# ANALYSIS AND ASSESSMENT OF POWDER METALLURGY TECHNIQUES FOR ARMOUR ELEMENTS PRODUCTION

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**Abstract**
The main aim of this work is to evaluate the possible application of powder metallurgy (PM) for the production of armour elements. Different materials were used, as starting base, consisting of pre-alloyed powders and powder mixtures with alloying elements like Mn, Mo, Cr, Ni and C.
Disc (ASTM G 99) specimens were compacted by applying a pressure of 700 MPa. The sintering was carried out in a vacuum furnace with rapid cooling applied from the sintering temperature, by means of nitrogen gas flowing with an integrated final tempering. The ballistic performance of the sintered steels was investigated against 7.62 x 51 mm NATO ammunition. The application of high sintering temperatures with rapid cooling appears to be a good option for the future extension of PM to the current commercially available (wrought) materials for the production of armour plates.

**Keywords:** Powder metallurgy, ballistic properties, armour, failure probability.

## 1 Introduction

The achievement of high performing sheets, in terms of good combination of properties, is commonly obtained from steels with martensitic – austenitic microstructure, where the great distortion imposed to crystal lattice is responsible of very good results commonly obtained in mechanical characterization [1-7].
Rolled and TRIP (Transformation Inducted Plasticity) steels, obtained from traditional metallurgic routes, are typical examples of products used when high performing steels are requested, as in the automotive sector or in a niche one, such as for the production of armours.
Armours, obtained from wrought steels, base their resistance to bullets on the combination of very high yield resistance, good ductility and hardness, so to obtain large plastic deformation as a mechanism to dissipate energy deriving from the impact.
Resistance against bullet impact is basically dependant to the thickness. Referring to UNI-EN 1522 normative, materials for armours are generally classified by the correlation between energy (proper of the bullet) and the thickness of the plate used.
The research in armour materials is currently focused on how to reduce the weight of the armours, to save energy and increase payload and mobility. Traditional armours are made of wrought alloyed steels ( carbon steel alloyed with Si, Mn, Cr, Mo, Ni), basically due to their high strength combined with good toughness, resulting in energy dissipation mechanisms, mainly based on the plastic deformation of the material.
Different techniques, such as heat treatment or metal forming processes (especially rolling) are used to increase the strength and ballistic protection level, resulting in reduction of thickness, and, finally, reduction of weight.

Ceramics reinforced materials were introduced over the years due to the convenient performances / weight ratio. Ceramics are, however, brittle and normally have to be backed by a laminate of high strength and high modulus; another disadvantage of ceramic armours is also related to their high cost compared to metallic armours.
A significant enhancement in the ballistic protection can be achieved when a hard ceramic layer is coupled to a metallic armour material. The resulting material is called laminated composite, and is capable of significant potential in reducing the weight of armour due to multifunctional components, providing outstanding protection level against conventional and non-conventional ammunitions [8-12].
Considering these aspects, powder metallurgy may provide a good opportunity for low cost high performing production.
High temperature sintering may however be necessary to reach high mechanical properties for the proposed application, coupled to high pressure compaction, effective in reducing porosity and increase density, allowing also to obtain good diffusion and bonding between powder particles. Mechanical properties are higher due to better carbon diffusion and reduction in both dimension and extension of porosities, resulting in better impact resistance, with good plastic deformation, and better hardness [13-17] thus causing a better penetration resistance.
Porosity (which is still present in the parts) acts as a defect into the structure that can fall in critical crack generation and propagation, both aspects that are not desirable for an armour element. Moreover, round shaped porosities, and the best possible diffusion, are mandatory, since from a strong bonding between particles leads to good cohesion and less tendency to dissipate energy creating cracks in spite of plastic deformation [13, 18-20].
In this paper the possible applications of powder metallurgy in the area of ballistic protection were investigated, with particular attention towards the armours for the protection of people, usually installed on transport vehicles.

## 2 Experimental

Different materials were used; consisting of commercial pre-alloyed powders and powder mixtures with alloying elements like Mn, Mo, Cr, Ni and C, see **Table 1**. In all studied materials 0.65 % of AW lubricant was added.
System M was prepared by mixing Distaloy LH, molybdenum, chromium and carbon powders.
System T was prepared by mixing Astaloy CrL, nickel and carbon powders.

**Table 1** The chemical composition of studied materials

| No. | Chemical composition ( wt. % ) of the investigated systems |
|---|---|
| M | 2.00 Mn; 2 Mo; 1.90 Cu; 1.25 Cr; 0.85 Ni; 0.35 C; bal. Fe |
| T | 1.50 Cr; 1.00 Ni; 0.40 C; 0.2 Mo; bal. Fe |

Discs (ASTM G 99) were obtained using 700 MPa compacting pressure. De-lubrication process was carried out in dedicated Nabertherm N120 furnace at temperature of 550 °C for 60 minutes, with continuous filled nitrogen atmosphere.
Sintering was performed in laboratory TAV vacuum furnace with a rapid cooling rate from the sintering temperature, applied within the cycle by means of nitrogen flowing gas, with an integrated final tempering.
The ballistic performance of sintered steel against 7.62 x 51 mm NATO ammunition was

investigated. Ballistic impact test was run following UNI-EN 1522. Only one shot was performed for every specimen and tests were repeated five times, with appropriate supporting system that eliminated the influence of the support itself to the mechanical resistance. The hardness and impact energy were evaluated on the samples, as well as macro and micro examinations on the impacted samples, to analyse the failure modes and correlations between mechanical properties and bullet resistance.

