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The Feasibility of a Shear-Compression Kolsky Bar with Simultaneous Wave Arrival at the Sample

by Christopher S Meredith

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14. ABSTRACT

Improving armor materials requires a full understanding of the constitutive response of a material subjected to a multiaxial stress state at dynamic strain rates. This has proved almost impossible to measure dynamically. This report assesses the feasibility of one method to produce an axial wave and a shear wave that arrive at a sample simultaneously. The method uses a modified Kolsky bar apparatus with a pair of gun barrels, where one projectile creates an axial wave and the other a shear wave in the Kolsky bars. The waves are created at opposite ends of the apparatus and travel toward the sample from opposite directions. The time difference created by sending the signals to the valves, the opening of the valves, and the time the projectile spends moving down the gun barrel needs to be consistent enough to be corrected for, since the waves travel at different velocities. The model system built shows the error is too large and, thus, this method is not feasible.

15. SUBJECT TERMS

split-Hopkinson pressure bar, Kolsky bar, multiaxial loading, shear-compression loading, shear-tension loading

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Contents

List of Figures

List of Tables

1. Introduction

Ballistic events inherently generate a multiaxial stress state in the target that occurs and evolves over microsecond time scales. Thus, understanding the multiaxial mechanical behavior of materials at dynamic strain rates is critical to developing next-generation armor for the Soldier to defeat emerging threats. Experimental methods for quasi-static loading, which generate a combined axial–shear stress state within the sample, are available and relatively straightforward. The samples are usually tubular and are loaded in torsion and compression or tension using a screw-driven or hydraulic load frame. The stress state can be complicated further by adding an internal or external pressure to the sample (Dieter 1986). However, at strain rates above approximately 10 s^{-1}, methods are few or nonexistent. At the very high strain rates of 10^4–10^6 s^{-1}, there are pressure–shear plate impact experiments, but these are extremely challenging and require thin-film samples (Klopp and Clifton 1985). Sample adaptations with the conventional compression Kolsky bar (also known as split-Hopkinson pressure bar) are the simplest option. A sample that is a tilted cuboid can generate a small shear component in a brittle material (Nie et al. 2007), and a sample with an angled slot cut into it (Rittel et al. 2002) will have a shear-compression stress state, but only the compression loading and displacement are measured in both cases, and the latter has a complicated 3-D stress state. More complicated are modifications to the torsion Kolsky bar, which utilizes a torqueing device to rotate the free end of the incident bar. A clamp between the sample and torqueing device holds the bar such that torque is only generated in the bar between these two locations. When the desired stored torque is reached, a notched pin that is part of the clamp is fractured. This releases the torque as an elastic shear wave down the incident bar. Calculation of the shear stress, strain, and strain rate uses the same fundamental 1-D wave-propagation equations as the compression Kolsky bar (Gilat 2000). A hydraulic cylinder that loads the same section of the bar as the torque can be added to provide compressive or tensile stored load, in addition to the torque. When the pin fractures, shear and axial waves travel toward the sample, but because the axial wave travels faster, the sample will always be loaded in tension–compression first and then shear.

This combined-loading Kolsky bar has mostly been used to study dynamic friction (Lewis and Goldsmith 1973, Rajagopalan and Prakash 1999, Espinosa et al. 2000, and Huang and Feng 2004); however, the torque required for friction is significantly less than what is needed to measure the constitutive response of a material. A paper by Chichili et al. (2004) did use this apparatus for adiabatic shear localization under combined loading, but that is not the same as the constitutive response of the material and, as before, lower torque is required. One other Kolsky bar modification by Zhao et al. (2011) used a wedge-shaped incident bar end (at the sample end) and a pair of transmitted bars aligned ±45°, where each wedge face is aligned with the end of each transmitted bar. A sample is sandwiched between each wedge face and one of the transmitted bars, so that when the axial wave arrives it generates simultaneous compression and shear in the sample. However, the shear component is relatively small and the measurements are not valid once the sample starts sliding. The only other technique with simultaneous compression and shear loading utilizes the compression Kolsky bar with a torque adapter between the incident bar and sample (Claus et al. 2017). The torque adapter consists of a couple of short-length pieces with key-slot joints. When the compression wave arrives at the adapter, the force generated at the joints causes the adapter pieces to rotate and this rotation is transferred into the sample. The transmitted bar is replaced with torque and compression transducers. However, as with some of the other techniques, the torque generated is relatively low and the amount of rotation is small. Thus, it is clear from the paucity of literature on this topic how challenging the problem is.

