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TITLE: STUDIES ON EXPLOSIVELY DRIVEN CRACKS UNDER CONFINING IN SITU STRESSES

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MASTER

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STUDIES ON EXPLOSIVELY DRIVEN CRACKS UNDER CONFINING IN-SITU STRESSES

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ABSTRACT

Successful explosive gas well stimulation requires a thorough understanding of explosively driven cracks under confining in-situ stresses. In a previous paper (Simha, et al 1983) the problem of explosively driven cracks was experimentally investigated to reveal the features of crack propagation. It was observed that the explosively driven crack propagation is the result of two different but overlapping phases. The first phase involving the initiation and early time crack propagation is entirely governed by the explosively generated stress transients. The rapidly decaying stress transients then lead to the second phase of crack propagation largely controlled by the in-situ stresses. The purpose of this paper is to more fully understand the characteristics of the first phase concerning the initiation and early time propagation of explosively driven cracks. Experiments are conducted with plastic models under biaxial compression and the dynamic event is observed with a high speed multiple spark gap camera of the Cranz-Schardin type. The experimental observations are utilized to propose analytical models of crack initiation under explosive loading to aid in the design of multiple fracturing necessary for successful application of modern well stimulation techniques.

INTRODUCTION

The ever growing need for oil and natural gas has led to several new sources of hydrocarbon fuels that require novel and often very costly means of extraction. In the United States gas-bearing deposits of Devonian Shale have been identified in the states of Pennsylvania, Kentucky and West Virginia along the Appalachian basin. Vast as these deposits are, only a few of the many fields have proved to be economically viable. The key factor for a well to be successful is that the shale surrounding the well bore be fractured to promote gas flow into the well bore. Towards this end various techniques have been attempted to stimulate wells. Stimulation by hydraulic fracturing has been moderately successful in this regard. However in recent times explosive stimulation has been enthusiastically investigated, although in some instances, the flow rates have actually been substantially reduced.

This has been attributed to a combination of factors including stress caging and excessive fragmentation causing crack closure by fines. However among other factors the successful application of explosive stimulation involves the phenomenon of dynamic crack propagation in the presence of confining in-situ stresses. Specifically, the problem involves linking the well bore to a pre-existing fracture network where it becomes necessary to drive cracks over long lengths as well as maintain control over their paths. While the crack length is largely determined by the borehole pressure generated by the explosion and the consequent gas flow into the propagating cracks, the crack path is significantly dependent on the existing in-situ stresses. In 1980 Warpinski, et al described the results of tests conducted at the U. S. Department of Energy's Nevada test site to examine the effects of in-situ stress variation on fracture. Earlier in 1976 Dally and Fourney reported on a simplified model to predict the crack curvature under a uniaxial stress field. Recently, an experimental investigation was conducted to extend this model to the general case of a biaxial stress field (Simha, et al 1983). In the above investigation the general features of explosively driven cracks were discussed with the emphasis on the nature of propagation in the presence of confining in-situ stresses. The purpose of this paper is to review the work in the light of additional experiments and specifically address the problem of crack initiation and early time propagation. These are the key issue involved in techniques such as tailored pulse loading and have still not been completely understood. Another purpose of this paper is to utilize the experimental observations to propose an analytical model of crack initiation under explosive loading.

EXPERIMENTAL INVESTIGATION

Transparent plastic was utilized in the experimental investigation. The models were nominally 205.4 mm (12") square and the cracks were driven from a 38.1 mm (1-1/2") borehole. The biaxial load was applied with a specially fabricated device capable of applying compression up to 4500 kg (10,000 lbs). Figure 1 shows a 50.8 mm (2") thick plexiglas model in the biaxial loading device. This device permitted the biaxial stresses to be varied independently from zero up to about 25 kg/cm^2 (350 psi). The stress ratio was varied by adjusting the thicknesses of the side shims. Plexiglas shims were used to reduce stress wave reflections and further reduction of wave reflections resulted upon providing rubber pads between the shims and loading