The apparent hardness HRA 60 (measured on the tested specimen surfaces) was determined by means of Rockwell hardness indenter; microhardness, HV 0.20, by means of digital tester LECO LM 700.

Microstructural and failure characterizations of the specimens were obtained by optical microscopy (OM) and scanning electron microscopy (SEM). Specimens for OM and SEM were prepared by conventional techniques of metallographic preparation.

Densities were evaluated using the water displacement method. Areal density was calculated according the equation (1):

$$A_D = \sum_{i=1}^{n} t_i \cdot \rho_i \quad \left[g \cdot cm^{-2}\right] \tag{1.}$$

Where: t – thickness of the armor components and ρ – density of the armor components.

## 3 Results

### 3.1 Failure probability

Ammunitions, used to test FB6 protection class, were hand added to comply technical data reported in normative:

- 7.62 x 51 mm NATO ammunition, Full Metal Jacket bullet, 9.5 g
- Muzzle speed of 830 ± 10 m/s

Finally, target distance, according to normative, was set at 10 ± 0.5 m.

FB6 NATO code is one of the ballistic protection levels stated in normative UNI-EN 1522. Codes start from category FB1 (lowest) reaching FB7 (highest) in relation to the ammunition used to execute the test.

In **table 2** pieces of information about perforation probability for the investigated steel specimens are provided. The failure probability of the specimens indicates how much percent of the specimens failed the test [21] under the impact of 7.62x51 mm NATO ammunition, according to FB6 class listed in UNI-EN 1522-1.

**Table 2** The perforation probability of studied specimens

| Type | Failure, on 5 tests | | | | | Failure probability, average |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | |
| M | Yes | Yes | Yes | Yes | Yes | System M = 100% |
| T | No | No | No | No | No | System T = 0% |

Ballistic resistance and deformation behaviour of the sintered steels changed with their areal density and hardness levels, **Table 3**.

**Table 3** Areal density and hardness of studied specimens

| No. | Areal density [g/cm$^2$] | Hardness HRA | Density [g/cm$^3$] |
|---|---|---|---|
| M | 9.745 | 56.48 | 6.961 |
| T | 9.965 | 58.12 | 7.118 |

*measured on the top surface of the specimens, thickness of 14 mm.

### 3.2 Microstructure

The application of high sintering temperature and rapid cooling rate determines dominant martensitic microstructures with some bainite areas, **Fig. 1** for system M. In the material T (**Fig. 2**), as for the system M, the rapid cooling condition also led to the formation of a mix of bainite and martensite. Moreover, the admixed nickel to the material supported the creation of nickel rich austenite areas.

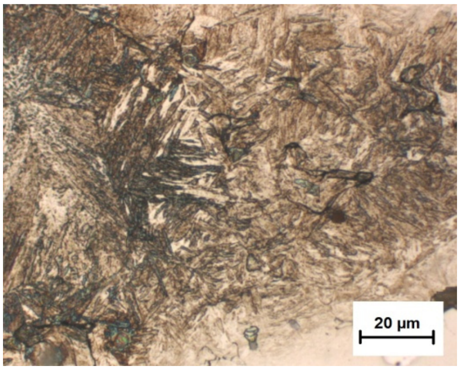


**Fig. 1** Microstructure of System M

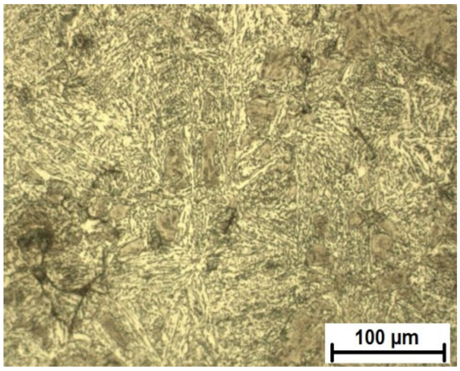


**Fig. 2** Microstructure of System T

### 3.3 Damage analysis

Impacts of sintered steel targets by a 7.62x51 mm NATO projectile at nominal velocities of ~830 meters per second resulted in the destruction of bullet.

Visual analysis reports that the outer jacket, made by copper alloy, had been lacerated, leading the inner, lead, core, being exposed and embedded into the cavity created by the impact (**Fig. 3**). SEM analysis confirmed considerations from visual analysis. Fracture surfaces pointed out a difference between the investigated materials (**Fig. 4** and **Fig. 5**). Investigation of the cavity revealed a bright white layer, made up of lead, which is the core of the bullet. **Fig 6** shows the molten lead, as an effect of high impact energy, revealing a large central interior residual lead projectile fragment. It is also possible to observe, in some different areas, parts from the jacket.

