Development and testing of novel advanced materials with very high thermal shock resistance

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ABSTRACT

Beam Intercepting Devices for last-generation particle accelerators, such as CERN Large Hadron Collider, must be designed to withstand the impact of intense particle pulses, safely operating over an extended range of temperatures in harsh environments. These requirements are to become even more demanding with the increase of machine performances expected in the near future, so that they can be hardly met by existing materials. Consequently, a far-reaching R&D program has been launched to develop novel materials, such as molybdenum-graphite composites, with high thermal shock resistance and excellent thermal conductivity, complementing presently used refractory metals like graphite, carbon/carbon composites, tungsten heavy alloys and molybdenum. The manufacturing methods and the remarkable properties of these materials will be presented, along with the results of a comprehensive experiment in which the dynamic effects induced by the direct impact of highly energetic proton pulses on several materials were measured and compared to advanced numerical simulations.

INTRODUCTION

The introduction in recent years of new, extremely energetic particle accelerators such as the Large Hadron Collider (LHC) [1] brought about the need for advanced cleaning and protection systems in order to safely increase the energy and intensity of particle beams to unprecedented levels. Accelerator components directly interacting with such extremely energetic beams, called Beam Intercepting Devices (BID), adopt materials which are to withstand the extreme conditions (temperatures, pressures and densities) induced by the accidental or deliberate impact of particle beam pulses; on top of outstanding thermal shock resistance, these materials are typically required a number of additional relevant properties, such as high electrical conductivity, geometrical stability and resistance to radiation damage. The present design of these devices largely relies on refractory materials like graphite, carbon/carbon composites, tungsten heavy alloys (such as Inermet180 produced by Plansee, Reutte, Austria) and molybdenum. Figures 1 provides an example of a BID: a collimator for the LHC [2], which is a fundamental element of the cleaning and protection system. Collimators are designed to: a) absorb the high energy particles which are unavoidably escaping from the beam core before they interact with very sensitive equipment like superconductive magnets (normal operation mode) and b) shield other
components by directly intercepting the beam in case of orbit errors, absorbing the extremely intense and rapidly deposited energy without catastrophic consequences (accidental operation mode).

Figure 1. Cutaway of a Beam Intercepting Device: a Secondary Collimator for the LHC. In this design, the active component of the part directly interacting with the particle beam, called jaw, is made of Carbon Fibre-Reinforced Carbon (AC150K produced by Tatsuno/Across Corporation, Japan).

It is hence of paramount importance to assess the responses to such potentially destructive events of impacted materials in collimators and other beam intercepting devices. Complex numerical methods have been used to study the dynamic phenomena, such as phase transitions, density changes, generation and propagation of shock waves, explosions, fragment projections, induced in matter when it is impacted by high energy particle beams. These phenomena have been successfully simulated relying on advanced wave propagation codes such as Autodyn or LS-Dyna [3,4].

Unfortunately, the material models which are required to perform such simulations, at the extreme conditions (temperature, pressure and density) induced by such impacts, are hardly available in scientific literature; besides, most of the existing information is often classified as it is drawn from military research mainly related to nuclear weaponry. Finally, very little data can be found for non-conventional alloys and compounds.

A comprehensive experiment, carried out at CERN HiRadMat facility, was devised and successfully completed to bridge this knowledge gap and gather experimental data upon which building and/or validating reliable material constitutive models for materials of interest.

On top of the challenges currently posed to machine protection by accelerators such as the LHC, one has to consider that in next years an important upgrade, known as High Luminosity LHC (HL-LHC) [5] is foreseen, further scaling up particle beam intensities, energies and energies. This will be even more the case for future programs like the planned 80÷100 km long Future Circular Collider (FCC) [6].

Furthermore, ambitious programs for the development of accelerator facilities, aimed at the massive production of elusive particles such as neutrinos or muons, rely on target systems submitted to the impact of proton beams at extraordinary intensities (power up to 5 MW) [7].

