Behaviour of advanced materials impacted by high energy particle beams

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Abstract. Beam Intercepting Devices (BID) are designed to operate in a harsh radioactive environment and are highly loaded from a thermo-structural point of view. Moreover, modern particle accelerators, storing unprecedented energy, may be exposed to severe accidental events triggered by direct beam impacts. In this context, impulse has been given to the development of novel materials for advanced thermal management with high thermal shock resistance like metal-diamond and metal-graphite composites on top of refractory metals such as molybdenum, tungsten and copper alloys. This paper presents the results of a first-of-its-kind experiment which exploited 440 GeV proton beams at different intensities to impact samples of the aforementioned materials. Effects of thermally induced shockwaves were acquired via high speed acquisition system including strain gauges, laser Doppler vibrometer and high speed camera. Preliminary information of beam induced damages on materials were also collected. State-of-the-art hydrodynamic codes (like Autodyn®), relying on complex material models including equation of state (EOS), strength and failure models, have been used for the simulation of the experiment. Preliminary results confirm the effectiveness and reliability of these numerical methods when material constitutive models are completely available (W and Cu alloys). For novel composite materials a reverse engineering approach will be used to build appropriate constitutive models, thus allowing a realistic representation of these complex phenomena. These results are of paramount importance for understanding and predicting the response of novel advanced composites to beam impacts in modern particle accelerators.

1. Introduction

The introduction in recent years of new, extremely energetic particle accelerators such as the Large Hadron Collider (LHC) [1] has required the development of advanced methods to predict the behavior of beam intercepting devices in case of direct beam impact. Such events can be simulated resorting to complex wave propagation codes like Autodyn or LS-Dyna [2]. These numerical tools, however, require accurate material models which scarce in scientific literature, especially for non-conventional alloys or composites. In order to probe and evaluate such models at the extreme conditions induced by particle beam impacts, a first-of-its-kind experiment was recently carried out at CERN HiRadMat facility [3]. The performed tests entailed the controlled impact of intense proton pulses on specimens

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made of six different materials, including advanced metallic alloys and newly developed composites: the present work focuses on modeling and results of Inermet® 180 (tungsten heavy alloy W-Cu-Ni), while the studies on the other materials are still ongoing. For a comprehensive characterization, experimental data were acquired relying on extensive embedded instrumentation (strain gauges, temperature and vacuum sensors) and on remote-acquisition devices (laser Doppler vibrometer and high-speed camera).

Two different specimen shapes were chosen for each material (Figure 1): cylindrical disks (type 1) for medium intensity tests, to measure axially symmetric shockwaves; cylinders with a half-moon cross section (type 2) for high intensity tests, allowing extreme surface phenomena (melting, material explosion, debris projections etc.) to be visualized and optically acquired. Specimens were arranged into a sample holder maintained under vacuum; a total of six Inermet® 180 specimens have been tested: three at medium intensity (type 1) and three at high intensity (type 2).

![Figure 1. Material specimen shapes for tests at medium and high intensity](image1)

![Figure 2. General assembly of the HRMT-14 test-bench. Red arrow represents the beam](image2)

2. Numerical methods

When solids are impacted by highly energetic particle beams, phenomena such as significant change of density, changes of phase and explosions can occur. Wave propagation codes used to study these complex cases rely on material constitutive models encompassing a very large range of densities and temperatures [4]. The input for numerical simulations is the map of the thermal load generated by the beam impact on the component. The deposited energy can be calculated through a Monte-Carlo particle transport code and is proportional to the density of the impacted material. Simulations described in this paper are performed with Autodyn [5], while energy deposition 3D maps are calculated with FLUKA [6],[7].

