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Finite Element behaviour of pure copper under high strain rates with varying configuration of striker of SHPB

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ABSTRACT
With the high rates of the strain the nature of the materials vary and it is important to figure out at the dynamic loading the feedback of the materials. Effect of the high rates of the strain on the nature of the material and the strain rate has been discussed. At the high strain rates the deformation of the specimen is experienced in the specific range of possible influence like as high forming of explosive, bang exercises like bumpers of the automobiles or the bang of the projectile with the armour plate that is materials of the armour under ballistic penetration, structural bangs, burst loading, earthquake, sliding wear at high velocities, external body blow etc. At the high strain rates the mechanical properties like strength, ductility and the behaviour under dynamic loadings can alter greatly as from those detected under conventional tests. So, at the dynamic loading conditions, the study of the material behaviour is of enormousattention to find-out the characterization of the material. Correlation of the outcomes, display a fine acceptation of the dynamic behaviour and diverse geometric configuration of the bar that certify the choice of the convenient system. Using ABAQUS/Explicit 6.14, numerical simulation of the pure copper under different striker bar shapes is performed. In addition,the sample aspect ratio is like-wise alternated from circular to square configuration to examine at high strain rate loading, the consequences of the body format sample.

Keywords; pure copper, high strain, dynamic acknowledgement, bar configuration, SHPB

Date of Submission: 14-05-2023 Date of acceptance: 26-05-2023

I. INTRODUCTION

Reason of the pure copper as a research substantial is related to the actuality that is widely used in different application like in defense and in the acceleration of the nuclear and particle mechanization. The hardness of the pure copper is low, can be often drawn into wires and is greatly malleable. Copper having 99.3% of copper as substituent is called as pure copper. Pure copper is generally soft, as already stated is malleable and very good at ductile property. It is a metal having very high electrical and thermal properties. Copper is among the few metals that exist in nature in a straight applicable form. Presently copper is widely used in the construction of the roofs of the buildings. Copper is mostly cited as copper sulphides. An alternative source of copper for collection currently being researched are poly-metallic modules, currently located at the depth of approximately 3000-6500m below sea level. Copper is among the few metals that can be recycled without the damage of the properties, either from raw or manufactured states. Process of recycling and extracting of the copper is almost same with the extra fewer steps in the extraction process. It is compelling to know the behaviour of the copper under the diverse ballgame in order to utilise the copper in various fields. At the high strain rates $>10^2$/s, the deformation of the materials is of greater importance in various fields. So the properties of the materials under the dynamic loadings are considered as an important area of research from past few decades. Thus evaluating the material properties using split-Hopkinson pressure bar beneath the dynamic loading becomes necessary. RajnishGoyal et.al took SHPB to evaluate the response of the OFHC copper at high temperature under tension. DI tests evaluated at the high strain rates are displayed to be nearby anyhow for split Hopkinson pressure bar. There is a change in the behaviour of pure copper ahead 10^3/s velocity is constant. S.K Samantha who used split Hopkinson pressure bar to understand the response of the Aluminium and the Copper at elevated heat. The dynamic behaviour of the face centred Aluminium and copper at high heat has been considered on probation to actuate their strain rate sensitivity. From this study we conclude that the aluminium and the pure copper are strain rates sensitive. J.Y et Al they studied the behaviour of copper(commercial grade) under the hot compression in the heat range between 843k to 993k from 10^{-3}/s to 10/s strain range. M.Scapin et.al investigated the properties of the materials under the tensile loading at the high heat up to 400˚c and at high strain rates. This work shows the behaviour of the copper as familiar in both strain rate and heat delicate but the high heat softening heavily bank on the rate of loading conditions. In addition between 200 to 300˚c, the strength properties are reduced. Kaiwan et.al utilised Split Hopkinson pressure bar system to execute the dynamic properties of the materials. Advancement in the SHPB in recent times made an analysis of diverse properties at high strain rates. The measuring methods of the dynamic compressive, tensile,flexural,shear strength and toughness fracture are enhanced. The ratio of the length to diameter compression at high strain rates is not stern. On the point of the tests performed normally due to the implementation of the pulsation sharping approach. SHPB may be used to arbitrate adequately the properties under the dynamic loading. MustaphaTarfaoui studied the response under the dynamic loading of the composite materials using SHPB. Numerical simulation is compelled to study the bars of pattern as square, triangular, hexagonal and comparing with the cylindrical shapes. This research carried out the response of aluminium at high strain rates via numerical simulation for different configuration of aluminium. Similar response of the different bar system and commensurate dissemination of the assorted Split Hopkinson pressure bar systems were observed. A.G Walker studied the properties of the copper at diverse range of the rates of strain and heat. Primary objective of the research is to actuate the copper properties at high rates of strain> 6×10^{3}/sand the temperature from 20-600˚c. Compressive and tensile tests were performed. Copper showed low strain rate sensitivity up to 10^{3}/s. Strain rates and the results were consistent. The strain rate sensitivity sharply increased above 10^{3}/s and there was an excellent correlation with a model based on the simulation influences of the thermal cavitation and viscous drag. At 1300/s fracture occurred under the dynamic tensile tests due to the multiple loading and the estimation of the fracture strain from SHPB records were observed in the dynamic tests than in Quasi-static tests.