This report details the results from testing the feasibility of one technique to have shear and axial waves reach the sample simultaneously, which requires microsecond control over the timing of the generation of each wave. If feasible, this technique could generate shear and tension or compression by using a separate gas gun to generate each loading on opposite ends of the pair of Kolsky bars. The waves travel toward each other and, if timed correctly, could arrive at the sample simultaneously.

2. Experimental Procedures

A fundamental problem of the stored-torque clamping technique mentioned previously is the fracturing of the pin for releasing the stored torque. The fracture itself is random, but once the pin is released and a shear wave generated there is not enough time to generate a compression wave (using a gas gun). An alternative method to generate a dynamic shear wave developed by Claus et al. (2015) is to fire a projectile that is perpendicular to the incident bar. Figure 1 is a schematic of their setup. The end of the incident bar has a tab that gets impacted by the projectile. At impact, a moment is created rotating the incident bar and sending a torsion wave down the incident bar. Cleverly, since a projectile is used, the shear pulse can be controlled like a traditional compression pulse by varying the length and velocity and using a pulse shaper.

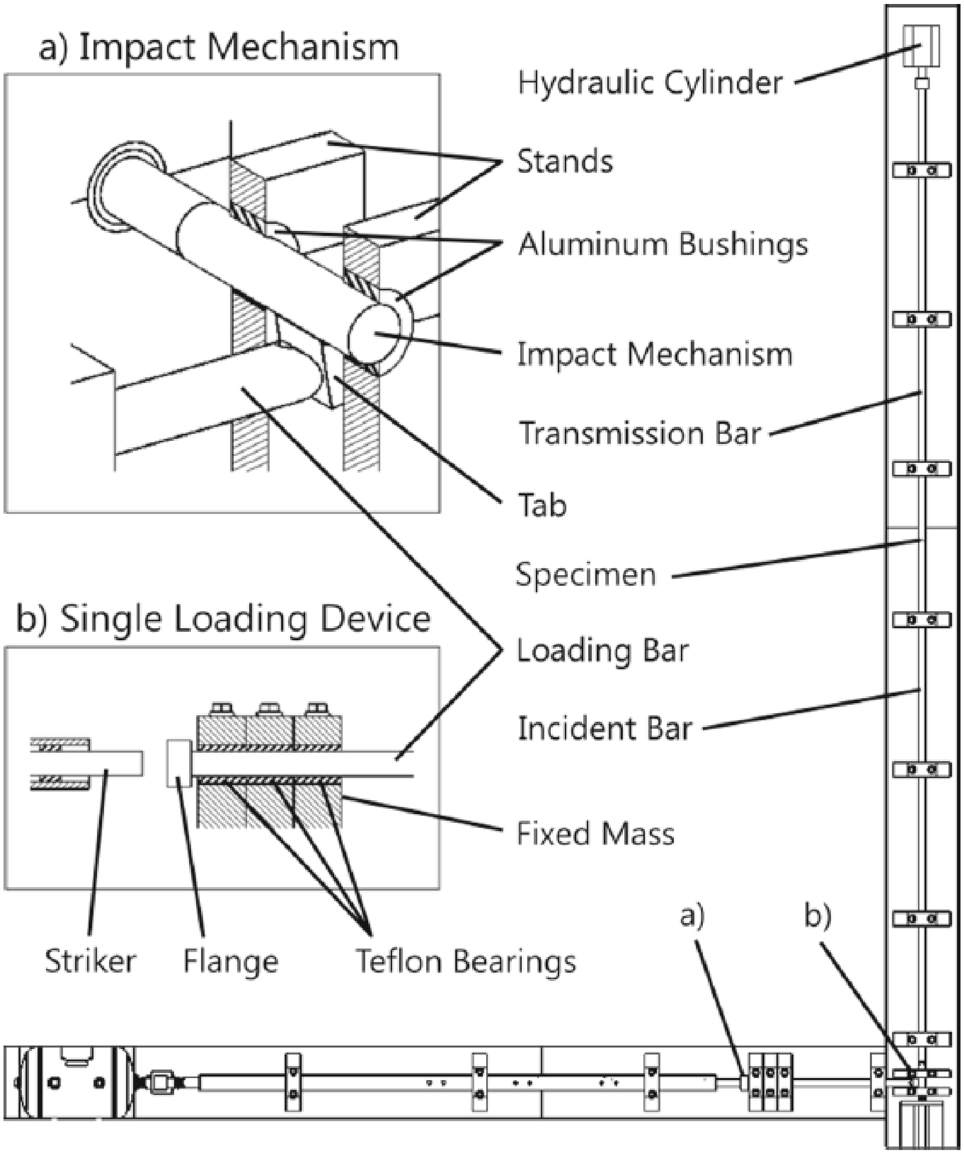

Fig. 1 Side-loading technique for generating torsion, diagram from Claus et al. (2015; used with permission of Springer Nature): hydraulic cylinders allow static compression to be applied before generating the dynamic torsion; note, it appears labeling of a) and b) should be flipped

The author proposed to modify the side-loading technique by replacing the hydraulic cylinder, labeled in Fig. 1, with a compression gas gun for generating a compression wave, the same as done in a compression Kolsky bar. Figure 2 is a schematic showing the modifications. With both loadings controlled by the firing of projectiles from gas guns, the questions were 1) can the relative timing of the firing of each gas gun be controlled such that the waves arrive at the sample simultaneously and 2) is the shot-to-shot error, also called jitter, low enough? In order to measure the jitter, the authors did not need to build the complete system of

Fig. 2. The time it takes each wave to travel the distance from wave generation to the sample is a constant time; the values are different because the wave speeds are different, but that difference can be calculated and accounted for. Thus, the opening of the valve and the projectile traveling down the gun barrel will be the largest sources of error. A much simpler system could be built consisting of duplicate gun barrels, projectiles, valves, breeches, and firing signals. Each projectile cutting a laser beam can be defined as the generation of each wave and the time difference between them can be measured. If the jitter was low enough that it can be corrected for by using a digital delay generator (DDG), then this setup as a whole is feasible. If the jitter was large enough, then a relative delay of the firing of each projectile would essentially be a guess, making the whole setup unfeasible.

