

## **STRAIN RATE EFFECT ON THE FAILURE STRAIN AND HARDNESS OF METALLIC ARMOR PLATES SUBJECTED TO HIGH VELOCITY PROJECTILE IMPACT**

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### **Abstract**

Post impact strain measurements of damaged plates were carried out experimentally after launching a spherical steel projectile at varying velocities against a fixed thin plate targets made of copper and steel materials and constrained at their outer periphery. Penetration or partial perforation of the target plates was achieved for projectile velocities of 120 m/s. The strain rates achieved during the experiments varied from  $8000\text{s}^{-1}$  to  $15000\text{s}^{-1}$  for steel specimens and from  $9000\text{s}^{-1}$  to  $19000\text{s}^{-1}$  for copper specimens for the projectile speeds of 68 to 120 m/s. Strain measurements for static and dynamic loading showed that steel deformation is excessive before failure resulting in higher failure strain at high strain rates while the failure strain for copper at high loading rates causes separation of material before reaching very large strains. At the same loading rates the plate thinning of steel was recorded to be severe than copper. Hardness values of materials subjected to high strain rate were measured experimentally showing a strong dependency upon strain rates calculated by using LS-DYNA software. Strain rate effect on the failure strain of metals was investigated.

*Keywords:* Strain rate, Hardness, Perforation, Projectile, Failure strain.

## 1. Introduction

Experimental work to determine the mechanical properties of metals at high strain rates has been carried out extensively [1-5]. The difficulties involved are numerous because at high strain rates the mechanical properties are not the same as under slow loading rates. The data obtained for high strain rates could be very valuable for the design of trauma plates in bullet proof vests, aircraft and missile impact on structures and buildings including nuclear power plants, crashworthiness of automotive systems, and space debris impact on space structures placed in orbits. If possible, the costly experimental work should be replaced by numerical simulations. Towards this end, certain material properties like yield strength, failure strain, hardness, and elastic modulus are required to be determined so that precise failure limits could be predicted. Post impact hardness values can be useful when a structure is subjected multiple impacts at the same point as can happen on the trauma plate. In many instances, experiments to measure the yield strength of partially damaged samples are not possible, therefore if hardness, which can be measured easily, is used to calculate the yield strength indirectly [6-7], it can be used to predict the impact results of second and subsequent impacts. In the present work high strain rate effect on the failure strains and the material hardness have been studied and the results are reported.

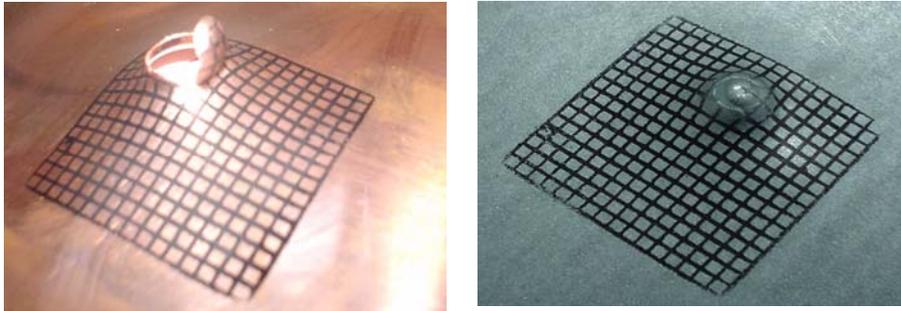
## 2. Experimental Procedure

A metal plate with 120mm diameter and 0.52mm thickness was secured at its periphery and a spherical steel projectile was launched from an air gun at varying velocities. A square shaped grid was stamped on the back surface of the plate. The experiments were done using steel and copper material plates. The resulting dent depth was measured for various projectile velocities. The mechanical properties of steel and copper plates are given in Table 1.

**Table.1. Material Properties.**

Material	Density (kg/mm <sup>3</sup> )	Elastic Modulus (GPa)	Tangent Modulus (GPa)	Yield Strength (GPa)	Poisson's Ratio
Steel	7.8e-6	205	0.721	0.272	0.30
Copper	8.8e-6	101	0.377	0.195	0.35

The square grid that falls exactly behind the spherical projectile and has its center coinciding with the projectile center is used to measure the plastic strains. In cases where the square grid does not fall in the center but is slightly eccentric, the change in the grid line thickness was used to measure the deformed dimensions to calculate the plastic strains. The back surface of the plate specimen with stamped grids and dent are shown in Fig.1.