In my work the entire research of the pure copper is accomplished under various rates of strain. The analysis of the varying strain rates is performed by using Finite Element analysis in ABAQUS under the dynamic conditions. The high strain rate characterization of the pure copper by means of SHPB apparatus is calculated. Based on the literature view it can be presumed that the performance of the material is dependent on the various parameters such as striker bar shapes, speed, length , aspect ratio. A generous intelligence buzz exists in the literature in conviction of the behaviour of the copper under the various conditions such as high rates of strain, alteration in the parameters of the SHPB and the alteration geometry of the study material. To curtail and to figure out the intelligence buzz, the present research aims to find out the response of the copper at high rates of strain using different parameters of specimen and the striker bar.

II. METHODOLOGY

Components such as incident, striker and transmitter bar have been represented by fig.1. The transmitter bar and the incident bar are glued with the strain gauges, allows us to understand the fact of the travel generation of the waves. Using kolsky (1-3) equations, determination of the rate of strain and stress strain curve is obtained.

$$\dot{\varepsilon}_s (t) = - (2c \div L_S)\, \varepsilon_R(t) \qquad (1)$$

$$\varepsilon_s (t) = - (2c \div L_S) \int \varepsilon_R (t) \qquad (2)$$

$$\sigma(t) = - (A_B E_B \div A_S)\, \varepsilon_T (t) \qquad (3)$$

Fig.1, exemplify the parts and working phenomenon of SHPB. For the computation of the behaviour of the materials at the high rates of strain, in 1914 an apparatus was made, known as kolsky bar or split Hopkinson bar. It can be used to determine the compression, tension and the shear behaviour of the materials. In 1914, the apparatus was refined by Herbert Kolsky for the amplification of the dynamic response in terms of the stress-strain of the materials. The apparatus comprises of the incident, striker and transmission bar. The work study material which is to be tested is kept in-between transmission bar and the incident bar. A high jet of the air is released from the compression, this is the input energy and this energy is transmitted to the study material through the incident bar. All these elements are connected in a suitable manner to the software to get the stress strain curve. 1D propagation of the wave is the principle of the Split Hopkinson bar. Generation of the stress-strain curve under the compression of the study material is possible. The incident pulse travels down the incident bar and into the study material, where it generates a stress wave that travels through the material. The transmitted stress pulse then travels down the transmitter bar. The transmitter stress pulse then travels down the transmitter bar towards the end of the bar, where it is detected and recorded by sensors. By analysing the shape and amplitude of the stress-pulses in the incident and transmitter bar, various researchers made several modifications in SHPB to obtain more precise and accurate results.

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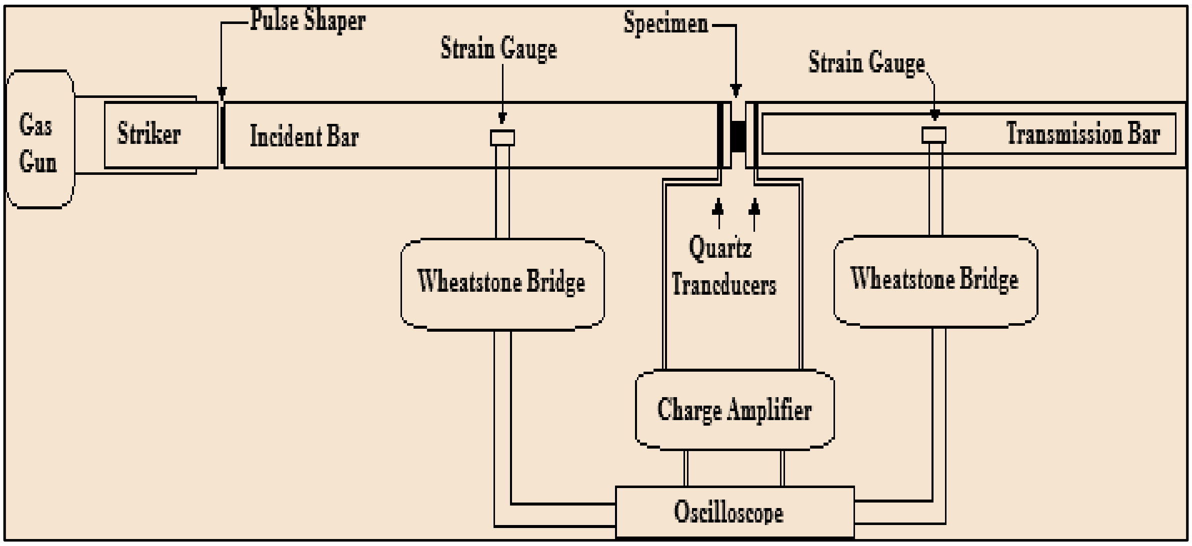