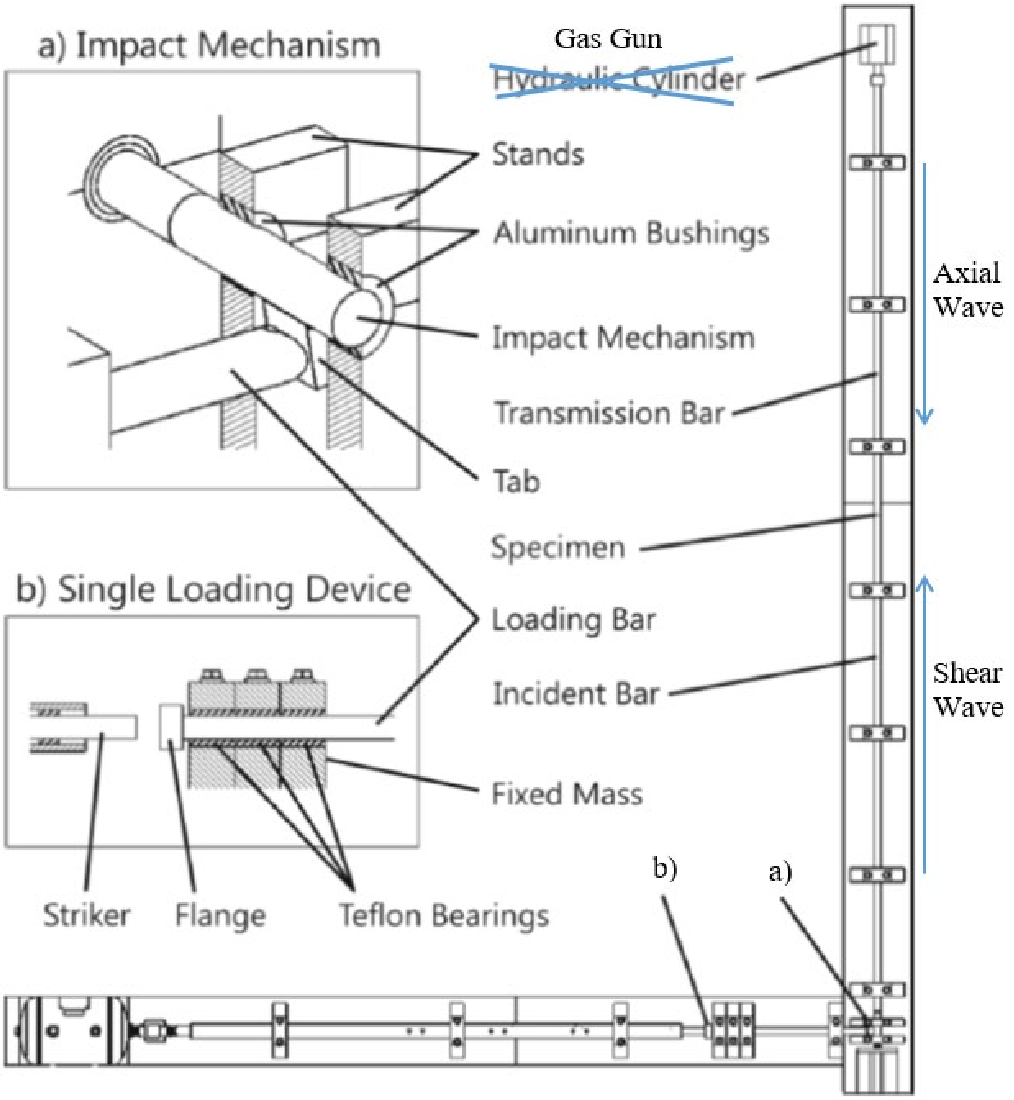

Fig. 2 Modifications to the side-loading technique for simultaneous shear and axial wave arrival at the sample (based on diagram from Claus et al. [2015]; used with permission of Springer Nature)

Figure 3 is a schematic of the apparatus built to measure the jitter for testing feasibility. Duplicate gas guns were built with identical breeches, valves, and gun barrels. They were assigned 1 and 2 so that the order of the projectiles cutting the lasers could be tracked. The projectiles were both 25.3-mm diameter × 305-mm long, Aluminum 7075-T6 projectiles, which is representative of a full system that would be built. Kolsky bars only require projectile velocities on the order of 10 m/s, so the firing pressures required for this study were only approximately 10 psi (69 kPa). The pressure to each breech was the same since the gas line was split from the output of the regulator on the source gas. When each projectile blocks the laser beam to the sensor, that voltage drop is recorded by the oscilloscope and the time difference is measured. By firing the guns multiple times, the jitter can be assessed. Note that for a complete system the projectiles likely would be a different length fired at different pressures. Keeping the projectiles the same length and fired at the same pressure is the simplest case.

