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Assessment of the Protective Properties of two Different UHA Steels Based on Material Testing and Numerical Simulation

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Abstract

The present contribution aims to assess the properties of ultra-high-hardness (UHA) armor steels. Characteristic of those steels are yield and tensile strengths reaching 1.6 and 2.0 GPa, respectively, and a hardness of around 600 Brinell or above. Accordingly, they are promising candidates for protective solutions. However, UHA steels are relatively new products and not yet frequently applied. Their potential for armor protection is not fully explored today and has to be investigated further. Ballistic testing of the protective properties of UHA steels is however limited by the commercially available material thicknesses. In the context of present applications, the available sheet thickness for UHA steel is typically below 15 mm, thus ballistic tests for some threat levels are possible only under overmatch conditions where failure mechanisms under shear and low confinement play strong roles. In order to be able to analyze the deep penetration into UHA materials – whether thick plates are today producible or not – we chose an approach based on material characterization and numerical simulation. Two different UHA steels were compared against a reference material from the high-hardness-armor (HHA) steel class. One of the UHA steels was a quenched and tempered steel, while the other was a maraging steel. Based on material testing, parameters for a non-linear equation of state, the Johnson-Cook plasticity model, as well as failure criteria for strain accumulation and wave induced spall rupture were derived and applied in hydrocode simulations of the perforation of thick steel plates by projectiles. From this numerical analysis, a consistent picture emerged. According to the simulations, the protective properties of the UHA steels are increased for thick targets compared to HHA, which was not directly inferable from ballistic tests.

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Keywords: UHA steel, quenched and tempered steel, maraging steel, material characterization, numerical simulation, protective properties

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1. Introduction

In the present paper, we investigate the properties of two different UHA steels. Variants of that material class may exceed values of 1.6 GPa for the yield strength, of 2.0 GPa for the tensile strength, and hardness numbers of 600 BHN. While the characteristics clearly indicate a general suitability for applications in ballistic protection, the recent development of those materials has been driven by an interest in lightweight solutions against small arms and fragments [1]. Accordingly, UHA steels are commercially available as relatively thin plates only, not allowing a direct experimental assessment of the ballistic properties of thick armor elements applied against projectiles from higher threat levels. Against those threats, UHA steels can only be tested in ballistic experiments under overmatch conditions. However, this implies conditions where failure mechanisms under shear and low confinement play strong roles, which differs from the processes occurring in the case of deep penetration. In order to be able to analyze the deep penetration into UHA materials – whether thick plates are today producible or not – we chose an approach based on material characterization and numerical simulation. Based on samples taken from thin UHA plates, quasi-static tensile tests and highly dynamic planar-plate-impact experiments were performed, in order to derive material parameters for hydrocode simulations. Afterwards, it was possible to make a first assessment of the protective properties by simulations for thick armor plates. In this sense, Section 2 starts with a short description of the considered materials. The material testing and the derivation and validation of simulation parameters are presented in Section 3 and Section 4, respectively. The application of the simulation parameters provides the numerical results of Section 5. A final discussion is given in Section 6.

2. Considered Materials

Two different steels from the UHA class were considered. As a reference material one HHA steel was also included in the analyses. The three materials are:

- ThyssenKrupp Secure 500, HHA steel, quenched and tempered – as reference material
- SSAB Armox 600, UHA steel, quenched and tempered
- DEW Ultrafort 6355, UHA steel, maraging steel

The quenched and tempered steels Secure 500 and Armox 600 could be considered as materials that fulfill typical armor specifications released by several countries for HHA and UHA, respectively. The material Ultrafort 6355 is a maraging steel and does not directly address military specifications. Some key parameters for the three steels are summarized in Table 1. The most important mechanical properties will be discussed in more detail based on the measured values in the next section. All materials were acquired by purchase and investigated independently.

Table 1. Designations, available plate thickness and typical material properties given by the manufacturers of the investigated steels [2], [3], [4], [5].

	Secure 500	Armox 600	Ultrafort 6355
Acronym	S500	A600	UF
Armor steel classification	HHA	UHA	UHA
Manufacturing process	Quenched/tempered	Quenched/tempered	Maraging
Available nominal plate thickness [mm]	7.3	10.0	9.5
Hardness range	480-530 HBW	570-640 HBW	56-60 HRC
Yield strength [MPa]	1300	1500	-
Ultimate tensile strength [MPa]	1600	2000	2300
Elongation at Fracture [%]	9	7	-