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JOINING JACKET AND CORE FOR JACKETED STEEL/TUNGSTEN PENETRATORS

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In first generation KE rounds a heavy metal core was embedded in a reinforcing jacket. Then came the self-supporting cores using heavy metal technology, leading to today's aspect ratios of 30. Increasing the aspect ratios towards 40 is extremely difficult, the bending stiffness of such tungsten cores becoming insufficient in view of launch and terminal ballistics. Therefore, the previous reinforcing method has to be applied again.
This paper treats the design of load transferring jacket/core joints.
Three joining methods have been tried out: shrinking/bonding, forging and build-up welding. All three methods were investigated analytically and experimentally. Jacketed penetrators of L/D = 40 were produced with all three methods and fired.
The shrinking/bonding joint does not achieve the expected basic values. The joints applied with the build-up welding and the forging technique performed well in test firings with different calibres.

INTRODUCTION

As shown in [2], tungsten cores with $L/D \cong 40$ can successfully be launched with a conventional high pressure gun, if they are reinforced by jackets of light and stiff materials. For an appropriate support the proportions of jacket and core should be related as

$$\frac{D^4}{d^4} = \frac{E_C + E_J}{E_J}$$

D : jacket dia
d : core dia
E_J : Young's modulus of jacket
E_C : Young's modulus of core

Composite steel/tungsten penetrators with these proportions already have demonstrated good terminal ballistic behaviour in various target materials as well as in spaced armour [3], [4]. In the course of the various test firings it became obvious that the joint of core and jacket is one of the main problems in composite projectile design.

At SW we therefore initiated some fundamental experiments around joining core and jacket.

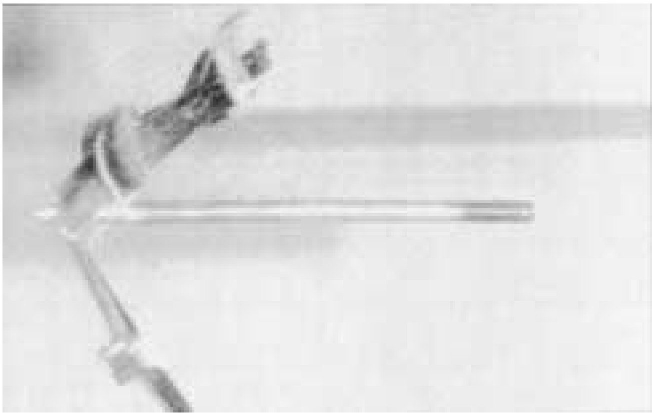


Figure 1. “The Lonely Jacket”. The problem Sabot-parts discarding from the steel jacket; tungsten core and fins are left behind (disassembled) due to insufficient joint properties of core/jacket.

First the acceleration forces and then the shear loads at the penetrator were determined. The load value limits the number of feasible joint designs. The required minimum shear stress τ can be calculated with the formula shown in Fig. 2. The joint between the jacket and the core should withstand at least a shear stress of about 40 MPa. Three methods for manufacturing of joints, including their test results, are presented.

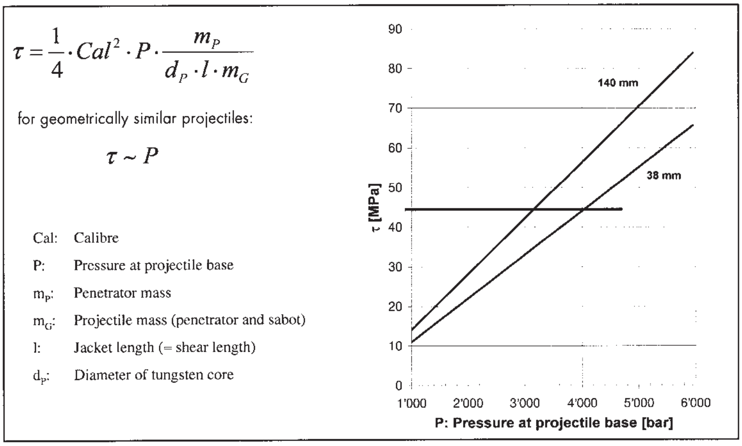
SHRINKING/BONDING

Structural bonding is a well proven technology. A short literature study shows that modern adhesives for metal applications have a shear strength of about 25 MPa which seems to be insufficient for our application. Otherwise, a design rule found for structural bonds under permanent loading mentions to use only a maximum shear stress of 7 MPa.