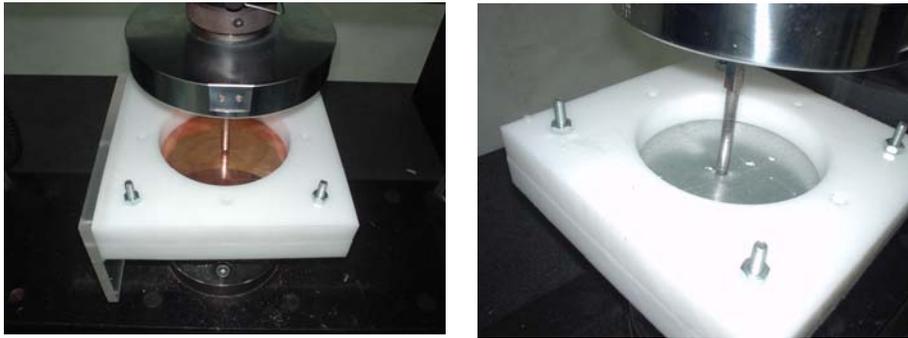


a. Copper plate

b. Steel plate

**Fig.1. Dynamically impacted (120m/s) copper and steel plates with square grids.**

Similar specimens were then subjected to a static denting load using a round end solid cylindrical tool with same diameter as the spherical projectile that is shown in Fig.2. The static dent was made to nearly the same depth or a little deeper as the one obtained in dynamic impact testing.



a. Copper plate

b. Steel plate

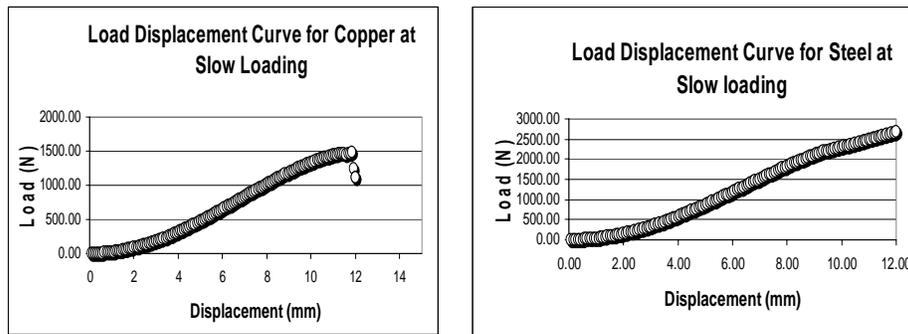
**Fig.2. Static denting test on copper and steel plates.**

The above mentioned impact tests were performed at projectile velocities of 68, 77, 88, 97, and 120m/s. The projectile velocity of 120 m/s was found to be the threshold failure point where complete penetration or partial perforation of the target plate took place. At this velocity the copper plate was penetrated through but the steel plate showed a crack initiation at the bulged surface without the projectile passing through. The resulting plastic strains for static denting and impact tests were recorded. Plastic strains of damaged tensile test specimens were also recorded for comparison.

Hardness values of virgin and damaged specimens under both static and impact tests were measured.

### 3. Experimental Results

Static denting load displacement curves for Steel and copper specimens are shown in Fig. 3. For a fixed displacement of 12mm the maximum load for steel is slightly above 2500 N while for copper it is about 1500 N. This displacement was obtained with crack initiation in the samples. Comparing to the damage under impact test, it was found that in static loading the failure strains were significantly higher with small amount of material failure. The maximum displacement obtained in impact tests ranged from 7 to 10.30 mm for both materials. The failure strain for static loading is shown in Fig.4.



**Fig.3. Load displacement data from static denting of and copper steel plates.**

As shown in Fig.4., the failure strain for steel at damage initiation is of the order of 0.4 while it is about 0.6 for copper located in the vicinity of dent peak. The maximum value is obtained from the peak.

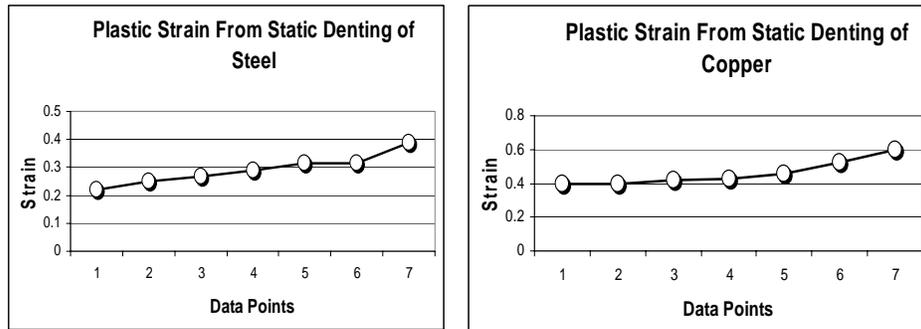
Failure strain for steel and copper tensile tests at slow loading rate are compared in Fig.5. In tensile tests, maximum failure strain for copper is 0.60 while steel has a maximum strain value of 0.40.