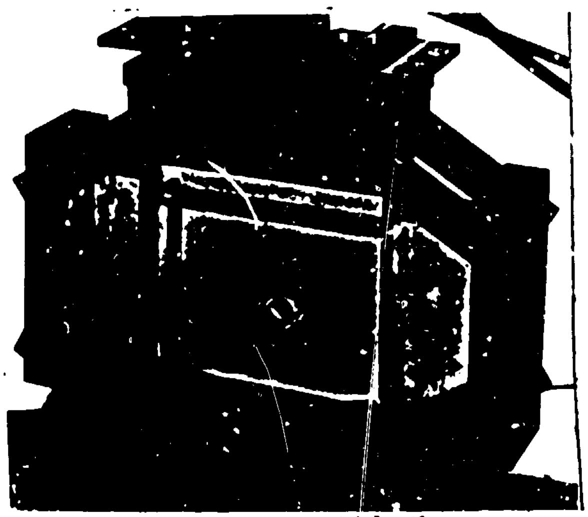

Figure 1 Plexiglas model in the biaxial loading frame

frame platens. The models were charged with up to 500 mg of explosives consisting of either PETN or a mixture of PETN and a propellant obtained from the Kinetech Corporation of Sacramento, California. Flaw sites on the borehole wall were simulated by making small notches on the borehole wall. The borehole was notched at two diametrically opposite locations to limit the number of cracks to two. The notches were all 1.6 mm wide and 3.2 mm deep. The charges were detonated while the models were in

a) Hydrostatic in-situ stress

b) Non-hydrostatic in-situ stress

Figure 2 High speed pictures of explosively driven cracks

the field of view of a high speed multiple spark gap camera of the Cranz-Schardin type. This camera is capable of sixteen pictures at framing rates as high as 850,000 per second and permits the study of high speed phenomena. The recording of borehole pressure generated by the explosion was achieved by the use of Kistler piezoelectric transducers in conjunction with the Nicolet digital oscilloscope. A pressure containment device consisting of two circular steel caps held by a through bolt was used to retain the explosive gases in the borehole. For more details on the experimental arrangement the reader is referred to the previous paper (Simha, et al 1983).

Figure 2 shows some high speed pictures taken by the Cranz-Schardin camera. For the case of explosively driven cracks in a model subjected to a state of hydrostatic compression, the cracks propagate radially straight and for other cases the cracks curve. A series of tests were conducted with different in-situ stress levels. The experimental data was utilized to understand the mechanics of initiation and early time phenomena involved in explosively driven cracks as discussed in the next section.

INITIATION AND EARLY TIME PROPAGATION OF EXPLOSIVELY DRIVEN CRACKS

If the concepts of static fracture mechanics are utilized, then cracks initiate whenever the stress intensity factor, K, exceeds a certain critical value, K_{IC}, termed as the fracture toughness. Stress intensity factors and fracture toughness values have been determined for a variety of crack situations and materials respectively (see for example Rock Fracture Mechanics Ed. Rossmanith, 1983). For the purpose of computing SIF it is assumed that the crack is completely pressurized to the borehole value. Accordingly for the present borehole/notch configuration the critical pressure necessary to drive the cracks in plexiglas model is about 11.5 MPa for which the fracture toughness value is 2 MPa $\sqrt{m}$. These values assume that there is no effect of the prestress on the fracture initiation process. While this assumption is not strictly valid, in the present investigation, the prestress magnitudes did not exceed about 20% of the peak dynamic borehole pressure and it was found that their effects were only important in the late time crack propagation (Simha, et al 1983). The hoop stress in the vicinity of an explosively loaded borehole plays an important role in crack initiation. If we now focus our attention on the hoop stress at the point of crack initiation; i.e., $\theta = 0,\pi$ and $r = a$, the value is

$$\sigma_\theta = \sigma_\theta^d - \sigma_1 + 3\sigma_2 \tag{1}$$

In the above equation $\sigma_\theta{}^d$ represents the dynamic hoop stress caused by the explosion and $\sigma_{1,2}$ are the in-situ stresses. While $\sigma_\theta{}^d$ can be determined for the case of radial symmetry, a general solution is rather formidable. A detailed discussion of this aspect is given in the previously mentioned reference.