Fig.1 compression split Hopkinson pressure bar

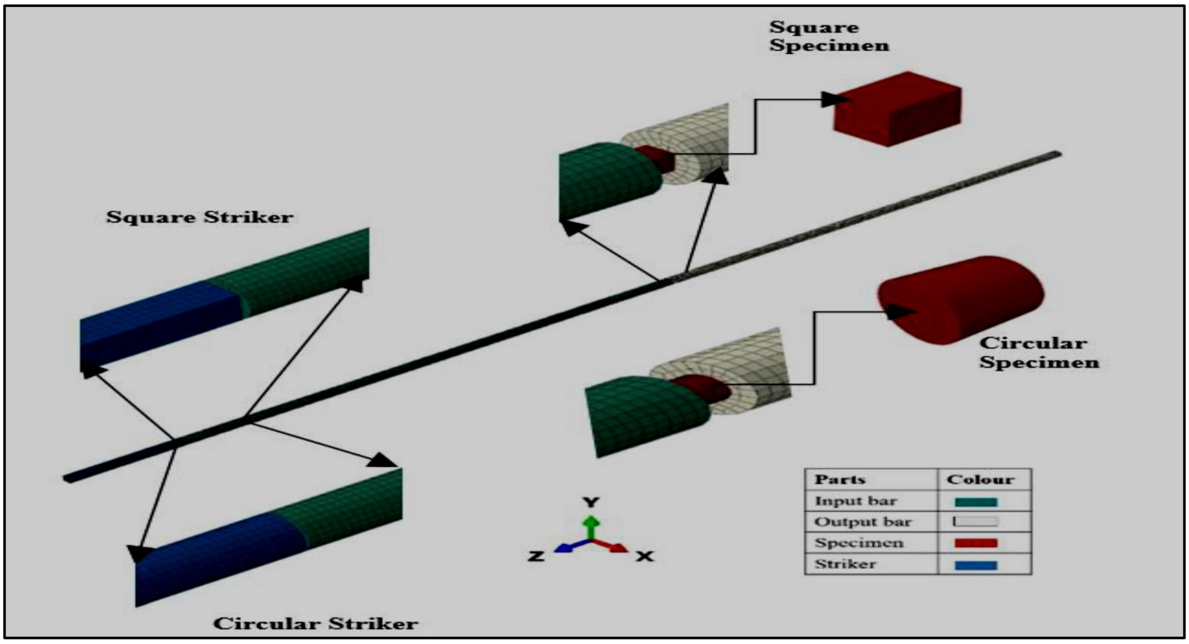


Fig.2 diagram of striker and specimen of SHPB in 3D

Using ABAQUS/Explicit software is used for the computation of the results. All of the parameters of the SHPB and the specimen are programmed in the software. Every element of the SHPBand the specimen configuration are formulated in the software as shown in the Fig2. Different configuration of the components of the SHPB, are used. The striker bar is contemplated as of the mild steel and the same case of the input and output bar, but the material of the studyis taken as pure copper. Finally all the parameters are provided in the software for the numerical simulation for the different configuration of the study material and the striker bar to obtain the results. The properties of the study material and the components of the Split Hopkinson Pressure Bar are represented in the table 1.

Copper	
Density	7800 kg/m^3
Elastic modulus	200 Gpa
Poisson’s ratio	0.3

Mild steel	
Density	8830kg/m^3
Elastic modulus	110 Gpa
Poisson’s ratio	0.34

Table.1 properties of copper and mild steel

Parameter		**Dimensions (mm)**
striker bar	**square**	**L= 250, S= 15**
	circular	**D= 20**
Input bar		**L= 100, D= 15**
Output bar		**L = 100, D= 15**
specimen	**square**	**L= 10, S= 10**
	circular	**D= 10**

Tabl.2 geometric dimension of bars and specimen

A	**B**	**N**	**C**	**M**
92 ×10^6	**292 ×10^6**	**0.31**	**0.025**	**1..09**

Table.3 pure Copper constants

Bars and specimens are webbed over mesh dimensions using C38RD elements. Different prospects can be used to mesh a part using module of mesh in the ABAQUS. Complicated configurations that arise most of the times is first meshed and analysed. For properly meshing a model the configuration and know-how of meshing and creating the model are the steps to be followed. Applying the proper boundary conditions for the output bar and the constant velocity to the input bar. For the meshing, taking the square configuration of the striker and applying with constant velocity of 20m/s as well as taking a square pure copper study material amid input and output bar.

