Chapter 5

Spall fracture and hardening of polycrystalline copper under shock loading

5.1 Introduction

Depending on the strain rates, the loading of the materials can be broadly categorized as quasi-static loading (strain rates ≤ ~ 10^{-3}/s) and dynamic loading (strain rates can range from 10^{-3}/s to 10^8/s). The dynamic loading can further be classified as intermediate (strain rates ~ 10^{-3}-10^0/s), high (strain rates ~ 10^0-10^4/s) and ultrahigh (strain rates ~ 10^4-10^9/s) strain rate regimes [1-3]. In many applications materials are not only subjected to the condition of high stresses, but also the condition of high strain rates. Few examples of such conditions are blast and impulsive loading, contact stresses under high-speed bearings, high-speed machining, explosive forming and ballistics. As various mechanical properties such as the yield strength and fracture strength of materials depends not only on the amount of the applied stress but also on the strain rates rate [4-8] i.e. the rates at which these are applied, it is not sufficient to have knowledge of these properties only under quasi-static loading conditions. It has been demonstrated experimentally that the yield strength and fracture strength of materials at high strain rates, commonly referred as dynamic yield strength and spall strength, are higher than those measured in quasi static experiments [4-6, 9] and the reason for this over-stressing has been associated to the inertia shown by material flaws to respond the rapid loading rates [5, 9]. In fact, in aluminum (Al) and copper (Cu), it has been found experimentally that that at ultrahigh strain rates ≥ 10^8/s the spall strength approaches the ideal value governed solely by inter-atomic forces and corresponds to the maximum tensile stress achievable before spall fracture [9]. Apart from this, for a given material, it has also been demonstrated experimentally that the thickness of the target material also has strong effects on the spall strength [10-11]. Therefore, in order to ensure the suitability of a material for applications pertaining to
high strain rates it is useful to measure the strength properties as a function of strain rate as well as thickness.

In past, measurement of dynamic yield strength and spall strength were limited due to unavailability of efficient experimental techniques to generate high tensile stresses at high strain rates and diagnostic techniques required for measurements. But significant advances made in techniques of producing [12-15] and measuring tensile stresses [16-17] at high strain rates in last two decades, have made it possible to generate data on dynamic yield strength and spall strength of many materials [5, 9-11, 18-24]. Apart from these continuum measurements, few advanced laboratories in the world have developed capabilities to carry out in-situ microscopy measurements at high strain rates which have facilitated the understanding of the mechanism of phase transitions or simple mechanical deformation in terms of the atomic level rearrangements [25-28]. The suitably configured shock loading experiments, e.g. plate impact experiments, are the one which not only can generate high compressive stresses but also high tensile stresses in target material at high strain rates varying from $10^4$/s to $10^9$/s. The detailed mechanism of generation of tensile stresses [29] in target material in plate impact experiments has been discussed in chapter 1. In brief, in a plate impact experiment, a planar shock wave propagates into the target material and reflects back as a release wave upon arrival at free surface. Similarly, a shock wave propagating into flyer plate in opposite direction also gets reflected as a rarefaction wave at flyer free surface. The interaction of these two opposite travelling release waves generates large tensile stress in the target which when exceeds the fracture strength causes spall fracture in the target material.

Recently, we have carried out plate impact experiments on commercially available 99.97% pure polycrystalline samples of copper and determined the yield strength and fracture strength at strain rates of $\sim 10^4$/s. Apart from this, we have performed the nanoindentation measurements on as received and shock treated sample and examined the effect of shock treatment on the mechanical properties such as hardness and Young’s modulus of the copper. Additionally, the shock recovery experiments have also been carried out on copper samples and analysis of recovered
samples has been done using x-ray diffraction (XRD) technique. In order to compare the results on the yield strength and fracture strength at high strain rates with that under quasi-static loading conditions, the quasi-static tensile test have also been carried out on suitably prepared copper sample. This chapter of the thesis presents results on these measurements.