Former work on hub/axle assemblies [1] shows that the combination of shrinking and bonding can increase the shear resistance to more than 45 MPa – almost twice as bonding only – which should be acceptable for jacketed penetrators up to a reasonable pressure level.

This technique is used especially for short cylinders with large diameters like in the traditional shaft-hub combinations or for fixing bearings. The goal was to analyse this technology for long and slender applications in jacketed penetrators.

The first step was to estimate the required minimum shear stress between the tungsten core and the steel jacket. Our assumption is that the joint has to withstand the maximum acceleration generated by the gas pressure behind the projectile.



$$\tau = \frac{1}{4} \cdot Cal^2 \cdot P \cdot \frac{m_P}{d_P \cdot l \cdot m_G}$$

for geometrically similar projectiles:

$$\tau \sim P$$

Cal:	Calibre
P:	Pressure at projectile base
m_P:	Penetrator mass
m_G:	Projectile mass (penetrator and sabot)
l:	Jacket length (= shear length)
d_P:	Diameter of tungsten core

Figure 2. Required minimum shear stress.

The variables for the masses and the geometry can be transformed into a function of the calibre. Thus a given penetrator is proportionally scaleable to the calibre. Then the shear stress is directly proportional to the pressure.

The 45 MPa shear strength mentioned earlier seems to be practicable at least for the 38 mm calibre test projectile.

The result of a test series of different bonding systems was compared with simple bonding and shrinking joints. Fig. 3 shows a summary of the shrinking/bonding tests. The test set-up is illustrated in Fig. 6. The geometry of the test series was closer to the jacketed penetrator than the shaft-hub assembly. The diameters were equal to the full scale penetrator. The length was given by the maximum available force of the existing test machine.

The jacket was made of thermally treated maraging steel, yield strength ≅ 2000 N/mm2, the core consisted of high strength tungsten with a yield strength of 1700 N/mm2.

Three different types (A, B and C) of adhesives were used. The shrinking/bonding (S/B) specimen (the first 3 bars on the left) had a light shrinking pressure based on the values given in the literature.

Two additional reference series were made with a standard bonding (second from right) and a standard shrinking combination (bar on the right). The small black lines show the dispersion.

The shrinked version has about twice the strength of the other versions. It is clear that the achieved strength values – based on the elastic limit – are well below those mentioned in the literature. This might be due to the different geometry and/or the adhesion problem of the tungsten surface. All specimens were pushed at a velocity of 1 mm/min.

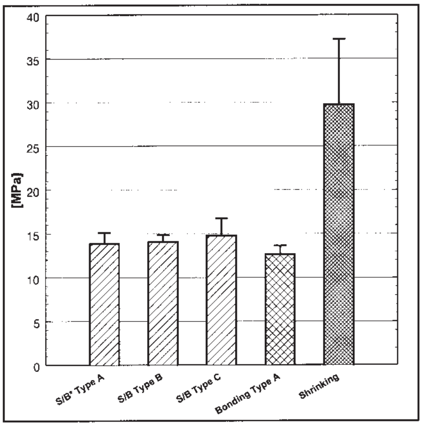


Figure 3. Results of bonding tests.

The test gun (Fig. 4) is a 35 mm anti-aircraft gun with an extended chamber and barrel, which was modified to a 38 mm smoothbore calibre. The firing at a relatively low pressure of 2200 bar was successful. The pressure at the projectile base is lower – but looking at Fig. 3 a shear strength of about 15 MPa was very close to the pressure limit. Another firing with 3400 bar breech pressure lead to a definite failure.