We can anticipate that fracture initiation depends on this hoop stress in a manner that will involve the stress intensity factor at the notch tip. Accordingly from Equation (2) the additional borehole pressure required to overcome the effect of in-situ prestress is $(3\sigma_2 - \sigma_1)$. In the present investigation this value ranged from zero to as high as 6.9 MPa. Yet no significant correlation was observed between this value and the explosive pressure necessary to initiate the cracks. This points to the extremely transient nature of crack initiation wherein the dynamic stress intensity factor due to the transient borehole pressure becomes the decisive factor. Figure 3 shows the crack tip position vs time for a borehole pressure loading shown in the same figure. In this test the principal biaxial in-situ stresses were 1.27 MPa and 0.9 MPa with the larger stress acting to close the crack. The borehole pressure reached a maximum of 17.9 MPa followed by decaying oscillations due to the combined effect of shock wave reflections inside the borehole and gas venting through the cracks. The crack tip plot in Figure 3 when extrapolated backwards indicated a fracture initiation time around 60 μs. At this instant of time the borehole pressure was about 13.8 MPa, about 14% more than the statically predicted value. Presently another polymeric material called Homalite 100 has achieved a prominent position in dynamic photoelastic studies of fracture phenomena. This material has a static fracture toughness of approximately 20% as that of plexiglas which translates to a critical borehole pressure of 2.3 MPa for the present model configuration. Figure 4 shows the results obtained with this material when there was no prestress applied to the model. The cracks initiated at 50 μs when the borehole pressure was 8.3 MPa and still rising. This corresponds to almost three times the value predicted by static fracture toughness concepts.

In conclusion the dynamic photoelastic experiments furnished valuable insight into the problem of explosively driven cracks from a flaw site. It was consistently observed in all the tests that the dynamic pressure required to initiate the cracks are greater than the values predicted using static fracture toughness concepts. In some experiments it was observed that the cracks initiated during the loading phase when the borehole pressure was still rising while in other tests it was observed that the cracks initiated during unloading after the pressure had reached its peak value. However no definite conclusion can be drawn regarding the fracture initation time except that the cracks wait until they are charged with sufficient energy to overcome the initial resistance of the material around the notches. These results once again suggest strongly that dynamic crack propagation from an explosively loaded borehole depends on the entire pressure history and not just the instantaneous pressure value. The experimental results obtained so far prompted formulating an analytical model of explosively driven crack initiation given in the next section. A detailed description of the model is given in another report (Simha, et al 1984) and here it will be only briefly summarized.