5.2 Experimental Method

5.2.1 Quasi Static Testing

A tensile test is a fundamental mechanical test on a carefully prepared specimen to determine the modulus of elasticity, elastic limit, proportional limit, tensile strength, yield strength, yield point and other tensile properties. The main outcome of a tensile test is load versus elongation data which is then converted to stress-strain curve. An ideal stress-strain curve for a ductile material appears as shown in Fig. 5.1. It has mainly three regions of importance. First portion of the curve is the linear elastic region where the Hooke’s law is followed by the material and thus stress is proportional to applied strain. The proportionality constant is known as the modulus of elasticity or the Young’s modulus. At some point, the stress-strain curve deviates from the linear relationship and after this point the material undergoes plastic deformation. This point is known as yield point and the corresponding stress is called the yield strength. The transition from elastic to plastic behavior is gradual and the exact point at which this transition occurs is hard to determine. For most of the engineering applications, yield strength is defined as the stress required for a small amount of plastic deformation which is known as offset yield strength. To determine this point a parallel line to the elastic part of the curve offset by some specified strain (0.2% offset) is drawn and the stress corresponding to the intersection of this line to the stress-strain curve gives the 0.2% offset yield strength (Fig. 5.1). After this yield point the material undergoes uniform plastic deformation and comes to a point where the stress is maximum which is known as ultimate tensile strength (UTS). After the ultimate stress, the cross-sectional area of the specimen begins to decrease in a localized region of the specimen, instead of over its entire length causing necking as
the specimen elongated further. At the end, the specimen ruptures at that localized position and the corresponding stress is the fracture strength of the material.

![Stress-Strain Diagram](image)

**Figure 5.1:** Ideal stress-strain relation for a ductile material. Three different region of this curve has been shown with horizontal arrow.

The tensile test of the as-received copper sample is carried out in the 100 kN screw-driven universal servo-hydraulic testing machine (Instron 1185 Machine). The schematic of this machine is shown in Fig. 5.2. Rectangular specimen of total length 85 mm and thickness 3.43 mm has been prepared for this purpose (Fig. 5.3). Gauge length of this specimen is 24 mm and gauge width is 6.14 mm. The holes in the sample are clamped between the crossheads of the machine. The crossheads are pulled apart by the screw driven hydraulic system with speed of the cross head kept at 0.10 mm/min.
Figure 5.2: Schematic of servo-hydraulic universal testing machine.

Figure 5.3: Specimen of copper plate used for tensile test measurement.
5.2.2 Plate Impact Experiments

![Diagram of a gas gun facility](image)

**Figure 5.4:** Gas Gun facility at Bhabha Atomic Research Centre, Mumbai [30] to conduct plate impact experiments.

The dynamic loading experiments have been conducted on polycrystalline copper samples in a 63 mm bore size single stage gas gun (Fig. 5.4) [30]. The gun has three main parts breech, barrel and target catch-up system (comprises target chamber and catcher tank). The breech is a vessel having capacity of 40 liters, which can hold gases compressed up to a pressure of ~ 420 bars. For plate impact experiment, the projectile consisting of an aluminium cylinder with a copper flyer plate of thickness 4.8 mm and diameter 57 mm attached to its nose was placed inside the projectile holder, residing at the central region of the breech and connecting to the barrel. In order to accelerate the projectile to a desired velocity the breech was filled with helium gas up to required pressure. A small amount of the high pressure gas was injected behind the projectile, causing it to move past the ports on the projectile holder and allowing the high pressure gas filled in the breech to rush behind the projectile. The projectile was accelerated to a desired velocity in a 3m long barrel before it impacted the target plate of the copper fixed in the Perspex target holder ring which was mounted on the target chamber at the muzzle end of the barrel (Fig. 5.5). As shown in the Fig. 5.5, to measure the impact velocity of the flyer plate, four pairs
of electrical pins were kept known distance apart from each other in the path of the projectile which got sorted with the moving the projectile body. The impact velocity was then determined from measured time interval between successive electrical output pulses generated by pulse forming unit due to shorting of four pairs of the pins and known distance between successive pairs of the pins. The motion of the free surface of the 15mm thick copper target plate upon the arrival of the shock wave was monitored through optical interferomerty technique known as velocity interferometer system for any reflector (VISAR) [31-32]. For this purpose the rear surface of the target plate was illuminated with the laser light (532 nm) and the laser reflected from the free surface of the target was collected back and fed to the interferometer to make fringe pattern. This interferometer which is basically a modified Michelson interferometer beat the two light signals reflected from the free surface of the target plate at two instants of time separated by a small interval of ~ few nanoseconds and corresponding fringe shift as a function time was recorded. This time dependent fringe shift was then utilized to derive the free surface velocity history which then was utilized to determine the dynamic yield strength and spall strength of copper plate.