The collimation system presently installed in the LHC, made up of more than 100 units, very well performed in the first years of operation; however, none of the materials currently employed in the
active part of collimators or for other beam intercepting devices are fulfilling all the requirements posed by these new designs.

To face such challenges, an ambitious R&D program has been launched at CERN exploring a palette of novel materials which were to combine the properties of carbon allotropes, graphite or diamond, namely their low density, high thermal conductivity, low thermal expansion with those of metals and transition metal-based ceramics possessing high mechanical strength and good electrical conductivity.

Studied materials include Copper-Diamond (CuCD), Silver-Diamond (AgCD), Molybdenum-Diamond and Molybdenum-Copper-Diamond (MoCD and MoCuCD) and Molybdenum Carbide-Graphite with and without Carbon Fibre reinforcement (MoGr and MoGrCF) [8].

This article focuses on the R&D on MoCuCD and on MoGrCF which is the most promising material, particularly because of its outstanding thermal properties.

Although these materials are being developed primarily for High-Energy Physics, it is interesting to note that they may be appealing for a large number of applications and domains such as high end electronics, avionics, gas turbines, aerospace, advanced braking systems, where efficient thermal management and high temperature operability are an issue.

**Molybdenum – Copper – Diamond Composites**

MoCuCD was jointly developed by CERN and BrevettiBizz, Verona, Italy and produced by Rapid Hot Pressing (RHP) by Brevetti Bizz.

The main goals of the development were to improve the performances, particularly at high temperatures, of copper-based materials, such as Glidcop (copper strengthened by a fine dispersion of aluminium oxide, developed by North America Hoganas, Johnstown, PA, USA) or copper-diamond composites (developed by RHP-Technology, Seibersdorf, Austria) thanks to the beneficial effects of molybdenum. Not only Mo possesses a very high melting point, a low CTE (Coefficient of Thermal Expansion) over an extended range of temperatures and excellent mechanical strength but it is also a strong carbide former, so allowing a good adhesion between the metal matrix and the diamond grains.

Unfortunately, Mo, to be adequately sintered, requires processing temperatures in the range of 1700° C, which are well in excess of the graphitization threshold of diamond, typically starting at around 1000° C. Graphitization onset can be partly delayed by adopting a series of measures as accurate cleaning of powders, reducing sintering atmosphere and fast heating and cooling cycles: even with this however, the admissible processing temperature remains well below the one necessary to attain a sufficient compaction rate of Mo. In order to limit this phenomenon, it was eventually decided to reduce the sintering temperature to 1200° C and add copper which would fill in open pores by liquid infiltration of Cu phase.

The composition of the grade presented here was 40% synthetic diamonds (45 µm), 35% Mo powder (5 µm), 25% Cu powder (45 µm); powders were pre-cleaned at 600°C under H2-N2 atmosphere. The composite was obtained in a Rapid Hot Pressing furnace, having graphite electrodes and moulds, at a pressure of 30 MPa, maintaining the sintering temperature (1200°C) for 30 minutes.

Synthetic diamonds are preferred to natural ones since their smoother and more regular surfaces provide less nucleation points for graphitization compared to the indented fractured surfaces of ground natural diamonds.

A comprehensive characterization was performed on MoCuCD in order to evaluate its mechanical, thermal and electrical properties.

Microstructural analysis of MoCuCD fracture surface (Fig. 2) shows adequate overall compaction, with good interstitial filling and a limited number of adjacent diamond particles. The fracture surface is preferentially developing on the interface between diamonds and the metal matrix.

Figure 3 provides an indication of the extent of graphitization of diamond particles, which is
globally fairly limited: secondary electrons image shows some degree of diamond surface indentation due to either carbide formation or graphitization on the diamond faces; back-scattered electrons from the same area confirm that the regular diamond on the centre is partly eroded by carbide formation but almost completely unaffected by graphitization, while a more irregular diamond on the left brings evidence of more pronounced graphitization.

Figure 2: SEM image of MoCuCD fracture surface, low magnification. The fracture is developing preferentially through the metal matrix, as confirmed by the small number of broken diamonds.