The failure strain for steel at all loading rates is higher than that for copper plate specimens. After a projectile velocity of 100m/s a remarkable difference in the failure strains can be observed. The failure strain for copper remains below 0.40 but for steel it escalates to a higher value of 0.60 and above. This was particularly observed at projectile velocities of 120m/s where target plate perforation occurred.

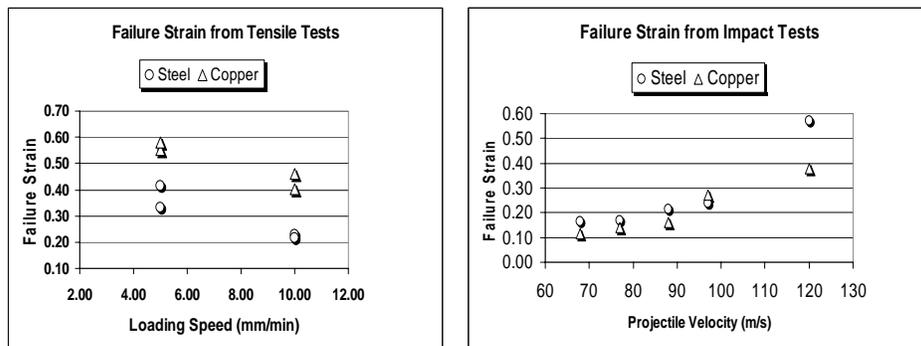
This can be understood in the light of the observation of the change in hardness values of both materials at high strain rates and the reduction in plate thickness respectively. Hardness values for virgin plates and damaged samples after projectile impact were measured. Fig.6. shows the change in hardness values of steel and copper after impact.

The hardness values for the virgin steel plate were found to be 63.33 HRB compared to 83.4 HRB for samples subjected to static denting load. In Fig.6. it can be

seen that at high loading rates the hardness for steel gradually decreases. This decrease of the projectile velocity range used in the present experiments does not show a significant variation but on the other hand copper plate hardness experienced a tremendous increase. Virgin copper plate hardness was observed to be only 14.10HRB while slow denting of the plate produced a value of 48HRB.

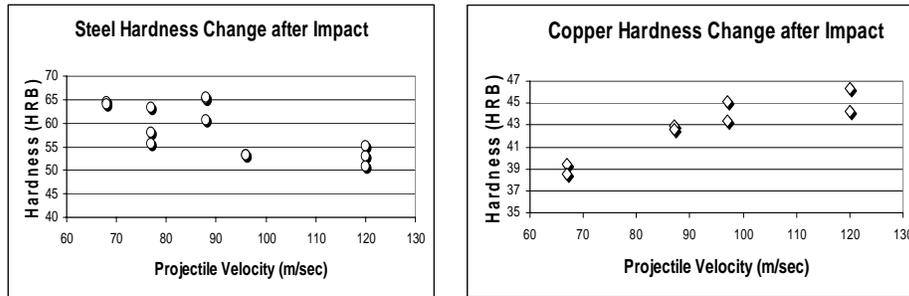


**Fig.4. Failure strain measured from steel and copper plate for static denting load at various**



**Fig.5. Plastic strain comparison for steel and copper at static tensile tests and plate impact loading at high velocities.**

Though the hardness values at increasing loading rate do not show any significant variation, the fact that undamaged plate had a hardness value of only 14.1HRB explains why the failure strain for this material shows a value of 0.40 at highest projectile speed that causes the perforation of the target plate. It can be inferred that due to steep increase in hardness this material failed in a rather brittle manner.



**Fig.6. Change in hardness values measured from the impacted samples of steel and copper at various projectile velocities.**

#### 4. Finite Element Analysis

It is difficult to paste strain gages on the back surface of the target plates, to obtain reasonable strain data, during high velocity impact since this may shatter the strain gages before they could provide data. It was decided to use numerical simulations instead. The projectile and the target plate were modeled in ANSYS with the experimental data obtained from tensile tests on both materials. The model was then transferred to LSDYNA software to conduct impact simulations. The plate failure is shown in Fig.7.