The required target and flyer plate in the form of circular discs have been prepared from a large plate of the copper. The initial density ($\rho_0$) of the copper plates was measured to be 8.905 ± 0.005 g/cc. The shock pressure of 10.4 GPa is generated in the target plate by impacting it with a 4.8 mm thick and 57 mm diameter impactor plate made of the same material and accelerated to the peak velocity ($V_p$) of 0.52 km/s.

Additionally, a shock recovery experiment has also been carried out in the copper sample. The aim of this experiment was to see the post compression effect on copper sample under uniaxial strain compression conditions. A typical schematic of the target assembly for this experiment is displayed in Fig. 5.6. A circular sample of copper of 10 mm diameter and 1.2 mm thickness was fitted into a matching hole of stainless steel (SS304) plate of diameter 44mm and this plate is then fitted in a SS304 ring of inner diameter 44.05mm and outer diameter 85mm. The presence of this ring mitigated the affect of lateral release waves on uniaxial strain compression condition. This assembly is then emplaced into a steel capsule of 88 mm of inner diameter and
Figure 5.5: Typical schematic diagram of experimental layout for plate impact shock wave experiment on copper target. As shown in figure the target copper plate having thickness 15 mm and diameter 57 mm is fixed in Perspex target holder ring of thickness of 5 mm. A VISAR probe consisting of a single mode launching fiber and a multimode collection fiber is mounted with fiber ends at a distance of ~ 2 mm from the free surface with a suitable mounting arrangement. The output of the collecting fiber is fed to the interferometer system.

110 mm of outer diameter as shown in Fig. 5.6. The sample was covered by a 3 mm steel cover plate and locked tightly by a locking nut. Two momentum trap plates of steel have been glued consecutively in the rear surface of the recovery fixture. The details of the working and momentum trapping mechanism have been discussed elsewhere (33). The catcher tank is used to arrest the target and projectile debris after the impact is taken place. The sample recovered after unloading from peak shock pressure of ~ 12 GPa has been analyzed through x-ray diffraction and nanoindentation method.
5.3 Method of Analysis of Experimental Data

5.3.1 The Analysis of Free Surface Velocity History

The impact of copper flyer plate on the stationary target plate generated planer shock waves propagating in forward direction in target plate and in backward direction in flyer plate (as discussed in chapter 1). The forward moving shock reached the free surface of the target and due to the impedance mismatch at the rear surface the shock wave reflected from target free surface as backward moving release wave. Similarly, the backward moving shock reflected from the flyer free surface as forward moving release wave. The interaction of these release waves in the target generated tensile stress and when this stress exceeded the strength of the material it spalled. The arrival of shock wave and the generation of release wave as well as spall fracture are manifested in the free surface velocity ($U_{fs}$) history of the impacted sample. To discuss the method of analyzing the free surface velocity history data, in
Fig. 5.7, an ideal free surface velocity profile of a material undergoing elastic to plastic transformation followed by phase transition and spallation has been displayed.

**Figure 5.7:** Ideal free surface velocity profile of material showing features corresponding to various phenomenons.

The first portion (i.e. from zero to peak velocity) corresponds to compressive stress, whereas, the later portion represents the tensile regime. The Hugoniot elastic limit ($\sigma_{HEL}$), strain rate ($\dot{\varepsilon}_c$) corresponding to $\sigma_{HEL}$, the spall strength ($\sigma_s$) and strain rate ($\dot{\varepsilon}_t$) corresponding to $\sigma_s$, are determined from this profile as follows [2-3, 26]:

\[
\sigma_{HEL} = \frac{1}{2} U_H \rho_0 c_i \quad (5.1)
\]

\[
\dot{\varepsilon}_c = \frac{U_H}{2\Delta t} \frac{1}{c_i} \quad (5.2)
\]

The dynamic yield $Y$ from the $\sigma_{HEL}$ is deduced using following expression:
\[ Y = \sigma_{HEL} \frac{(1-2\sigma)}{(1-\sigma)} \]  
\[ \sigma_s = \frac{1}{2} \Delta U_{fs} \rho_0 c_b \]  
\[ \dot{\varepsilon}_t = \frac{\Delta U_{fs}}{2\Delta t_2} \frac{1}{c_b} \]  

Here, \( U_{HF} \) is free surface velocity at \( \sigma_{HEL} \). The \( \Delta t_1 \) is the time taken for free surface to reach a velocity of \( U_{HF} \). The \( c_b, c_l \) and \( \sigma \) correspond to the bulk sound speed, longitudinal sound speed and Poisson ratio, respectively. The pull back velocity is defined as \( \Delta U_{fs} = U_f - U_m \) where \( U_f \) is the peak free surface velocity and \( U_m \) is free surface velocity just ahead of spall pulse. The \( \Delta t_2 \) is the time taken by the free surface to retard from the peak velocity \( U_f \) to \( U_m \).