Figure 3. Right: Secondary electrons image of MoCuCD fracture surface. Detail of diamond superficial aspect: diamond rougher surfaces (which may be due to graphitization or carbide particles formation) appear brighter because of the charging effect on asperities. Left: backscattered electrons of the same area. Carbides and graphite on diamond surfaces can be distinguished thanks to their different densities (lighter materials are darker). Upper right edge of central diamond is covered by MoC_1.0, while the other darker regions are mostly graphitized areas.

Figure 4 shows one example of a broken diamond on the fracture surface. This permits to verify the absence of graphitization within the diamond core (bulk graphitization) and the formation of a homogeneous carbide layer on the diamond surface which favours matrix adhesion.
Figure 4. SEM (secondary electrons) image of MoCuCD fracture surface. Example of a broken diamond: note cleavage planes and surface erosion indicating formation of carbides.

Mechanical measurements on MoCuCD included temperature-dependent compressive and tensile tests, static and dynamic performed at Politecnico di Torino [9]; in the latter case, a Hopkinson bar setup was used. As it can be seen by the very limited plastic strain and the difference between tensile and compressive strength (Fig. 5), material behaviour is brittle, as expected. The reduction in mechanical strength at high temperature is mostly due to the softening of the copper phase.

Figure 5. Tensile tests of MoCuCD at Room Temperature (t2) and at 600°C (t4) (left). Compressive measurements, c1 and c2 are obtained with static tests, h2 and h3 with the Hopkinson bar setup, at a strain rate of 1000 s⁻¹ (right).

Extensive thermo-physical measurements up to 900°C were also performed, assessing density, specific heat, thermal diffusivity, thermal conductivity, CTE and electrical conductivity. As for mechanical strength, the increase in CTE above 700°C (Fig. 6) is due to the copper phase in the system.
Properties of MoCuCD, measured at room temperature, are summarized in table 1.

<table>
<thead>
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<th>Value</th>
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<td>Density</td>
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<tr>
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<td>$\lambda$ W/mK</td>
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<tr>
<td>Electrical Conductivity</td>
<td>$\sigma$ MS/m</td>
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<tr>
<td>Young’s Modulus (Flexural)</td>
<td>$E$ GPa</td>
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<tr>
<td>Flexural Strength</td>
<td>$R_f$ MPa</td>
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</table>

Table 1. Molybdenum-Copper-Diamond measured properties.

As shown above, this material has interesting performances, in particular when it comes to electrical conductivity and mechanical strength; however the potential use of MoCuCD as a BID material is somehow limited by several drawbacks, namely brittle behaviour, relatively high CTE with a drastic increase above 700° C, moderate thermal conductivity, most likely limited by carbide interfaces and by some diamond surface graphitisation and fairly high density. Finally, the presence of copper phase hampers its use at very high temperatures because of its low melting point.

Molybdenum Carbide – Graphite Composites

As shown above, the full exploitation of molybdenum potential in composites for high temperature thermal shock applications in High Energy Physics can be hindered by the diamond degradation at the high processing temperatures required to sinter Mo and/or by the softening of copper which is added to get full compaction rates at the lower processing temperatures imposed by diamond. During the course of the R&D program, graphite was identified as a promising alternative to diamond. In fact, if the process of graphitization and crystallite re-ordering is sufficiently extended, graphitic materials possess low density, extremely high service temperature, large damping capacity (particularly useful in attenuating shock waves) as well as, at least in direction aligned with crystallite basal plane, excellent thermal conductivity and very low CTE.

When combined with graphite at high temperatures, molybdenum rapidly carburizes, forming MoC$_{1-x}$ stable carbides. In a joint effort between CERN and Brevetti Bizz, several Molybdenum Carbide – Graphite (MoGr) composites were investigated with processing temperatures ranging from 1700° C to 2600° C: in all cases molybdenum completely reacted with graphite, transforming the material into a Ceramic Matrix Composite.
Figure 7. Molybdenum – Carbon phase diagram. Note that given the high C atomic content (~88%), in equilibrium conditions, the melting point for the \( \alpha\)-MoC\(_{1-x}\) phase is 2857K (2584ºC).