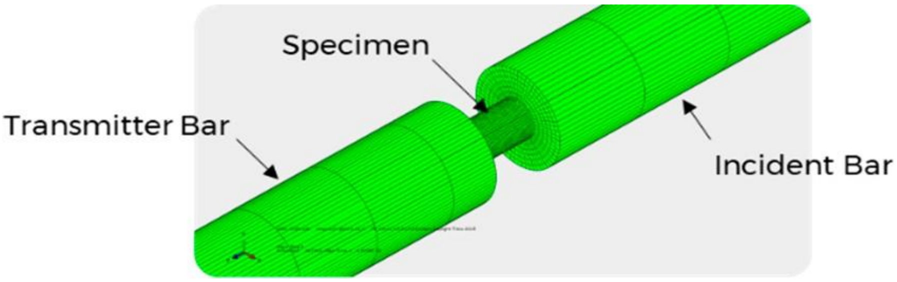
Factors		**Elements**	**Nodes**
striker Velocity	**20 m/s**	**42107**	**52435**
Striker shape	**Square**	**42107**	**52435**
	Circular	**44238**	**54656**
Specimen Shape	**Square**	**42107**	**52435**
	Circular	**47768**	**58441**

Table4. No.of nodes and elements

III. Results and Discussions

This study characterizes the behaviour and accoutrements of the pure copper when a pure copper is exposed to high rates of strain and the alteration in the frame of pure copper and striker by means of SHPB simulation.

Figure 3 diagram ofmesh.



3.1 Effect of Shape of striker

In this work a number of the analysis were performed to recognize the ascendancy of the various configuration of the striker. Initially the geometry is taken as square at a velocity of 20m/s. After the impact, the striker's configuration is now altered from square to circular at the same velocity. As already mentioned in the table, the dimensions of the striker are taken as diameter of 20mm in case of circular and 15mm incase of the square configuration, with the length kept same for the both at 200mm .Observation of the analysis performed is displayed in figure 4 which shows the propagation of waves under the different configuration of striker and the observation showed the wave propagation through input bar is afflicted and the travel is unaffected at the output bar. These changes are directly related with the configuration of the striker bar. There is a change in the nature of the pure copper over the various striker'configuration as shown by flow curves. As from the table 4, the yield and the ultimate strengths can be seen to be heightened as the configuration of the striker is made circular from square.

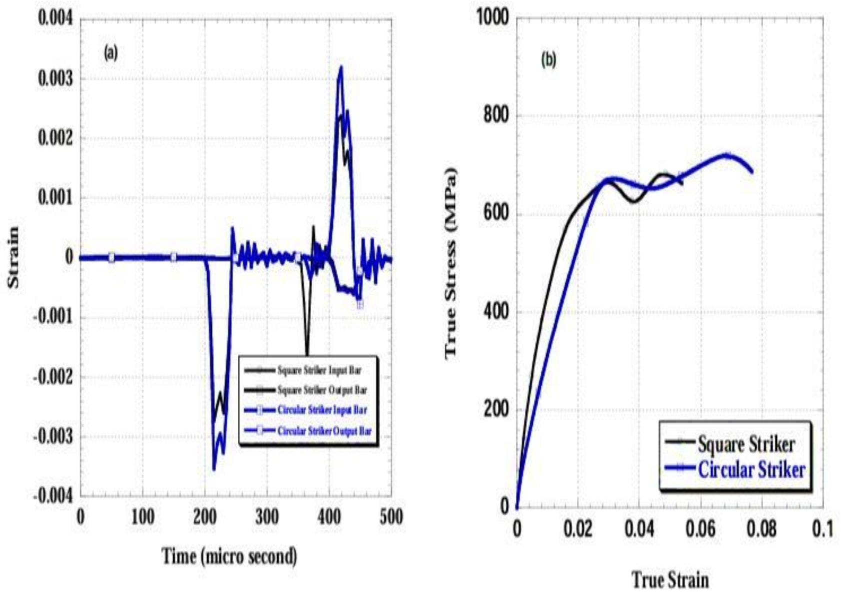


Figure4, effectson(a)differentwavesofbarsand(b)flowcurvesofcopper.

3.2Effect of shape of work material

Outcome of the alteration of the work material is displayed in the fig.5. for the circular work material diameter is assigned as 10mm and for square work material length is allocated as 10mm. In this case striker velocity is fitted to 20m./s. the striker configuration is made as square and it strikes with the same velocity to the work material of the square configuration. In the 2nd case at the same impact the configuration of the work material is altered to circular. Results displayed in the fig.5 depicts that the configuration of the incidence remains unaltered and while changing the configuration of the work material to circular it is observed that there is a diversity after the impact waves(i.e. transmitted and impact waves). From fig.5b it is found that there is a variance in curve of stress strain as the configuration of the work material is altered. Table 4 represents the fallout of parameter alteration on the health of the work material. It is clearly depicted in the table that the yield strength decreases in-case of the circular striker configuration while the same increases with the circular work material. True ultimate crushing strength increases to the circular configuration of the striker but shows decrement to circular configuration of the work material.

