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Hypervelocity impact into a high strength and ductile steel alloy

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ABSTRACT

The unusual properties of nitrogen alloyed austenitic steels have been reported in the recent two decades in many papers. In this work it is aimed to investigate a P900 alloy subjected to a hypervelocity impact. The P900 alloy was work hardened to a medium hardness of 380 HV30 by cold expansion of a ring. Tungsten heavy metal and pure tungsten were used as projectile materials. The geometry of the long rods was 3 mm × 30 mm for diameter and length, respectively. Ballistic tests were performed with a two-stage light-gas gun at velocities from about 2000 m/s up to about 4500 m/s. It was found that two kinds of crater geometry are possible depending on the tendency of the projectile material to adiabatic shear banding or brittle fracture. The brittle *W* material achieved a deeper crater than the shear band forming *W* heavy alloy.

1. Introduction

In Ref. [1] it was shown that nitrogen alloyed austenitic steels have under dynamic loading a performance, which is considerably increased compared to the quasi-static properties. The ballistic protection capability was compared and found to be similar to that of a conventional armor steel at an impact velocity of 2500 m/s. Quasi-static and dynamic compression tests performed on P900 and conventional armor steel confirmed this result. Hardness measurements revealed an increased hardness around the crater of nitrogen alloyed steels, whilst the hardness of conventional armor steels did not change. In this work it is aimed to investigate the ballistic protective capability of nitrogen alloyed austenitic steels under high velocity impact ranging from about 2000 m/s up to about 4500 m/s.

Nitrogen alloyed austenitic steels are interstitially alloyed with a considerable amount of nitrogen. It is a relatively new group of material, which is still in development. Nitrogen has to be in solid solution and then it is resulting in unusual combinations of strength, toughness, corrosion resistance, wear resistance and non-magnetizability [2]. The solubility of nitrogen is increased by Cr, Mn, Mo and V and decreased by Ni and Si [3,4]. Nitrogen in solid solution prevents the formation of deformation martensite α' and enables a materials deformation of more than 95% without austenite becoming instable. It also leads to a plane arrangement of dislocations and the very low stacking fault energy due to the nitrogen content shifting the onset of mechanical twinning to lower strain. This micro mechanism extends strongly the plastic deformation capability, because the macroscopic plastic deformation related to dislocation gliding is limited. In Ref. [5] it is described how nitrogen alloyed steels may achieve the very high tensile strength of 3380 MPa due to work hardening and a thermal treatment.

The nitrogen alloyed austenitic steels are interesting because of their extraordinary mechanical properties. Nitrogen in solution increases not only the strength and ductility, but also strongly the internal friction resulting in enormously high strain rate sensitivity. These properties make nitrogen alloyed austenitic steels a potential candidate as an armor material, but which now must be studied under the conditions of ballistic impact/penetration.

2. Experimental setups

Quasi-static compression and tensile tests have been performed at room temperature on a universal test machine at strain rates of about $5\cdot \times 10^{-3}\,\mathrm{s}^{-1}$. Dynamic compression and tensile tests at strain rates ranging from $1\times 10^{3}\,\mathrm{s}^{-1}$ to $5\times 10^{3}\,\mathrm{s}^{-1}$ were conducted at room temperature using a split-Hopkinson-pressure-bar (SHPB) and a Hopkinson tensile bar. Compression tests specimens (5 mm in diameter and 4–5 mm in length) were cut from the P900 material using electro-discharge machining. Tensile specimens were turned on a lathe. Subsequently, the specimens were ground to obtain smooth surfaces. Prior to testing the compression test specimens were lubricated with ball bearing grease in order to reduce frictional effects.

Ballistic tests were performed with a two-stage light-gas gun at velocities ranging from about 2000 m/s up to 4500 m/s. The launch

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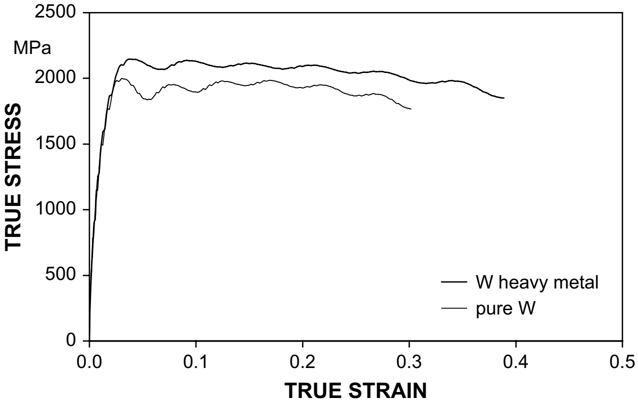


Fig. 1. Dynamic true stress–strain compression curves of the rod materials.

tube is 6 m long and has a caliber diameter of 30 mm. In the hyperballistic tunnel there was a pressure of 420 Torr. The geometry of the rods was 3 mm in diameter and 30 mm in length (L/D = 10). To determine hardness the Vickers test was used. It can be defined as indentation hardness testing that involves forcing a diamond indenter of square-based pyramidal geometry with face angles of 136° into the surface of the test material. Parameters used for the macroscopic hardness tests are a mass of 30 kg and a duration of 30 s.