Also, a broad range of compositions, powder types and dimension were explored. In this section, we mostly focus on a composite obtained from natural graphite flakes and molybdenum with the addition of mesophase pitch-based carbon fibres (MoGrCF): volume percentages in the green compact are 40% natural graphite (around 45 \( \mu \)m), 20% molybdenum (5 \( \mu \)m), 20% short carbon fibres (300 \( \mu \)m), 20% long carbon fibres (3 mm).

It is worth noting that in spite of the ceramic nature of molybdenum carbide, these composites remain attractive for applications requiring low electromagnetic impedance since MoC\(_{1-x}\) possesses a fair electrical conductivity (\( \sigma \approx 1 \) MS/m).

The most appealing properties were obtained from grades processed at temperatures around 2600º C: these materials were hence produced by Liquid Phase Sintering (LPS) since this temperature is above the melting point of molybdenum carbide, which, at the carbon content of the mixture (~88% C atom percentage), is at around 2580º C (Fig. 7).

One of the most outstanding features of several Metal- and Metal Carbide-Carbon composites, particularly when processed above the melting point of metals or carbides, is the high degree of carbon graphitization which can be obtained thanks to the catalysing effects of these additives: this phenomenon has been known since long time, but it was apparently extensively studied only in the ‘60s [10]. The basic mechanism of catalytic graphitization apparently depends on the transport of atoms through the liquid (carbide or metal), with graphite crystallite growing through molten material as graphitization proceeds. The addition of reactive metals, including molybdenum, to strengthen graphite and enhance graphitization was also first explored in the ‘60s [11, 12, 13].

As opposed to previous developments, mesophase pitch-derived carbon fibres were introduced: thanks to their well-ordered graphitic structure (Fig. 8), these were selected to act as structural reinforcement, nucleation sites for enhanced graphitization so contributing to the improvement of thermal properties and mechanical strength.
The microstructural analysis of MoGrCF, hot pressed at 30 MPa and maintained at 2600º C for 10 minutes, reveals a very homogeneous structure with a regular distribution of carbide particles and a strong orientation of carbon fibres (Fig. 9). To favour liquid carbide infiltration and material compaction rate a consistent quantity of molten carbides was allowed to flow out of the moulds during LPS, so that the final density of the material was reduced to 2.7 g/cm³, equivalent to ~7% carbides in volume (material grade MG-4110P). Specimens were obtained from 90 mm–diameter graphite moulds with specimen thicknesses ranging from 4 to 22 mm.

The carbide phase forms a fine dispersion of homogeneously distributed small grains wetting the graphitic matrix. SEM analysis in the direction parallel to the pressing direction, confirms the good homogeneity of the material and excellent wetting of both graphite flakes and carbon fibres, even if small, dense fibre aggregates can be identified (Fig. 10). The graphitic phase tends to orient in the direction normal to the pressing direction, giving birth to an orthotropic material.
The mechanical strength of MoGrCF composites was systematically measured at room temperature relying on four-point bending test, showing flexural strengths increasing with the amount of compaction, while it decreased with lower carbide contents. However, even with density as low as 2.7 g/cm³, an average flexural strength of 85 MPa was obtained thanks to the very good adhesion between matrix and reinforcement (Fig. 11).

The thermo-physical characterization of these materials is still on-going: preliminary measurements already provide outstanding results: the thermal conductivity measured at room temperature in the plane reached 770 W/mK, while the coefficient of thermal expansion between RT and 400°C was less than 2x10⁻⁶ K⁻¹. Results for the MG-4110P grade are summarized in table 2 (⊥ and // denote directions perpendicular and parallel to pressing direction, respectively).

The superficial electrical conductivity of MoGr can be substantially increased by cladding or coating the material with a thin layer of pure molybdenum: tests showed that excellent adhesion is obtained between Mo layer and MoGr bulk material thanks to the formation of a homogeneous carbide interface.