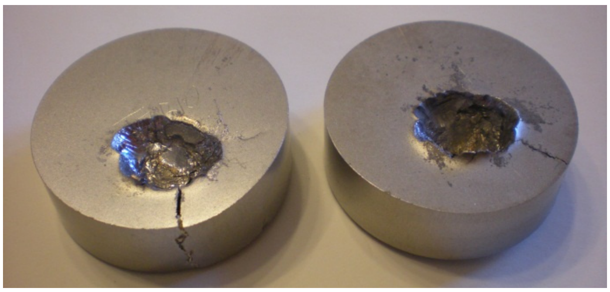

**Fig. 3** The damage of tested material ( System T )

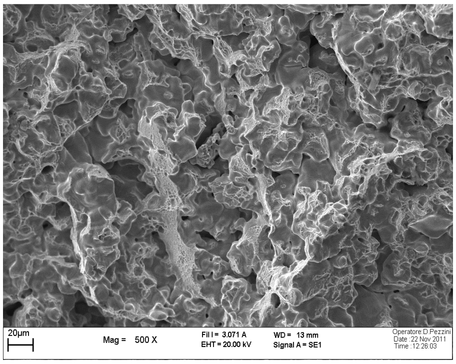


**Fig. 4** Fracture surfaces of System M

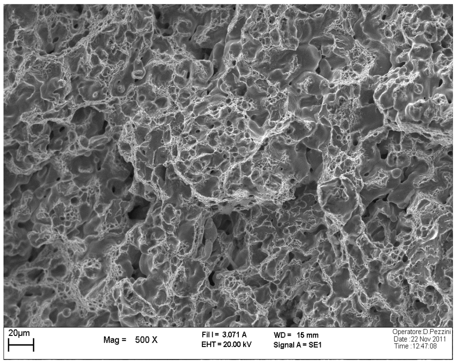


**Fig. 5** Fracture surfaces of System T

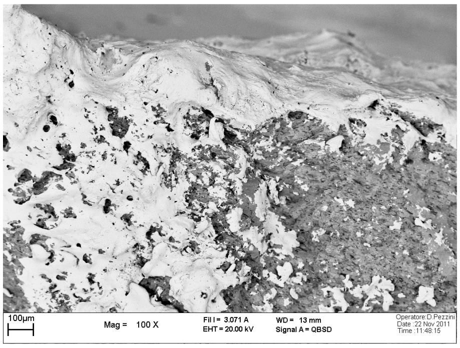


**Fig. 6** The damage of tested material ( System T )

## 4 Discussion

No extensive plastic deformation was observed near to the fracture detected for all tested specimens, since a large part of energy owned by the bullet is spent to remove material from the sample.Nevertheless, this dissipation mechanism takes place where it is not possible to have large plastic deformation, and is strictly related to the nature of the samples. This, in a microscopic analysis (Fig 4 and 5), is directly related to the brittle fracture mechanism rather than to the ductile fracture. In terms of energy absorption, hybrid structures (martensite, bainite, and austenite), typical of system T, show a clear advantage over dominant martensitic microstructures. The martensite phase formed a network structure surrounding the nickel rich austenite structure, which led to enhancing the ductility and toughness of the target.

In macroscopic analysis, several phenomena must be considered, since more aspects can have an influence on the behaviour of component. The chance provided by powder metallurgy, to fine tune the chemistry, can be detrimental if all variables are not considered regarding influence on the final mechanical properties.

Common armours from traditional metallurgy base their resistance on a balanced combination of surface hardness, plastic deformation in the impact area, and yield stress.

Sintered materials, in this field, offer in addition the opportunity of energy dissipation provided by the destruction of the whole network formed between powder grains during sintering. This dissipation method is clearly visible during the observation of the surface of cavity, appearing rough and matte.

The impact analysis shows different phases. Starting from the impact moment, surface hardness offers the first resistance to penetration. Plastic deformation starts in the same moment, and if the bullet has enough energy to beat the surface and start penetration, cavity starts to be created, with the mechanism reported above.

Given the brittleness of the failure mechanism, cracks are created; nevertheless, in case enough energy is dissipated following the aforementioned mechanism, the cracks do not became critical for the integrity of the sample, and no failure occurs.

In terms of properties, System T provided the the best protection against 7.62x51 mm NATO ammunition, showing good plastic deformation coupled to good energy dissipation mechanism. The lower ballistic performance of the system M is mostly due to its lower ductility and hardness in comparison to the system T.

SEM analysis confirms the differences in ballistic protection behaviour provided by bullet impact test. Brittleness, and weak bonds between particles, is clearly visible in System M, cleavage phenomena are large and diffused, and porosities are pointed and shaped. As for System T, cleavage phenomena are smaller and lower than for System M.

## 5 Conclusions

Results show that hardness can be one of the important parameters to reach good ballistic protection, but also ductility and toughness are very critical for protection: only a good combination of these properties is suitable for bullet-proof devices. PM steels, with qdequate hardness and deformability, can provide the formation of a cavity into the material, which is dissipating large part of the bullet energy. The process, however needs to be stopped within an acceptable thickness of the PM component, not to reach its failure due to crack propagation.

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