### 5.3.2 Analysis of Nanoindentation Data

The nanoindentation measurements have been carried out on as-received and shock treated samples. The analysis of the nanoindentation data to determine the micromechanical properties, e.g. nanohardness and Young's modulus was carried out using well known Oliver-Pharr [34-35] model. The nanoindentation experiment were carried out using a nanoindentation machine (UNHT S/N: 50-00002) at a fixed maximum load (\( P_{max} \)) of 30 mN, with force and depth sensing resolutions of 0.2 \( \mu \)N and 0.1nm. Experiments were conducted using a load-time sequence. For each loading-unloading cycle, the loading and unloading rates were 60 mN/minute, i.e. the loading and unloading cycles each lasted 30s, respectively. During each test run, a personal computer collected and stored data for the load and displacement as the indenter was driven into the sample (loading segment) and then withdrawn from it (unloading segment). The raw data were then used to construct the load-displacement
plot. The deformation during loading is assumed to be both elastic and plastic in nature, however, during unloading it is assumed that only elastic deformations are recovered [34-35]. The hardness (H) is estimated from the expression [34-35]:

$$H = \frac{P_{\text{max}}}{A_r}$$  \hspace{1cm} (5.6)

Here \( P_{\text{max}} \) is maximum load and \( A_r \) is the area of the residual indentation in the sample. The Young’s modulus (\( E \)) is determined using the expression [34-35]:

$$\frac{1}{E'} = \frac{1 - \nu^2}{E} + \frac{1 - \nu_i^2}{E_i}$$  \hspace{1cm} (5.7)

With \( E' \) is the effective Young’s modulus and, \( E \) and \( E_i \) are Young’s modulus of sample and indenter, respectively. The \( \nu_i \) is the Poisson ratio of the indenter. The \( E' \) is related to the unloading stiffness and contact area with following expression [34-35]:

$$E' = \frac{S}{2\beta \sqrt{A_r}} \sqrt{\pi}$$  \hspace{1cm} (5.8)

Here “\( S \)”, which is obtained from the slope of the upper portion of the unloading curve, is called elastic unloading stiffness. The indenter geometry dependent constant \( \beta \) is 1.034 for Burkovich indenter [34-35].

5.4 Results and Discussions

5.4.1 Yield Strength and Fracture Strength from Quasistatic Test

Fig. 5.8 shows the stress versus elongation curve for as-received copper sample under quasistatic loading condition. The large strain hardening region of the stress-elongation diagram implies that copper is ductile in nature. Tensile strength at yield point (0.2% offset) has been found to be 130 MPa. The ultimate tensile strength is found to be 221 MPa corresponding to elongation of 11.802 mm.
Figure 5.8: Stress versus elongation curve for the as received sample of copper.