<table>
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<th>Symbol</th>
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<td>GPa</td>
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<tr>
<td>Flexural Strength (⊥)</td>
<td>Rf</td>
<td>MPa</td>
<td>85</td>
</tr>
</tbody>
</table>

Table 2. CF-reinforced Molybdenum Carbide-Graphite (grade MG-4110P) measured properties
Figure 1. Fracture surface of MoGrCF (sintered at 2200° C). Good bonding between fibres and matrix as well as cleavage fracture surface of carbides are visible. No sign of damage on fibre internal structure.

The HiRadMat-14 Experiment

As previously said, to probe and validate the constitutive models required for the advanced numerical simulations of extreme phenomena induced in matter by particle beams, a first-of-its-kind experiment [14] was carried out at CERN HiRadMat facility [15], entailing the controlled impact of 440 GeV proton pulses on specimens made of several different materials for BID. For a comprehensive characterization, experimental data were acquired relying on integrated instrumentation (strain gauges, temperature probes and vacuum sensors) and on remote-acquisition devices (laser Doppler vibrometer – LDV – and high-speed camera). The material sample holder consisted of a vacuum vessel and a specimen housing featuring 12 material sample tiers arranged in two arrays of six (Fig. 12). The housing could be accurately positioned via a two degree-of-freedom actuation system.

Specimens were made of materials currently used for BID such as Inermet 180, Glidcop Al-15 LOX and Molybdenum, as well as novel materials under development (MoCuCD, CuCD, MoGr and MoGrCF).

Two different specimen shapes were chosen for each tested material: 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. The number of specimens per tier varied as a function of the radiation and nuclear interaction lengths of the sample material (related to density).

The impacting proton pulses were constituted by trains of particle bunches at 440 GeV energy. Bunches had an intensity of up to 1.3e11 protons and were spaced by 25 ns. A pulse could include up to 144 bunches.
A very large amount of data was acquired online during the experiment. Measurements and numerical simulations were compared, both at medium and high intensity. In Fig. 13, hoop strains obtained from simulation are compared to values measured by three strain gauges placed on the external surface of Glidcop® specimens, circumferentially spaced by 90°.

The 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 Fig. 14, a large quantity of hot material was ejected at high velocity from the two most loaded Inermet 180 type 2 samples; the high temperatures reached are attested by the intense light emitted by the fragments during a few hundred microseconds. SPH mesh-less simulation results are consistent with camera acquisitions: both ejected particle front shape and velocity are
comparable with high-speed camera acquired data (Fig. 15), even considering the differences between real and the simulated scenarios. The acquired velocity of the fragment front is about 275 m/s, well matching the simulated velocity of 316 m/s.

Figure 14. Image sequence of the impact on Inermet of a 72 bunches proton pulse. Beam is coming from the left; three Inermet samples are partially visible (numbered 1 to 3).

Figure 15. Comparison between simulation (SPH method) and acquired image ~125 μs after the impact for Inermet specimens.

Post-irradiation observation allowed gathering valuable information about the beam impact resistance of tested materials.

Inermet experienced a brittle failure, with no signs of plastic deformation on the brim of the damaged area and on the flat surface. The low-melting point of copper and nickel probably played an important role in determining the extent of damaged zone.

The simulated damage extension is consistent with experimental observations (Fig. 16).

It is interesting to note that, for the same energy and intensity, no apparent damage can be observed on the surface of molybdenum specimens, if we except a surface crack generated on a less loaded specimen, for which metallographic investigations must be performed, once the tank can be opened (Fig. 17). A second pulse was shot on the same samples at double intensity with a vertical offset: a groove was this time produced on the surface of most loaded specimens; even so, its extension was still lower than in the Inermet case; figure also evidences a ductile fracture, with plastic deformation confirmed by metallic burrs still attached to the samples.
Figure 16. Post-irradiation observation of damage on Inermet provoked by impact of particle 72 bunches, 9.05e12 protons (left), compared to simulated failure (right). Note Inermet fragments on the lower plate ejected during the explosion, which were also captured in flight (4th frame in Fig. 14).