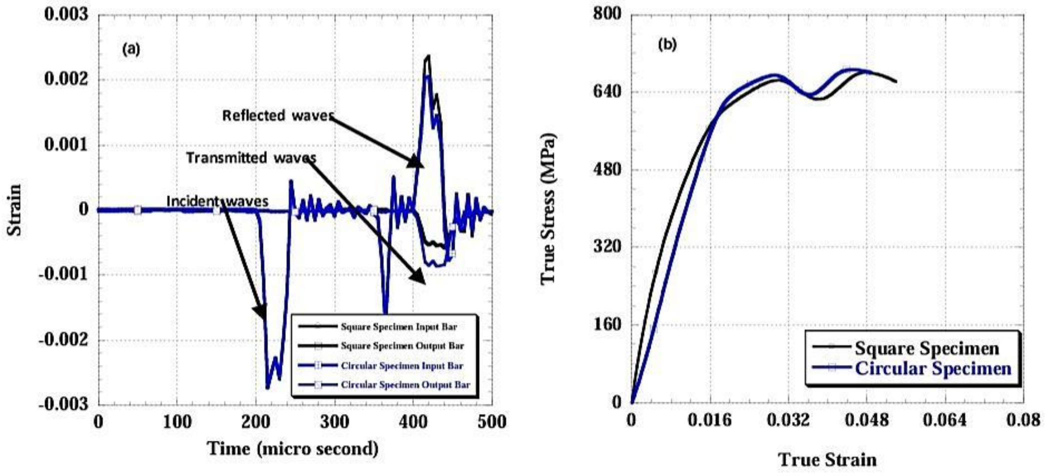


Figure 5 work material configuration affects (a)waves and ((b) curves of copper

3.3 Outcomes of various compression tests

From the various analysis that were performed with the pure copper as the study material under the various circumstances and the over different configuration, the outcomes of which are abbreviated in the table4. It is clearly summarized that over the various shapes of the pure copper there is a change in the behavior of the copper as the configuration of the pure copper is shifted from square to circular. With the material the yield strength, and ultimate strength shows depreciation with respect to the circular study material with the said strengths shows an increment. The circular study material experienced rapid deformation and exhibited significant plastic deformation. The study material also experienced strain localized necking due to high strain rates and exhibited some degree of strain hardening and softening. The square study material also experienced rapid deformation and high strain rates during the impact. The square study material influenced the distribution of stress and strain potentially leading to different deformation patterns. Strain localization, shear bands also occurred in the square study material and significant plastic deformation and dynamic recrystallization at strain rates up-to 10^3/s with 20m/s impact velocity.

Parameters		**True Yield strength (MPA)**	**True ultimate crushing strength (MPA)**	**Percentage of compression.**
Striker velocity	20m/s	470	685	5.40
Striker shape	square	470	675	4.89

	circular	451	715	8.01
Specimen shape	square	470	675	4.89
	circular	620	670	4.70

Table 4 behavior obtained for different factors

IV. CONCLUSION

The dramatizing of the copper at high strain rates over the different specimen dimensions and the different shapes of the striker bar at 20m/s speed are discussed as ;

Material behavior bartered,concealed by the influences of strikerbarshape.The specimen size influences ductility, yield strength, and ultimate compressive strength. With the square shaped specimen and the square shaped striker bar the yield strength decreases while the ultimate strength increases with the square shaped specimen and the circular striker bar of the SHPB. For the circular shape of the striker compression is increased. With the square to circular alteration of the specimen there has been an addition in theYS and a little decrement in the ultimate compressive strength and the percentage of the total compression is also showing a little depreciation.

References

[1]. https://www.farmerscopper.com/defense.html#:~:text=Military%20contractors%20require%20metal%20products,communications%20and%20satellite%20systems%2C%20and

[2]. https://www.google.com/search?q=applications+of+copper+in+defense&oq=applications+of+copper+in+defense&aqs=chrome..

[3]. S. J. Zinkle: ‘Copper alloys for high flux structure applications, atomic and plasma-material interaction data for fusion’, vol.5; 1994, Vienna, international atomic energy agency.

[4]. Biswas AK, Davenport WG.Extractive metallurgy of copper. Pergamon Press; 2002.p.518.

[5]. Trixie R, Devaguptapu R, MobasherEffect of copper slag on the hydration and mechanical properties 1997;27(10)

[6]. Halo, C.; Mehdi, Y.; Antonio, M. Dynamic Inter-Fibre Failure of Unidirectional Composite Laminates With Through-ThicknessReinforcement. Compos. Sci. Technol. **2019**,176,64–71.

[7]. Ryud, D.; Catania, N.; Bhakta, R. Fracto-Mechanoluminescent Light Emission Of Eud4tea-Pdms CompositesSubjected To High Strain-Rate Compressive Loading.Smart Mater.Strut.**2016**, 26, 085006.

[8]. Hopkinson, A Method of Measuring the Pressure Produced in the Detonation of High Explosives or by ImpactofBullets.A**1914**,213,375–457.

[9]. Davies,R.M.ACriticalStudyoftheHopkinsonPressureBar.Proc.R.Soc.Lund.A**1948**,240,375–457.

[10]. Gary, G.T., III. Classic Split-Hopkinson Pressure Bar Testing.In ASM Handbook:Mechanical Testing and Evaluation; ASM International,Metals Park, OH, USA, 2000; pp. 1027–1036.

[11]. Kolsky,H.StressWavein materials.InDoverBooksonPhysics;DoverPublications:NewYork,NY,USA,1983.