5.4.2 Yield Strength and Fracture Strength from Plate Impact Experiment

Fig. 5.9 displays the free surface velocity history of Cu target plate recorded using VISAR. The peak free surface velocity of 0.51 km/s is very close to the impact velocity of 0.52 km/s measured by successive shorting of four pairs of electrical pins by the flyer plate just before the impact. This is expected as in the symmetric impact configuration, *i.e.* impactor and target made of same material, the maximum free surface velocity is almost equal to the impact velocity. As expected, there is not any signature of polymorphic phase transition in the free surface velocity profile. The $U_{H}$ and $\Delta U_{f}$ determined from the free surface velocity history are 0.014 km/s and 0.075 km/s with the time interval $\Delta t_{1}$ and $\Delta t_{2}$ of 0.3 μs and 0.6 μs, respectively. The $c_{l}$, $c_{b}$ and $\nu$ are taken to be 4.76 km/s, 3.96 km/s and 0.34 from available literature [36, 37]. These quantities upon substitution in Eqn. (5.1) through (5.5) yielded the $\sigma_{HEL}$, $\dot{\varepsilon}_c$, $Y$
, $\sigma$, and $\dot{\varepsilon}$, as listed in Table 5.1. As shown in Table 5.1, the yield strength and spall strength of copper measured at strain rates $\sim 10^4$/s in the present work is found to be 0.14 GPa and 1.32 GPa. The spall strength found from this dynamic compression experiment is higher by a factor of $\sim 6$ than the quasi static values, whereas, the yield strength measured at these high strain rates is marginally higher than the quasi static value. Further, as shown in Table 5.1, the spall strength measured in the present symmetric plate impact experiment agrees well with that measured by Moshe et al [9] in laser shock experiments and by Kanel et al. [38] in explosive driven asymmetric plate impact experiments. Additionally, the spall strength of 1.32 GPa measured in bulk polycrystalline copper in the present experiment is much lower than the 3.0 GPa measured in the nanocrystalline copper [24] and $\sim 4.5$ GPa measured in single crystal of copper along [100] direction [11, 38]. The reason for the higher spall strength of nanocrystalline copper than the polycrystalline bulk copper could be associated to the presence of relatively large number of grain boundaries [24]. However, the large spall strength exhibited by single crystal copper could be due to presence of relatively less number of damage nucleation sites in highly homogeneous single crystal of copper [11].

![Figure 5.9](image)

**Figure 5.9:** The free surface velocity history of shock loaded copper target recorded using VISAR.
Table 5.1: The dynamic yield strength, spall strength and corresponding average strain rates measured in the present work. A comparison also made with data measured under quasi static loading conditions.

<table>
<thead>
<tr>
<th>Properties</th>
<th>High strain rate loading (present work)</th>
<th>High strain rate loading (other sources)</th>
<th>Quasi static loading (Present work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{HEL}$ (GPa)</td>
<td>0.29 ± 0.003</td>
<td>0.31[32]</td>
<td></td>
</tr>
<tr>
<td>$\dot{\varepsilon}_c$ (s$^{-1}$)</td>
<td>4.90 ± 0.060×10$^3$</td>
<td>7.90×10$^3$[32]</td>
<td></td>
</tr>
<tr>
<td>Y (GPa)</td>
<td>0.14 ± 0.001</td>
<td>0.15[32]</td>
<td>0.13</td>
</tr>
<tr>
<td>$\sigma_s$ (GPa)</td>
<td>1.32 ± 0.01</td>
<td>1.25[6], 1.23[32]</td>
<td>0.22</td>
</tr>
<tr>
<td>$\dot{\varepsilon}_t$ (s$^{-1}$)</td>
<td>1.57 ± 0.158×10$^4$</td>
<td>10$^4$[6], 1.5×10$^4$[32]</td>
<td></td>
</tr>
</tbody>
</table>

5.4.3 Nanoindentation Measurements

Figure 5.10: Indentation load-displacement curve of shock treated and as received copper sample.
In order to determine the hardness and elastic modulus of as received and shock treated polycrystalline copper sample the nanoindentation experiments using Berkovich indenter have been conducted at the maximum load of 30 mN. Fig. 5.10 displays indentation load-displacement diagram for loading as well as unloading cycle. As can be seen from this figure both the maximum depth of penetration and the permanent depth of penetration for the shock treated samples is less as compared to that for the as received Cu sample (Table 5.2), indicating the increase in hardness or stiffness of the Cu sample after shock treatment. Various parameters measured from nanoindentation experiments on the shock treated and as received Cu are listed in the Table 5.2. As shown in Table 5.2, the S parameter of shock treated sample is increased by ~14% as compared to that of the as received Cu. Finally, the hardness and Young’s modulus of shock retrieved sample has increased by ~18% and ~29%, respectively. These results of nanoindentation experiments on shock treated and as received Cu samples suggest that the passage of the shock through Cu target plate has increased its hardness and Young’s modulus.

Table 5.2: Various parameters measured from nanoindentation experiments.