Figure 17. Thermo-mechanical effects produced on molybdenum by two pulses at different vertical positions: 72 bunches, 9.05e12 protons (same as Inermet) and 144 bunches, 1.96e13 protons.

High energy impacts (144 particle bunches, 1.96e13 protons) on MoCuCD led to extensive damages similar in size and pattern to those experienced by Inermet. On the other hand, while one sample of high density MoGr was damaged by the same impact, all MoGrCF survived without any apparent sign of damage (Fig. 18). It is to be noted that tested MoGrCF samples were solid-state sintered at 1700°C (3.7 g/cm³), since LPS-processed grades were not yet available at the time of the experiment. One can reasonably infer that the samples of material processed at 2600°C (such as MG-4110P), with lower density and higher thermo-mechanical properties could only perform better.

Besides experimental assessment of material robustness under high intensity beam impacts, additional tests are currently on-going in several laboratories in Germany, Russia and the US to evaluate material damages induced by long term particle radiation.
Figure 18. Post-irradiation picture of MoGr and MoGrCF impacted by 144 bunches \( \text{. The latter has a density of 3.7 g/cm}^3 \) and was processed at 1700° C by solid state sintering. Only MoGr samples show signs of damage.

**Conclusions**

Beam Intercepting Devices (BID) for last-generation particle accelerators, such as CERN Large Hadron Collider, must be designed to withstand the impact of intense particle pulses, safely operating over an extended range of temperatures in harsh environments. These requirements are to become even more demanding with the increase of machine performances expected in the near future, so that they can be hardly met by existing materials. The research of new materials for BID is therefore receiving great impulse in the High Energy Physics community with the goal to improve the cleaning efficiency and the robustness of BID.

A comprehensive R&D program has been started at CERN to develop, characterize and produce new composite materials to be used in the near future for BID and in particular for upgrades of LHC Collimators. These materials must satisfy multiple requirements as to density and average atomic number (cleaning efficiency), electrical conductivity (electromagnetic impedance), mechanical strength (impact resistance), thermal conductivity and thermal expansion (thermal stability). In this respect, composite materials combining the properties of carbon allotropes, graphite or diamond, with those of metals and transition metal-based ceramics were identified as the most promising.

Several materials were investigated: in this paper, the manufacturing methods, microstructures and properties of Molybdenum-Copper-Diamond (MoCuCD) and Molybdenum Carbide-Graphite-Carbon Fiber (MoGrCF) are reported.

MoCuCD exhibited excellent electrical properties and good mechanical strength; however its use at high temperatures is hindered by the softening of copper and the tendency to graphitize of diamond.

MoGrCF is a novel material in which mesophase pitch-derived carbon fibre where added to molybdenum and natural graphite flakes and hot pressed up to temperature of 2600° C in the presence of a liquid phase. The high temperature reaction between molybdenum and graphite promoted the complete transformation of molybdenum in refractory MoC\(_{1.5}\) while liquid carbides catalysed and enhanced carbon re-ordering and graphitization; carbon fibres also contributed to graphitization and increased mechanical strength. This led to outstanding thermo-physical properties, with thermal conductivity in excess of 750 W/mK and CTE below 2 ppm/K.
A complex and comprehensive experiment was carried out at CERN to characterize, mostly in real time, different materials, including tungsten heavy alloy, molybdenum, MoCuCD and MoGrCF under the impact of 440 GeV intense proton pulses. Measurements and damage observations well match results of advanced computations, providing encouraging indications on the validity of the constitutive models used for these materials. Results confirm that, so far, MoGrCF is the most appealing material to meet demanding Beam Intercepting Devices requirements. Although these materials are being developed primarily for High-Energy Physics, their properties might be appealing for a large number of applications and domains where efficient thermal management and refractoriness are an issue, such as high-end electronics, avionics, gas turbines, aerospace, advanced braking systems.

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References