2.1. Lagrangian method

Impacted components can often be modeled with a lagrangian mesh: even when high deformations or material spallation occur, it is possible to overcome the limitations of the lagrangian method by, for example, implementing the erosion of elements at given thresholds of stress, temperature or deformation. This approach was therefore adopted to simulate the response of type 1 samples impacted at medium energy during the test in the HiRadMat facility. When importing the thermal load in Autodyn, a subroutine interpolates the energy deposition map calculated by FLUKA and assigns the corresponding energy density to the Autodyn elements: ideally, no interpolation artifacts are generated throughout the process if the two meshes are identical. On the other hand, in order to decrease the simulation time, the mesh in Autodyn is often coarser and is refined only around the impact point, i.e. in the volume containing the most loaded elements.
The impinging proton pulse is constituted by trains of bunches spaced by 25 ns, while the impact duration of each bunch is 1 ns. The energy distribution deposited by one bunch, calculated with FLUKA, is therefore uploaded in Autodyn every 25 ns: this means that the time step of the simulation should be lower than 1 ns in order to correctly reproduce the impact phenomenon. The time step can be increased after the end of the beam impact up to 10 ns for numerical stability.

2.2. Smoothed-particle hydrodynamics (SPH)

The abovementioned lagrangian method is no longer adequate when the main goal of the study is to model the material fragments ejected after high-energy impacts. In such case, one has to adopt a different approach, such as the smoothed-particle hydrodynamics (SPH) technique. In this computational method, the material is modeled by discrete elements (particles) with a spatial distance of interaction (smoothing length) over which their properties are weighted by a kernel function. For example, material density in a given position \( x \) is:

\[
\rho(x) = \sum_{j=1}^{n} m_j W(|x - x_j|, h)
\]

where \( m_j \) is the mass of particle \( j \), \( W \) is the kernel function and \( h \) is the smoothing length.

This method was used for the simulation of high energy deposition on HiRadMat type 2 samples; since the SPH algorithm requires high computational time, only the inner volume of the specimen was modeled with SPH particles, while all the other regions were meshed with lagrangian elements.

3. Inermet180 material model

3.1. Equation of state

An equation of state (EOS) is a constitutive relation between the state variables of a material; usually it expresses the pressure (or the internal energy) as a function of two independent variables such as density and temperature. Most widely adopted EOS for wave propagation in solids are Shock, Tillotson and Mie-Grüneisen: these formulations involve complex theoretical models based on the band theory and combine them with shock compression experimental data. However, analytical modeling can describe only a single region of the EOS [8], excluding the description of phase transitions. Tabular EOS overcome this problem, integrating different analytical formulations to describe the behavior of different phases and the related phase transitions [9].

The EOS used in this work is the tabular SESAME N.3550 [10]; it has been devised for pure tungsten, for which experimental Hugoniot data are close to those of W-Ni-Cu heavy alloys [11].

3.2. Strength model

The strength model simulates the deviatoric behavior of the material and has to take into account the phenomena occurring in the matter during the beam impact, such as the melting of the impacted volume (loss of material strength), the variations in elastic and plastic behavior in the termally-altered zone and the hardening due to high strain rates in order to evaluate the propagation speed, the intensity and the damping during the travel inside the sample and obtain the wave intensity on the free surface.

A widely adopted model that considers the abovementioned effects is the Johnson-Cook (JC) model [12], whose parameters can be obtained through a set of experimental tests, which include Hopkinson Bars, Taylor cylinders, tensile and compression tests at different temperatures. JC model expresses the flow stress as:

\[
\sigma_y = (A + B \varepsilon_{pl}^n) \left( 1 + C \ln \frac{\dot{\varepsilon}_{pl}}{\dot{\varepsilon}_0} \right) \left( 1 - \left( \frac{T - T_m}{T_m - T_r} \right)^m \right)
\]

where \( A \) is the elastic limit, \( B \) and \( n \) are the work hardening parameters, \( C \) and \( \dot{\varepsilon}_0 \) express the strain-rate sensitivity and \( m \) describes the thermal softening. Parameters for the JC model used in the present
work are reported in Table 1; such values are based on the experimental results on W-Fe-Ni alloys and were slightly modified to fit Inermet® 180 mechanical properties.

3.3. Failure model
This model contains the set of conditions which lead to the bulk failure of the material; its choice heavily depends on the physical fracture mechanism. In case of particle beams impacting close to a free surface, the compressive shockwave immediately reflects back and turns into a tensile wave in the adjacent volume, causing the bulk failure of external crust and the projection of melted material.[13]. This mechanism could be reproduced in Autodyn through the Minimum Hydrostatic Pressure model ($P_{\text{min}}$); the model also implements the energy necessary for crack formation, calculated on the basis of the material fracture toughness. Reference values have been obtained experimentally with laser-induced spallation tests on polycrystalline tungsten [14].