In the LSDYNA simulations the spherical projectile was considered to be of rigid material with no deformations while the plate material model was considered as plastic kinematics. Stresses, strains, strain rates, and thickness variations during the impact process were recorded.

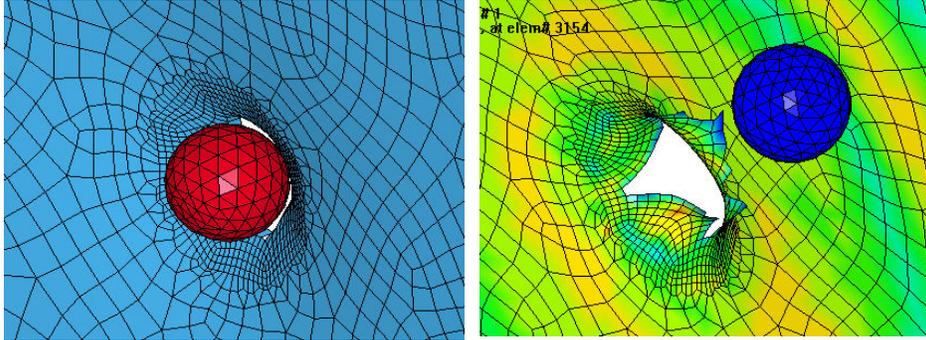
For an original plate thickness of 0.52 mm for both materials (steel and copper), the thickness reduction at maximum displacement were noted. The plate thickness change showed a very good agreement with experimental work. The strain rate values at increasing projectile velocities are compared in Fig.8.

The strain rates calculated using LSDYNA were subsequently compared to the failure strains obtained experimentally as shown in Fig.9.

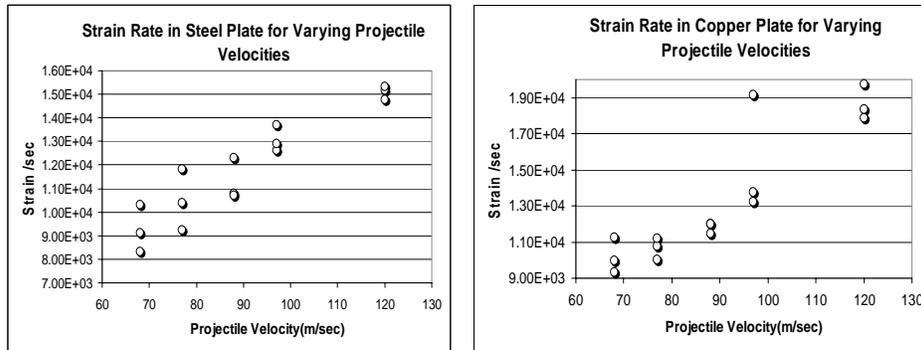
When assessing the performance of materials subjected to impact loads, it is important to know their mechanical properties under high strain rates so that failure could be predicted. In hydrocodes like LSDYNA the metallic material models require failure strain input. The purpose of this research was also to confirm that the numerical analysis can simulate the experimental behavior as closely as possible.

Equivalent stress plots at impact are shown in Fig.10. The strain rate effect on equivalent stress is shown in Fig.11.

The finite element model for copper could not simulate the impact event at high strain rates due to some error in data input, therefore the strain rate effect on equivalent stresses or failure strain may be not reliable at this stage. The model discrepancies have been identified and another model like Johnson-Cook [8] model would be implemented in future simulations.



**Fig.7. Plate perforation at projectile velocity of 120m/s for steel and copper target plates.**



**Fig.8. Strain rates obtained at increasing projectile velocities for steel and copper samples.**

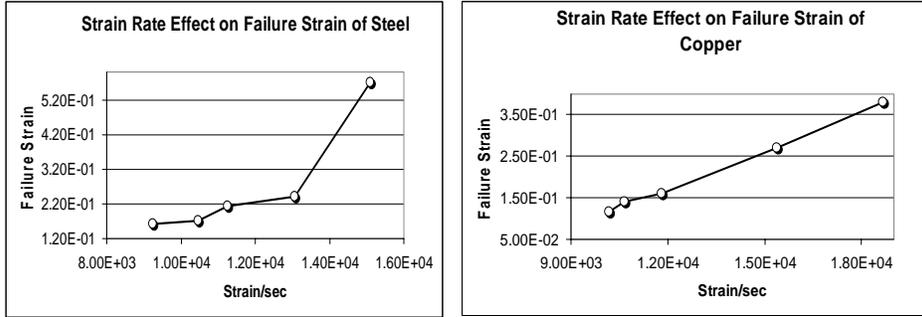


Fig.9. Strain rate effect on the failure strains of steel and copper.