[12]. Kraft, J.M.; Sullivan, A.M.; Tipper, C.F. The Effect of Static and Dynamic Loading and Temperature on the YieldStressesofIronandMildSteelinComparison.Proc. R.Soc. Lund. A**1954**,221,114–127.

[13]. Follansbee,P.S.TheHopkinsonBar.InMechanicalTesting,ASMHandbook, 9thed.; ASMInternational:Metals

[14]. Park,OH,USA,1995;pp.198–217.

[15]. Nemat-Nasser,S.;Isaacs,J.B.;Starrett,J.E.HopkinsonTechniquesforDynamicRecoveryExperiments.

[16]. Proc.R.Soc.Lund.**1991**,435,371–391.

[17]. Gary, G.T.; Blumenthal, W.R. Split Hopkinson pressure bar testing of Soft materials.In ASM Handbook, MechanicalTestingandEvaluation;ASM:MaterialsPark,OH,USA,2000;pp.488–496.

[18]. Field, J.E.; Walleye, S.M.; Proud, W.G.; Gold-rein, H.T.; Siviour, C.R. Review of Experimental Techniques for High Rate Deformation and Shock Studies.Int. J.ImpactEng. **2004**, 30, 725–775.

[19]. Baranowski, P.; Malachowski, J.; Gieleta, R.; Damask, K.; Mazurkiewicz, L.; Kolodziejczyk, D. Numerical studyfordeterminationofpulseshapingdesignvariablesinSHPBapparatus.Bull.Pol.Acad.Sci.Tech.Sci. **2013**, 61, 459–466.

[20]. Naghdabadi, R.; Ashrafi, M.J.; Arghavani, J. Experimental and Numerical Investigation of Pulse-Shaped SplitHopkinsonPressureBarTest.Mater. Sci. Eng. A**2012**,539,285–293.

[21]. Baranowski, P.; Janiszewski, J.;

Malachowski, J. Study on computational methods applied to modelling of pulseshaperinsplit-Hopkinsonbar.Arch. Mech. **2014**,66,429–452.
[22]. Baranowski,P.;Gieleta,R.;Malachowski,J.; Mazurkiewicz,L.;Damask,L.K.SplitHopkinsonBarImpulse ExperimentalMeasurementwithNumericalValidation. Medrol. Meas. Syst. **2014**,21,47–58.
[23]. Kareem,M.A.;Benton,J.H.;Roan,D.Misalignmenteffectinthesplit Hopkinsonpressurebar technique.
[24]. Int.J.ImpactEng.**2012**, 47, 60–70.
[25]. Govender, R.A.; Cloete, T.J.; Nurick, G.N. A numerical investigation of dispersion in Hopkinson Pressure Barexperiments.J.Phys. IV**2006**,134,521–526.[CrossRef]
[26]. Chen,W.;Lu,F.;Zhou,B.AQuartz-crystal-embeddedSplitHopkinsonPressureBarfor SoftMaterials.
[27]. Exp.Mech.**2000**,40,1–6.[CrossRef]
[28]. Aghayan, S.; Reppel, T.; Bieler, S.; Weinberg, K. Experiments on Wave Propagation in Soft Materials.Proc. Appl. Math. Mech. **2018**,18,e201800346. [CrossRef]
[29]. Ramesh, K.T. High Strain Rate and Impact Experiments.In SpringerHandbookofExperimentalSolidMechanics;Sharpe,W.N.,Ed.;Springer:Boston,MA, USA,2008;pp.929–960.
[30]. Zhao,H.;Gary,G.OntheUseofSHPBTechniquestoDeterminetheDynamicBehaviorofMaterialsintheRange of Small Strains.Int. J. Solids Struct. **1996**, 33, 3363–3375.[CrossRef]
[31]. Gray,G.;Rota,L.;Zhao,H. TestingViscousSoftMaterialsatMedium andHighStrainRates.InConstitutive
[32]. Relation in High/Very High Strain Rates:IUTAM Symposium Noda, Japan (1995); Kawata, K.S.J., Ed.; Springer:Tokyo, Japan, 1996; pp. 25–32.
[33]. Gray,G.;Blumenthal,W.;Trujillo,C.;Carpenter,R.InfluenceofTemperatureandStrainRate onthe MechanicalBehaviorofAdipreneL-100.J.DePhys. IvColloq. **1997**,07,523–528.
[34]. Follansbee, P. The Hopkinson Bar, Mechanical Testing.In ASM Handbook Mechanical Testing and Evaluation;ASMInternational:Cleveland,OH, USA,1985;Volume8,pp.198–203.
[35]. Davies,E.D.H.;Hunter,S.C.TheDynamicCompressionTestingofSolidsbytheMethodOfTheSplit HopkinsonPressureBar.J.Mech. Phys. Solids**1962**,11,115–179.[CrossRef]
[36]. Song,B.; Ge,Y.; Chen,W.; Weerasooriya,T.RadialInertiaEffectsinKolskyBarTestingofExtra-SoftSpecimens.
[37]. Exp.Mech.**2007**,47,659–670.[CrossRef]
[38]. Chen, W.; Song, B. SplitHopkinson(Kolsky)Bar:Deign,Testing andApplications; Springer:New York, NY, USA, 2011.
[39]. Chen, W.; Zhang, B.; Forrestal, M.J. A Split Hopkinson Bar Technique for Low-impedance Materials.Exp. Mech. **1999**, 39, 81–85. [CrossRef]
[40]. Song,B.;Chen,W.DynamicStressEquilibrationinSplitHopkinsonPressureBarTestsonSoftMaterials.
[41]. Exp.Mech.**2004**,44,300–312.[CrossRef]
[42]. Ravichandran,G.;Subhash,G.CriticalAppraisalofLimitingStrainRatesforCompressionTestingof CeramicsinaSplitHopkinsonPressureBar.J. Am. Ceram. Soc. **1994**,77,263–267.[CrossRef]
[43]. Song,B.;Forrestal,M.J.;Chen,W.DynamicandQuasi-StaticPropagationofCompactionWavesina Low-Density Epoxy Foam. Exp. Mech. **2006**, 46, 127–136. [CrossRef]
[44]. Mutter, N.J. Characterization of Dynamic and Static Mechanical Behavior of Polyetherimide.Master's Thesis,UniversityofCentralFlorida,Orlando,FL,USA,2012.
[45]. DassultSystemes.AbaqusUserGuideManual;AbaqusSimulia:Providence,RI,USA,2012.
[46]. Ogden,R.W.LargeDeformationIsotropicElasticity— OntheCorrelationofTheoryandExperimentforIncompressibleRubberlikeSolids.Proc. R.Soc. Lond. A:Math. Phys. Eng. Sci. **1972**,326,565–584.[CrossRef]
[47]. Treloar,L.R.G.Stress-StrainDataforVulcanisedRubberUnderVariousTypesofDeformation.Trans.Faraday
[48]. Soc.**1944**,40,59–70.[CrossRef]
[49]. Chaudhry, M.S.; Carrick, R.; Czekanski, A. Finite Element Modelling of a Modified Kolsky Bar Developed forHigh Strain Rate Testing of Elastomers.In Proceedings of the ASME International Mechanical EngineeringCongressandExposition,Houston, TX,USA,13–17November2016.
[50]. Chaudhry,M.S.;Carrick,R.;Czekanski,A.DesignofKoskyBartoCharacterizetheDynamic Response ofElastomersUnderHighStrainRate.InProceedingsoftheCANCAM,London,ON,Canada,31May– 4 June 2015.