### Table 1. Inermet® 180 material model.

| Equation of state  | Strength Model          | Failure Model                        | Hydrostatic Minimum Pressure |
|-------------------|-------------------------|--------------------------------------|-----------------------------|
| SESAME 3550       | Johnson Cook            | $P_{\text{min}}$                      | 2.7 GPa                     |
| $A$                | 140 GPa                 | Fracture Energy                       | 515 J/m$^2$                 |
| $B$                | 715 MPa                 |                                      |                             |
| $n$                | 177 MPa                 |                                      |                             |
| $C$                | 0.12                    |                                      |                             |
| $m$                | 0.016                   |                                      |                             |
| $T_{\text{melt}}$ | 1.00                    |                                      |                             |
| $T_{\text{melt}}$ | 1616 K                  |                                      |                             |
| Ref. Strain rate  | 1 s$^{-1}$              |                                      |                             |

4. Numerical simulations and experimental results
Table 2 reports the characteristic values of the impacting beam during tests on Inermet® 180 in the HiRadMat facility. Numerical simulations adopted the same parameters, except for the beam transverse dimension which was set to 2.5 x 2.5 mm$^2$.

### Table 2. Beam parameters for tests performed on Inermet® 180 during HRMT-14 experiment

| Medium intensity test | High intensity test |
|-----------------------|---------------------|
| Proton energy         | 440 GeV             | 440 GeV             |
| Number of bunches     | 24                  | 72                  |
| Pulse intensity       | 2.7e12 protons      | 9.05e12 protons     |
| Energy deposited on the most loaded specimen | 8.35 kJ | 25.1 kJ |
| Theoretical impact point | Centre of type 1 specimen | 2 mm from type 2 specimen flat surface |
| Beam transverse dimension | 1.4 x 2 mm$^2$ | 1.9 x 1.9 mm$^2$ |

4.1. Medium intensity impacts
Strain gauges measured axial and hoop strains on the external surface of type 1 samples, while the laser Doppler vibrometer (LDV) acquired the radial velocity. Acquired raw data were then compared to the results of numerical simulations (Figure 3,-Figure 4). A strong electromagnetic noise induced by the particle beam perturbed the strain gauge measurements during the first few microseconds after the impact, concealing the first deformation peak. However, this effect was limited to the beam impact
duration, allowing to capture the remainder of the phenomenon. Measured and simulated signals are in good accordance during the first three reflections of the shockwave; afterwards, the modifications in the material bulk induced by the shock wave lead to an overestimation of the wave speed. Random spikes in the signal of gauges and LDV will be treated during more accurate signal processing.

4.2. High intensity impacts
The developed high-speed camera system allowed for the first time, to the best of authors’ knowledge, to record images of the impact of a proton beam on solid targets and of the effects induced.

As shown in Figure 5, a large quantity of hot material was ejected at high velocity from the two most loaded Inermet® 180 type 2 samples, generating the large cavities shown in Figure 7. Concerning the SPH simulation results, ejected material front shape and calculated absolute velocity (ABS VEL in Figure 6) are both consistent with the high-speed camera measurements, even considering the differences in beam size between real and simulated scenarios. The velocity of the fragment front has been estimated by measuring the displacement between two successive frames and is about 275 m/s, well matching the calculated velocity of 316 m/s (difference is about 15%).

5. Conclusions
A complex and comprehensive experiment has recently been carried out at CERN, aiming at the characterization, mostly in real time, of six different materials impacted by 440 GeV/c intense proton pulses.
Preliminary measurements on Inermet® 180 specimens well match results of advanced computations, providing promising indications on the validity of the constitutive models used for this material. A large amount of data is still to be treated and will hopefully help deriving constitutive models for the less known composite materials. An extensive post-irradiation campaign, implying direct observations, non-destructive and destructive testing, is to be launched in future months to complete the experiment and provide additional valuable information.

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