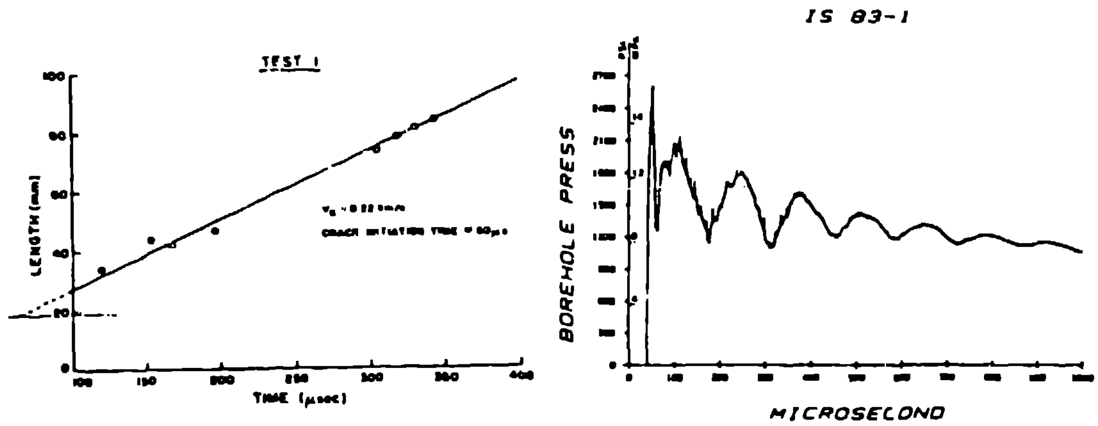

Figure 3 Explosively driven crack growth in plexiglas

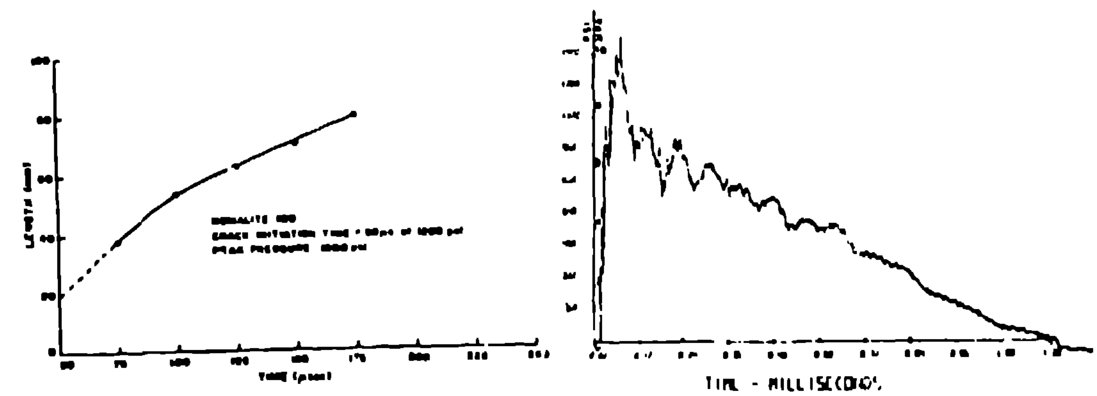

Figure 4 Explosively driven crack growth in Homalite 100

ANALYTICAL MODELING OF EXPLOSIVE LOADING

In recent years the tailored pulse loading has emerged as an enticing concept for achieving multiple fracturing for well stimulation. The basic idea is to generate a borehole pressure high enough to initiate as many radial fractures as possible but not too high to crush the rock. Intuitively this implies a pressure loading history that initially rises steeply but then maintains a value just enough to overcome the crack resistance of the rock. In this context the subject of fracture mechanics provides many useful guidelines. There is a general tendency to rely on static fracture mechanics concepts to predict dynamic fracture phenomena such as explosively induced fracture. This is not surprising due to the ease with which one can establish the relevant material parameters such as fracture toughness, K_{IC} or the critical crack opening displacement. While these parameters have been well tested for static loading conditions, it has not been verified whether these results can be extrapolated into the dynamic loading regime. In general it can be said that static approaches provide incomplete guidelines for estimating the outcome of a dynamic fracture event. There is a definite experimental evidence as seen here and by other investigators (Grady and Hollenbach 1977) that loading rate affects the process of fracture initiation significantly.

Shockey, et al 1983, have assessed several existing dynamic fracture criteria experimentally and concluded that for crack initiation, the dynamic stress intensity factor must equal or exceed the fracture toughness value for a certain minimum time. In the present paper an attempt is made to model crack initiation directly on the basis of the borehole pressure loading history. The modeling is guided by the experimental observations and basic dynamic fracture mechanics and for more details the reader is referred to the report.

Tentatively one can postulate that fracture instability is possible only when the energy release rate exceeds the static crack resistance. Secondly it can be postulated that there is a definite time lag before the onset of fracture instability after reaching the above condition. Further during this time lag energy is fed into the process zone to overcome the dynamic crack resistance of the material for a given crack speed. During this phase there is some subcritical crack growth that occurs with the crack growing non-uniformly. The transition from subcritical crack growth to the final fracture instability depends on the material response to dynamic loading. This transition can be conveniently modeled by an apparent increase in the crack length by Δa due to the formation of the process zone. This implies that the subcritical crack growth need not actually take place physically. It is only the occurrence of irreversible processes around the crack tip that makes the crack behave as if it were longer than its physical size. This approach was originally suggested by Irwin, 1958, to account for crack tip plasticity effects in metals. With regard to multiphase systems such as rocks and ceramics the situation becomes more complex. The microcrack process zone in these materials is characterized by the local fracture toughness which varies significantly from point to point. This variation can make the microcrack process zone extend to considerable lengths from the crack tip. Although there is much evidence of a microfracture process zone in rocks, comparatively little is known about its shape and size. All these issues pose problems in predicting the onset of dynamic fracture instability. In the context of dynamic loading, finite times associated with crack initiation and early time crack acceleration depend on the formation of process zone of the correct shape and size. At extremely high loading rates, as may be the case in explosive loading, the time for the accelerating phase is of the same order as that required to achieve fracture initiation [Grady and Hollenbach 1977]. The foregoing concepts were utilized in formulating a fracture initiation criterion. The criterion was developed from the following two fundamental requirements.