[51]. Baranowski, P., Małachowski, J., Gieleta, R., Damaziak, K., Mazurkiewicz, Ł., Kolodziejczyk, D.: Numerical study for determination of pulse shaping design variables in SHPB apparatus. Bull. Pol. Acad. Sci. Tech. Sci., 61: 459–466 (2013).

[52]. Chen, W., Song, B., Frew, D.J., Forrestal, M.J.: Dynamic small strain measurements of a metal specimen with a split Hopkinson pressure bar. Exp. Mech., 43: 20–23 (2003).

[53]. Lee, W.S., Lin, C.F.: Impact properties and microstructure evolution of 304L stainless steel. Mater. Sci. Eng. A, 308: 124–135 (2001).

[54]. Kajberg, J., Sundin, K.G.: Material characterisation using high-temperature Split Hopkinson pressure bar. J. Mater. Process. Technol., 213, 522–531 (2013).

[55]. Zencker, U., Clos, R.: Limiting conditions for compression testing of flat specimens in the split Hopkinson pressure bar. Exp. Mech. 39: 343–348 (1999).

[56]. Yang XL, He Yong, He Yuan, Wang CT and Zhou J. Investigation of the shock compression behaviors of Al/PTFE composites with experimental and a 3D mesoscale-model, Defence Technology 2022; 18(1), 62-71.

[57]. Wen Y, Xu L, Chen A, Dong F and Qin B. Dynamic compressive response of porcine muscle measured using a split Hopkinson bar system with a pair of PVDF force transducers, Defence Technology 2022; https://doi.org/10.1016/j.dt.2022.08.011.

[58]. Li M, Hao H, Cui J and Hao Y. Numerical investigation of the failure mechanism of cubic concrete specimens in SHPB tests. Defence Technology 2022; 18(1), 1-11.

[59]. Han Z, LiD and Li X. Dynamic mechanical properties and wave propagation of composite rock-mortar specimens based on SHPB tests. International Journal of Mining Science and Technology 2022; 32(4), 793-806.

[60]. WangJ, Ma L, Zhao F,Lv B, Gong W,He Mand LiuP. Dynamic strain field for granite specimen under SHPB impact tests based on stress wave propagation. Underground Space 2022; 7(5), 767-785.

[61]. Cui J, Hao J and Shi Y. Numerical study of the influences of pressure confinement on high-speed impact tests of dynamic material properties of concrete. Construction and Building Materials 2018; 171, 839-849.

[62]. Kim KM, Lee S and Cho JY. Influence of friction on the dynamic increase factor of concrete compressive strength in a split Hopkinson pressure bar test. Cement and Concrete Composites, Volume 129, May 2022, 104517.