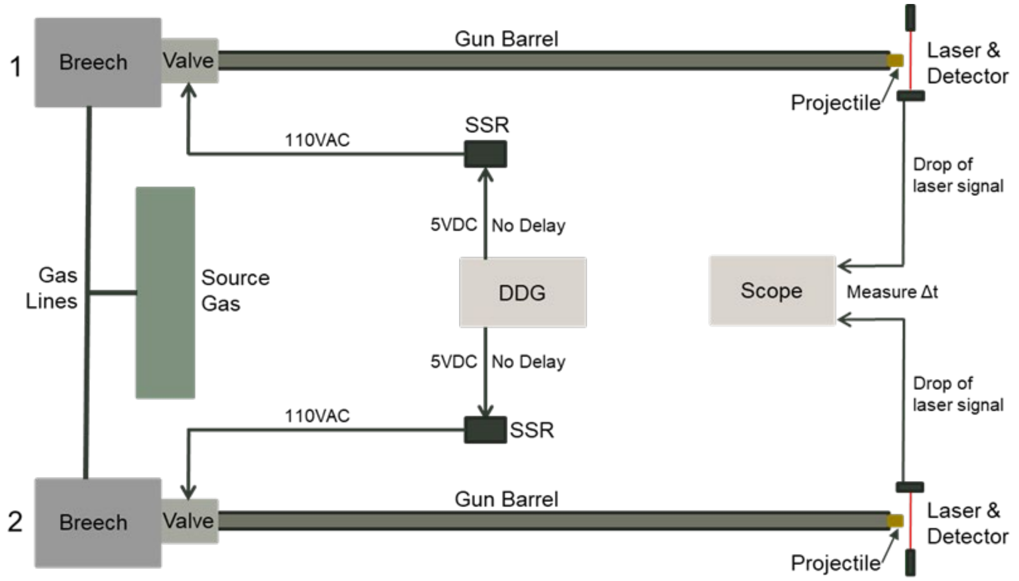

Fig. 3 **Schematic of apparatus built for this feasibility study; image not to scale**

The actual firing sequence of each gun had to be the same as for a complete system so that all errors could be incorporated into this study. Firing started with the DDG; for each gun the DDG sends a 5-volt direct current (VDC) signal to a solid-state relay (SSR). The SSR then closes the 110-volt alternating current (VAC) circuit to open the valve. For this study no delay among the 5-VDC signals was used because the simplest case was desired. The timing difference with the 5-VDC signals is on the order of nanoseconds, but is unknown with SSRs. The author suspects it is a smaller source of error than the opening of the valves and the projectiles traveling down the barrels. For the complete system, the relative timing among the 5-VDC signals is what would allow the researcher to control the timing such that the waves arrive simultaneously at the sample. But for each configuration (length of the projectiles and the pressure in each breech), the researcher would need to measure the jitter in order to correct for it.

3. Results and Discussion

Thus far the phrase "simultaneous arrival" of the waves has been used; however, the timing does not need to be truly simultaneous. For a typical experiment on a ductile metal, the loading time up to the yield point for the axial and shear stress would be approximately 100 µs. The yield point is dependent on the magnitudes of each applied stress, so both axial and shear stresses should be large by the time yielding of the sample occurs. Put another way, at yielding the stress state should not be dominated by axial stress (thus a small amount of shear stress is applied) nor dominated by shear stress (thus a small amount of axial stress is applied), but rather both stresses should be of similar magnitude at yielding. This means the arrival-time difference of the waves might be tolerated up to approximately 50 µs. Thus, the jitter has to be on the order of 50 µs for the researcher to have a realistic chance of achieving the desired wave timing.

Table 1 is an overview of all of the shots performed to determine the jitter. Shot 1 was an initial test shot and was not at the same pressure, so it is not included. Shot 4 is such an outlier; the author probably measured the time difference incorrectly or there was a mis-trigger, so the timing was not used in the subsequent calculations or analysis. At the most fundamental, if the order of which projectile cuts the laser beam first is not consistent or predictable, then this system is already not feasible. For these shots, Projectile 2 was first 9 out of 12 times. Is that good enough? For the sake of further analysis, the author concludes it is. Only the nine shots where Projectile 2 was before 1 are considered because, if all shots were considered, a new (or different) time = 0 would need to be used to properly calculate the average and standard deviation of the timing. However, there really is not an obvious one to use, which would have required a modified triggering method. The average firing pressure in the breeches was 10.43 psi with a standard deviation of 0.03 psi, which is 0.3% of the average. Thus, pressure was well controlled. The average time between Projectile 2 cutting its laser and then Projectile 1 cutting its laser was 2.560 ms with a standard deviation of 0.78 ms, which is 30.5% of the average and 100× larger than the pressure. The 2.56 ms represents the delay that would be used in the DDG to correct the timing in order to achieve simultaneous wave arrival. The 0.78 ms is essentially the jitter. Compare the jitter with the aforementioned tolerated time difference of wave arrival at the sample, 50 µs. The jitter is greater than 15× the allowable time difference, so this system does not appear feasible. Also, the maximum total loading time of the sample for the complete system would be approximately 300 µs, so the jitter is about 2.5 times the entire loading time. Thus, the author's conclusion is this method for simultaneous wave arrival is not feasible.