$$G^{dyn} > G_{IC} \text{ or } R_C \; ; \quad \int_0^{\Delta a} G^{dyn} da > \int_0^{\Delta a} R_c da \qquad (2)$$

Using the above conditions it is possible to establish a relationship between the time delay and dynamic fracture toughness. If we assume $da = Q_n t^n$ and R_c = constant, then the time delay, T, for $n = 1$ is given by the following integral equation

$$K_{Id} = \sqrt{\frac{1}{T}\int_0^T K^2 dt} \qquad (3)$$

The above equation ascribes a root mean square calculation for K_{Id}, the dynamic fracture toughness. This equation was applied to the Homalite 100 model to estimate the dynamic fracture toughness at the loading rate observed in this test. The experimental data is the same as presented earlier in Figure 4. In this experiment the fracture instability occurred at 50 μs when the borehole pressure was 8.2 MPa and rising. The average rate of pressure rise was 0.2 MPa/μsec corresponding to a $\dot{K}$ of 0.03 MPa$\sqrt{m}$/μsec. Assuming a static fracture toughness of K_{Ic} = 0.44 MPa$\sqrt{m}$, the time delay for Equation (3) is approximately 27 μs. Utilizing this value in (3) gives K_{Id} = .51 MPa$\sqrt{m}$. This represents a 17% increase in its fracture toughness from the static value.

In conclusion the problem of fracture instability under transient loading conditions depends on the material behavior at high strain rates. When the flaw size is large the instability is also governed by the relative duration of the load and the time that it takes for the stress wave to traverse the length of the crack. In the context of explosively driven fracture utilized for well stimulation or controlled blasting operations, the more important parameter is the pressure time history exerted on the borehole wall. As developed in the fracture instability criterion the pressure history or equivalently the stress intensity factor history determines whether or not a crack propagates from a borehole. It is also possible employing the analysis developed in this paper to qualitatively understand the time delays involved with different types of pressure loading.

CONCLUSIONS

An experimental investigation has been conducted to study the influence of confining in-situ stresses on explosively driven cracks from a well bore. High speed photography in conjunction with the photoelastic technique was used to observe the dynamic event of the propagation of cracks from an explosively loaded borehole in plastic models. The study revealed that crack initiation and early time propagation is entirely governed by the transient borehole pressure loading. The entire history of the borehole pressure is involved in determining whether or not a crack initiates from a flaw site on the borehole wall. The experimental observations in conjunction with the principles of modern fracture mechanics were utilized to formulate an analytical model of crack initiation under explosive loading. The analytical modeling was designed to aid in applying the modern concept of tailored pulse loading to multiple fracture.

ACKNOWLEDGMENT

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REFERENCES

Dally, J.W. and Fourney, W.L., 1976, "Fracture Control in Construction Blasting", Report to the National Science Foundation, University of Maryland Contract No. APR 73-07908-A01

Grady, D.E. and Hollenbach, R.E., 1977, "Rate-Controlling Processes in the Brittle Failure of Rock", Sandia Lab. Rept. # 76-0659 to United States Energy Research and Development Administration.

Irwin, G.R., 1958, "Handbuch der Physik VI, Flügge Ed, Springer, pp. 551-590.

Rossmainth, H.P., Ed., 1983, Rock Fracture Mechanics, Springer-Verlay, Germany.

Shockey, D.A., Kalthoff, J.F. and Erlich, D.C., 1983, "Evaluation of Dynamic Crack Instability Criteria", Int. Journ. of Fracture, 22, 217-229.

Simha, K.R.Y., Fourney. W.L., Barker, D.B. and Shukla, A., 1983, "Model Studies on Explosively Driven Cracks Under Confining In-Situ Stresses", Proc. I Intl. Symp. Rock Fragmentation by Blasting, Lulea, Sweden.

Simha, K.R.Y., Fourney, W.L. and Dick, R. D., 1984, "Explosively Driven Fracture Initiation Under Confining In-Situ Stresses", Photomechanics Lab. Rept., Univ. of Maryland.

Warpinski, N.R., Schmidt, R.A. and Northrop, D.A., 1980, "In-Situ Stresses: The Predominant Influence of Hydraulic Fracture Containment", Proc. I Annual Symp. on Unconventional Gas Recovery, p. 83.