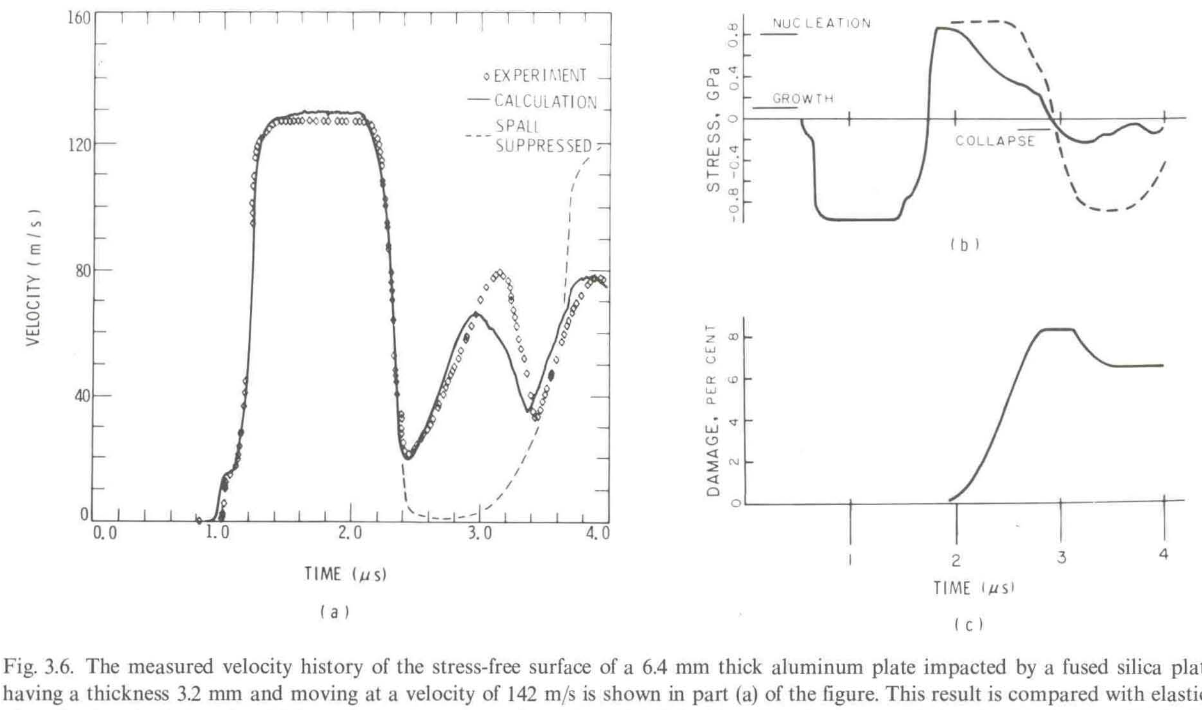

Fig. 3.6. The measured velocity history of the stress-free surface of a 6.4 mm thick aluminum plate impacted by a fused silica plate having a thickness 3.2 mm and moving at a velocity of 142 m/s is shown in part (a) of the figure. This result is compared with elastic-viscoplastic calculations in which spallation is suppressed and in which it is allowed to develop and interact with the stress field. The corresponding calculated stress histories at the midplane of the aluminum plate are shown in part (b) of the figure, along with threshold stresses for nucleation, growth, and collapse of voids. The history of damage accumulation at this plane (defined as volume fraction of voids) is shown in part (c), (after Davison et al. [77D1]).

measurements and a quantitative description of the damage observed in recovered samples. Several such theories have been developed [73D1, 76S2, 77D1, 77C1, 79D1] and some results of an example calculation that illustrates both the sort of prediction obtainable from a typical theory and some features of the spall process itself are given in fig. 3.6. It is noteworthy that, in the ductile case, at least, the theoretical predictions are in general conformity with a broad range of observations [79D1]. The complexities introduced by the varying orientation of the cracks that develop in some polycrystalline metals have so far prevented analyzing their behavior on the basis of a completely sound, internally consistent theory.

The state of knowledge of spall phenomena can be summarized by saying that much practical information is available and pragmatic understanding is well advanced, but almost nothing fundamental is known about either the nucleation or late growth stages of the process and much remains to be learned about the early growth phase. The influence of viscous heating and inertial resistance to growth are cases in point. Some calculations suggest that the heating attributable to plastic flow can raise the temperature of void surfaces to nearly the melting point, but this effect has not been included in the growth models. Inertial effects are known to slow the exponential growth observed for small voids [71S1] but this effect is not included in interpretations of data. The influence of void coalescence on observed growth rates also remains to be investigated, and this influence could be very great if nucleation at adjacent sites is correlated. Finally, the effect of variations in microstructural parameters is almost completely unknown.

3.6. Residual metallurgical effects of shock loading

The limited mechanical, electrical, and optical measurements that can be made during shock compression, or while the material is held in the compressed state, can usefully be augmented by examination of samples recovered after the load is removed. These examinations not only disclose features of the shock process, but also provide a means for extending many conventional metallurgical investigations to conditions of strain rate and compression not achievable by other means.

The value of careful examination of recovered samples was demonstrated in an early investigation of Smith [58S1] in which twinning was disclosed as a high-strain-rate deformation mechanism in copper and a number of unusual effects were found to result from the $\alpha \rightarrow \varepsilon$ phase transformation in iron. The field has remained active since this early work, and has been reviewed periodically as indicated in section 1.1. Two recent reviews are of particular interest; that by Otto and Mikesell [67O1] because it contains tabular and graphical information on residual mechanical properties, and that by Leslie [73L1], who provides an authoritative summary of work in the area of physical metallurgy through 1972. Some subsequent work is summarized in table 3.7.

Typical peak compressions achieved in investigations of residual metallurgical effects have been 5 to 20 per cent (pressures to ~ 50 GPa), with most of this compression occurring during the few nanoseconds required for the plastic wave to pass a given material point. The uniaxial compression process is, of course, accompanied by a substantial and rapid inelastic shear. Following passage of the compression waves, the material is held in the compressed state for a time depending on the experimental configuration but not exceeding a few microseconds, after which a decompression wave allows the material to expand adiabatically to atmospheric pressure. Significant shock heating also occurs; for example, compression to 30 GPa causes the temperature of aluminum to increase by about 400 K and that of copper to increase by almost 200 K. Even after decompression, temperatures are increased by 170 and 70 K, respectively. Few experiments have been