3. Materials behavior

3.1. Long rod material

Rods consist of a tungsten heavy metal ($W = 94\%$, density = 17.85 g/cm^3), which tends to create adiabatic shear bands (ASB). For comparison to rods showing brittle behavior pure tungsten was used. The dynamic true stress–strain compression curves of the rod materials are shown in Fig. 1. Pure *W* possesses a compression strength of 2000 MPa, while *W* heavy metal exceeds slightly the compression strength of 2000 MPa. *W* heavy metal fractures due to ASB, while pure *W* fractures brittle.

3.2. Target material

A nitrogen alloyed austenitic steel designated X8 Cr Mn N 18 18 (ASTM A289, DIN-Code 1.3816) was employed for the targets. This alloy is well known as P900. The chemical composition of the investigated nitrogen alloyed steel is shown in Table 1. The steel alloy was supplied in cold worked condition (cold expansion) up to a macro hardness of 380 HV30 in average. Some specimens from this alloy were solution annealed. In the solution annealed condition the average Vickers hardness amounts about 280 HV30. Some of the solution annealed specimens have been cold rolled to macro hardness exceeding 400 HV30 strongly and a few were subjected to a strain aging at 500 °C for 10 min in order to increase further the strength.

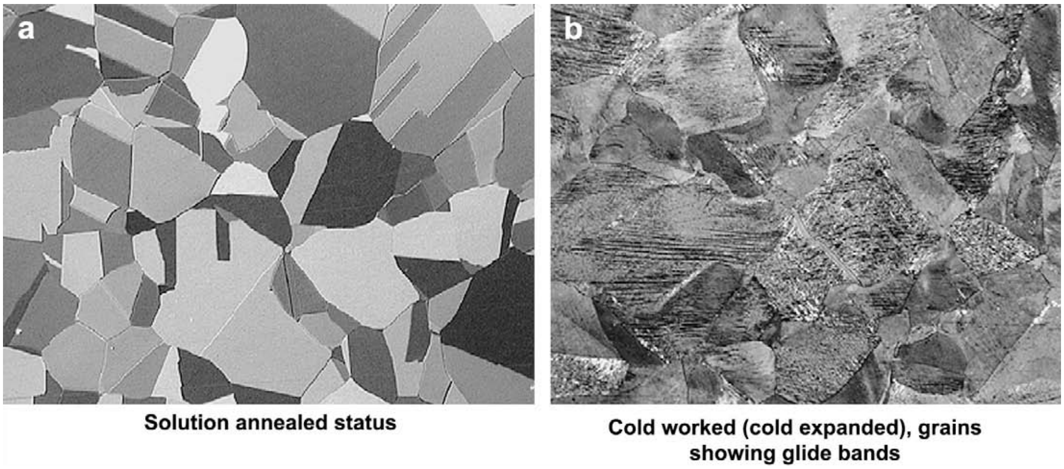
Table 1
Chemical composition of the investigated steel (weight %)

P900	C	Si	Mn	Cr	N
	0.033	0.3	19.02	18.4	0.62

The microstructure of the P900 in the solution annealed status can be seen in Fig. 2a. Fig. 2b shows the microstructure in the supplied cold expanded status. It is characterized by slightly deformed grains and a high density of glide bands. Fig. 3 summarizes the quasi-static tensile tests for different treated P900. The tensile specimen in the solution annealed condition possesses a macro hardness of 251 HV30. It has a long uniform strain about 40% and strain hardens from 600 MPa to about 1300 MPa. Work hardening is increasing the yield stress strongly, but reduces the uniform strain and the strain hardening. The onset of striction is shifted to lower strains. The stress–strain curves obtained by dynamic tensile tests are shown in Fig. 4. By increasing the strain rate the yield strength is significantly augmented. The results obtained from quasi-static compression tests on P900 are shown in Fig. 5. The compression yield strength is strongly increased by cold working.

An additional strain aging of strongly cold worked samples increases the compression yield strength further by pinning of dislocations. Hence, this mechanism which only works effectively after a severe deformation, is a powerful way of increasing the compressive strength. Since none of the specimens was fractured during quasi-static compression, there is sufficient deformability up to a hardness of 510 HV30 under quasi-static conditions. Fig. 5 also shows that strain hardening decreases with increasing cold working. Fig. 6 summarizes the results of dynamic compression tests with alloy P900. It is obvious that the dynamic compressive yield stress is considerably higher than the corresponding quasi-static yield stress.

Since nitrogen in solid solution increases the internal friction of the lattice [4], the strain rate sensitivity increases. The dynamic compression yield stress of the solution annealed specimens is



Solution annealed status

Cold worked (cold expanded), grains showing glide bands

Fig. 2. Microstructure of nitrogen alloyed steels.