[63]. Pajak M, Baranowski P,Janiszewski J, Kucewicz M, Mazurkiewicz L andPiekarczyk B. Experimental testing and 3D meso-scale numerical simulations of SCC subjected to high compression strain rates. Construction and Building Materials, Volume 302, 4 October 2021, 124379.

[64]. You W, Dai F and Liu Y. Experimental and numerical investigation on the mechanical responses and cracking mechanism of 3D confined single-flawed rocks under dynamic loading. Journal of Rock Mechanics and Geotechnical Engineering, Volume 14, Issue 2, April 2022, Pages 477-493.

[65]. MałgorzataPająk and JacekJaniszewski, Influence of aggregate and recycled steel fibres on the strain rate sensitivity of mortar and concrete, Construction and Building Materials Volume 363, 11 January 2023, 129855.

[66]. Yuanyuan Ma, Zhiyong Wang and Youquan Qin. Impact of characteristic length and loading rate upon dynamic constitutive behavior and fracture process in alumina ceramics, Ceramics International, Volume 49, Issue 3, 1 February 2023, Pages 4775-4784.

[67]. Li M, Hao H, Shi Y and Hao Y. Specimen shape and size effects on the concrete compressive strength under static and dynamic tests. Construction and Building Materials, Volume 161, 10 February 2018, Pages 84-93.

[68]. Markovsky PE, Janiszewski J, Savvakin DG, Stasiuk OO, Cieplak K, Baranowski P and Prikhodk SV. Mechanical behavior of bilayer structures of Ti64 alloy and its composites with TiC or TiB under quasi-static and dynamic compression. Materials & Design, Volume 223, November 2022, 111205.

[69]. Markovsky PE, Janiszewski J, Dekhtyar OI, Mecklenburg M and Prikhodko SV. Deformation mechanism and structural changes in the globular Ti-6Al-4V alloy under quasi-static and dynamic compression. To the question of the controlling phase in the deformation of α+β titanium alloys. Crystals, 12 (2022), p. 645, 10.3390/cryst12050645.

[70]. Markovsky PE, Janiszewski J, Stasiuk OO, Bondarchuk VI, Savvakin DG, Cieplak K,Goran KD, Soni P and Prikhodko S.Mechanical behavior of titanium based metal matrix composites reinforced with TiC or TiB particles under quasi-static and high strain-rate compression.

Materials, 14 (22) (2021), p. 6837, 10.3390/ma14226837.Zhang L. Thermo-mechanical characterization and dynamic failure of a CoCrFeNi high-entropy alloy. Materials Science and Engineering: A. Volume 844, 2 June 2022, 143166.

[71]. Li P, Yuan K, Guo W, Wang R, Chen L, Gao M and Du P, Dynamic compressive behavior of a single crystal nickel-base superalloy at ultra-high temperature: mechanism investigation with a modified electric synchronous SHPB technique, Journal of Materials Research and Technology, Volume 18, May–June 2022, Pages 637-657.

[72]. Yaocheng Zhang, Li Yang,Ziyun Fan,Song Pangand Wei Chen. Evaluation of tensile creep behavior of spray formed and extruded 7075 aluminum alloy by equivalent stress. Volume 22, January–February 2023, Pages 1476-1490.

[73]. Naka T and Yoshida F. Deep drawability of type 5083 aluminium–magnesium alloy sheet under various conditions of temperature and forming speed. Journal of Materials Processing Technology 89/90 (1999) 19.

[74]. Wagenhofer M, Erickson-Natishan MA, Armstrong RW and Zerilli FJ. Influences of strain rate and grain size on yield and serrated flow in commercial Al-Mg alloy 5086.Scripta Mater. 41 (1999) 1177.

[75]. Kolsky, H.: An investigation of the mechanical properties of materials at very high rates of loading. In: Proceedings Physics Society. London: Institute of Physics (Journal) Ltd., 676−700 (1948).

[76]. Abaqus, Abaqus user’s. Manual. "Version 6.14." DassaultSystemesSimulia Corp., Providence, RI, USA, (2014).

[77]. Johnson, G.R., Cook, W.H.: A constitutive model for metals subjected to large strains, high strain rates and high temperatures. In: Proceedings of the Seventh International Symposium on Ballistics, Hague, The Netherlands, 19–21 April; Volume 54, pp. 1–7 (1983).

[78]. Børvik T, Hopperstad OS, Pedersen KO. Quasi-brittle fracture during structural impact of AA7075-T651 aluminum plates. Int J Impact Eng2010;37(5):537-551.

[79]. Brar NS, Joshi VS, Harris BW. Constitutive model constants for Al7075-T651 and Al7075-T6. AIP ConfProc 2009;1195(1): 945–948.

[80]. Afdhal, Annisa, A.K., Leonardo G.: Development of a numerical model for simulations of split hopkinson pressure bar, ARPN Journal of Engineering and Applied Sciences, VOL. 11, NO. 10, (2016).