Table 1 Shots performed and the time difference between the cutting of the laser beams; No. 4 is an outlier not included in the calculations

	Breech pressure (psi)	Time between cutting of laser beam (ms)	Projectile order
Shot 2	10.44	1.59	1 before 2
Shot 3	10.46	3.691	2 before 1
~~Shot 4~~	~~10.39~~	~~46.3~~	~~1 before 2~~
Shot 5	10.42	2.189	2 before 1
Shot 6	10.43	2.318	2 before 1
Shot 7	10.45	1.516	2 before 1
Shot 8	10.36	2.311	2 before 1
Shot 9	10.47	2.533	2 before 1
Shot 10	10.46	1.53	2 before 1
Shot 11	10.42	3.728	2 before 1
Shot 12	10.39	2.708	1 before 2
Shot 13	10.41	3.626	1 before 2
Shot 14	10.44	2.983	2 before 1
Average	10.43	2.560	Only 2 before 1
Standard deviation	0.03	0.78	

There are certain "upgrades" to the apparatus tested that could get closer to making the complete system feasible. To even begin to think the complete system is feasible, the jitter would have to be reduced by around a factor of 15. The components used in this study were purposefully off the shelf (cheap) that were already available around the lab. The barrel could be substantially shortened, probably by more than half without creating any issues. Certainly, measuring the jitter of the off-the-shelf SSRs used would be wise. If the SSR jitter is large, the author does not know if faster acting SSRs can be bought/made. The better option is to do away with the SSRs completely and use a DDG that can output larger voltage and current. 24-VDC valves are essentially universally available and so would be the natural choice, but would require a more expensive DDG. Finally, the valves could be upgraded to a much faster acting designs. The valves used were simple solenoid valves; off the shelf, air-actuated valves might open three times faster, but this is not likely to reduce the jitter enough. Air-actuated valves specifically designed for high-velocity gas guns might be the only solution—so-called regenerative-type valves, a wrap-around breech, or double-diaphragm breech (these breeches function as both a breech and a valve). However, these can cost many tens of thousands of dollars each. A simple powder gun may also be feasible. A completely different type of gun, like a rail gun that accelerates a projectile using the Lorentz force, might be possible. Finally, going back to the clamping method for releasing the torque could be an option if the pin fracturing could be controlled, such as by using explosives to cause the pin to fracture. Combined with a gas gun for generating the axial stress, this method could result in timing that is actually controllable. However, it is speculation whether the jitter can be reduced enough with any combination of these upgrades. It is not surprising that no one has built such a system before, given the expense and difficulty involved.

4. Conclusions

The ability to load a sample to generate a stress state that combines shear and compression or tension would be of great benefit to the Army. Impact and penetration events are inherently dynamic and multiaxial, so being able to measure the multiaxial mechanical response of materials would allow for more accurate constitutive models to be developed and incorporated into simulations. An improved predictive capability, and potentially improved materials for armor, would be the result. This report detailed one such attempt at designing a modified Kolsky bar apparatus that might allow for simultaneous arrival of an axial and shear wave at a sample, using gas guns to generate both waves. A model system was built to measure the jitter of a dual gas-gun system, and it was found the jitter was way too high for the method to be utilized. The jitter would need to be reduced by approximately 15 times to even begin to be feasible. Possible solutions were discussed, but there is no method that shows much promise.

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List of Symbols, Abbreviations, and Acronyms

1-D	1-dimensional
3-D	3-dimensional
DDG	digital delay generator
SSR	solid-state relay
VAC	volt alternating current
VDC	volt direct current

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