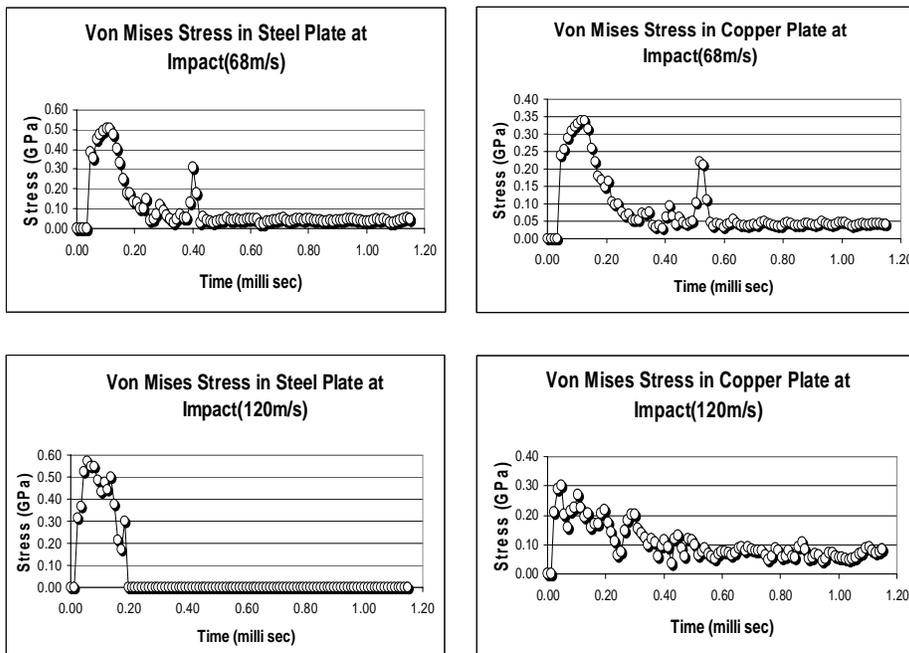
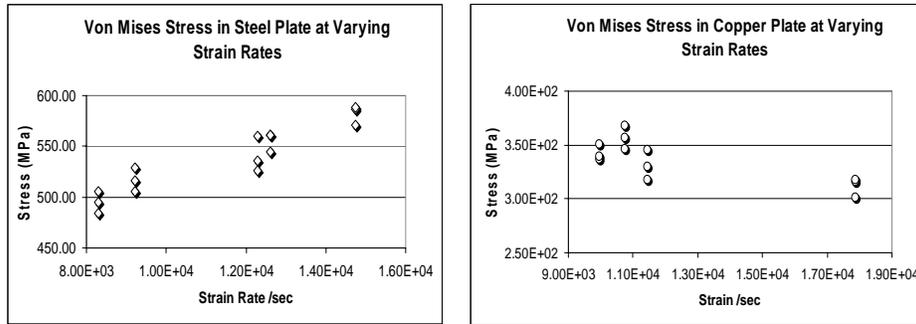


Fig.10. Equivalent stress plots for projectile velocities of 68 and 120m/s for steel and copper samples.



**Fig.11. Effect of strain rate on the equivalent stress of steel and copper.**

## 5. Conclusions

Circular plates of 120mm diameter made up of steel and copper with 0.52 mm thickness were subjected to a spherical projectile (diameter = 8.73mm) impact at varying velocities. Post impact plastic strains, hardness, and plate thickness reduction were recorded. The impact event was modeled into LSDYNA code and strain rates were calculated for various loading speeds. It was found that at high strain rates the hardness of steel decreases while the copper plate hardness increases. Undamaged samples of copper plate showed a hardness value of 14.10HRB which is 1/3 of the hardness obtained at high strain rate. Therefore copper failure experienced brittle failure. Steel hardness at high strain rates decreased, though not very significantly, therefore it followed a partially brittle and partially ductile failure process.

Strain rate effect on the failure strain was simulated and a good agreement was found between them. At high strain rates the failure strain of steel is enhanced significantly while for copper it has a linear trend (Fig. 9.).

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