<table>
<thead>
<tr>
<th>Properties</th>
<th>As received Cu</th>
<th>Shock treated Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{\text{max}}$(nm)</td>
<td>933.09</td>
<td>849.69</td>
</tr>
<tr>
<td>$S$(mN/nm)</td>
<td>1.0316</td>
<td>1.1726</td>
</tr>
<tr>
<td>$h_r$(nm)</td>
<td>889.89</td>
<td>801.91</td>
</tr>
<tr>
<td>$A_r$(nm$^2$)</td>
<td>2.488×10$^7$</td>
<td>2.097×10$^7$</td>
</tr>
<tr>
<td>H(GPa)</td>
<td>1.207</td>
<td>1.433</td>
</tr>
<tr>
<td>$E'(\text{GPa})$</td>
<td>177</td>
<td>219</td>
</tr>
<tr>
<td>E(GPa)</td>
<td>185</td>
<td>239</td>
</tr>
</tbody>
</table>
5.4.4 X-Ray Diffraction Measurements

**Figure 5.11**: ADXRD patterns of shock treated copper sample. Also displayed is the diffraction pattern of initial unshocked sample for comparison.

**Figure 5.12**: Most intense diffraction peaks (111) and (200) of the shock recovered sample and the as-received sample.

The sample recovered from peak shock pressure of ~12 GPa from shock recovery experiment has been analyzed through angle dispersive x-ray diffraction (ADXRD)
technique. The x-ray diffractions of the copper sample are carried out in Ultima IV machine of Rigaku make. Continuous 2θ scanning mode is used with scanning speed of 2.000 deg/min and step width of 0.0200 deg. Scan (2θ) is done from 30 deg to 100 deg. The diffraction pattern of shock treated sample has been compared with that of the as received (unshocked) sample. Fig. 5.11 shows the diffraction patterns of the shocked as well as the initial unshocked sample. The diffraction peaks of both unshocked and shock treated samples are indexed for fcc structure. As is shown in Fig. 5.11, all the diffraction peaks of the shock treated copper sample are shifted towards higher angles as compared to those of as received sample. For more clarity the most intense (111) peak and (200) of shocked and as received samples are also displayed in Fig. 5.12(a) and 5.12(b). The percentage change in the d-spacing of different set of planes is listed in Table 5.3. These observations indicate that the shock treated copper sample has undergone a uniform compressive residual strain.

Table 5.3: Percentage fractional shift in d-spacing of various crystallographic planes measured from x-ray diffraction. Here $d_0$ and $d_p$ are the d-spacing of various (hkl) planes of as received and shock retrieved Cu sample, respectively. $100\times(d_p-d_0)/d_0$ is the percentage shift in d-spacing of shock treated Cu.

<table>
<thead>
<tr>
<th>(hkl)</th>
<th>d-spacing (Å)</th>
<th>Percentage shift in d-spacing (100×(d_p-d_0)/d_0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$d_0$(Å)</td>
<td>$d_p$(Å)</td>
</tr>
<tr>
<td>(111)</td>
<td>2.0929</td>
<td>2.0891</td>
</tr>
<tr>
<td>(200)</td>
<td>1.8127</td>
<td>1.8085</td>
</tr>
<tr>
<td>(220)</td>
<td>1.2806</td>
<td>1.2788</td>
</tr>
<tr>
<td>(311)</td>
<td>1.0920</td>
<td>1.0903</td>
</tr>
<tr>
<td>(222)</td>
<td>1.0449</td>
<td>1.0443</td>
</tr>
</tbody>
</table>
5.5 Summary

To summarize, quasistatic and high strain rate tensile tests have been carried out in polycrystalline copper of purity 99.99%. The yield strength and fracture strength measured in quasi static loading conditions are 0.13 GPa and 0.22 GPa, respectively. The high strain rate loading in copper sample has been achieved in plate impact experiment carried out using single stage light gas gun. The average strain rates generated in the copper sample were ~ $10^4$/s with impact velocity of ~ 0.52 km/s and peak shock pressure of ~ 10 GPa. The yield strength and spall (fracture) strength determined at these strain rates from measured free surface velocity history are 0.14 GPa and 1.32 GPa, respectively. The value of yield strength measured at these strain rates is marginally higher than that measured in quasi static test, whereas, the fracture strength increases by ~ 6 fold as compared to that at quasi static conditions. The spall strength measured in the present work agrees well with 1.25 GPa, that available from other source [9].

The nanoindentation measurements carried out in shock treated and unshocked copper sample reveal that the shock treatment has increased its hardness and elastic modulus by ~ 16% and ~29%, respectively. The comparison of the x-ray diffraction patterns of the unshocked and shock treated copper sample showed: (i) the shift towards higher angles in all diffraction peaks of the shock treated sample as compared to that of the unshocked sample. This shift could be due to a residual uniform compressive strain in the shock retrieved sample.
References

33. N. Suresh, Thesis, Mumbai University.