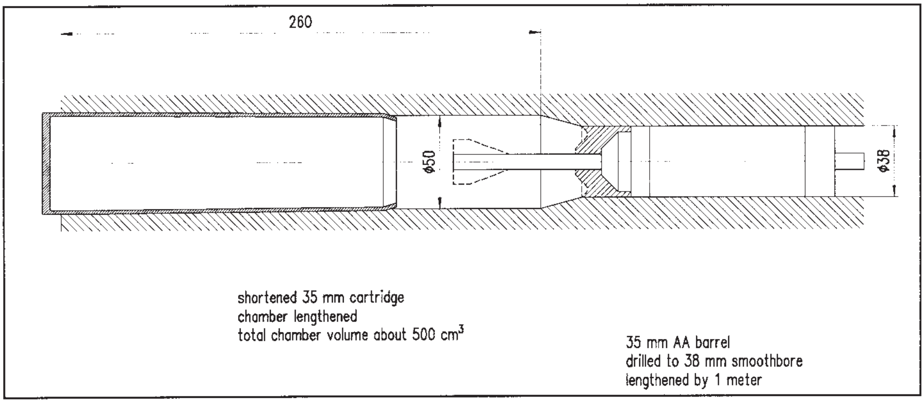


Figure 4. 38 mm Test Gun.

FORGING

One practicable concept of applying the reinforcing jacket onto the core is by means of a cold forging machine. In the first stop the jacketed penetrator is planned for an application on a 38 mm calibre test gun. Besides the transformation degree of the sleeve special attention has to be given to the core design.

The Core

The tungsten core is designed with grooves to resist the high load transfer due to the firing acceleration. The tungsten rod should have a tensile strength of at least 1600 N/mm^2 in order to avoid deformation during the forging process. Before forging the surface of the grooves should be polished and cleaned.

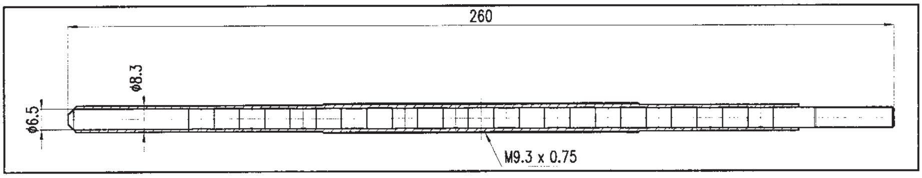


Figure 5. Jacketed penetrator after machining.

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The Jacket

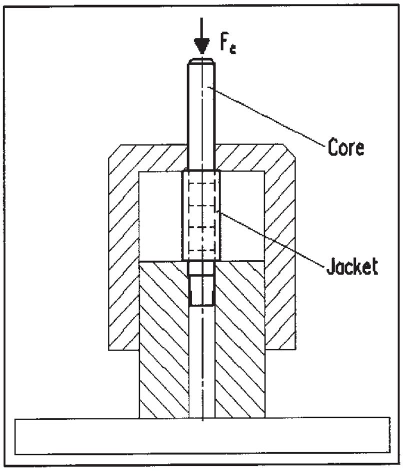
After forging the sleeve has the desired outline (Fig. 5), which fits the sabots as well.

Thermal Treatment

After machining the outer part of the jacket, the core/jacket system is subjected to an ageing process at 480°C during 3 hours. Thereby the ultra-high-strength properties of the jacket are obtained. This thermal treatment leads to a slight shrinking of the jacket and therefore to an improved load transfer in the joint.

On the cross-section of the sample hardness measurements were done. Thus the measured values gave us information for the further steps to go. The heat treatment approximately doubled the jacket hardness.

Force Measurements



Figur 6. Push-test device.

Measurements on test samples were done before firing the ammunition with the jacketed penetrator.

This test device (Fig. 6) was used in order to find out the force limits of the joints.

For the evaluation of the joint quality the push-out-test is determining.

Push-out tests with different groove shapes were executed. Stress concentrations on the core must be avoided. The surface of the core was therefore also polished

Table 1 shows the “shear stress” τ, derived from the joint of the jacket and the core. These converted values show at least 50 N/mm^2. It is remarkable that no sudden slipping of the core has been located after achieving the maximum of the compression strength.

Table 1. Results of the push-test

Sample No.	η [%]	W_G [mm]	N_G [-]	**L** [mm]	F_c [kN]	τ [N/mm^2]
1.1	6	5	2	20	25	61
1.2	6	5	2	20	25	61
4.1	3	10	1	20	25	61
4.2	3	10	1	20	25	61
V1	5.5	8	2	32	33	50
V2	5.5	8	2	32	39	59

Some definitions used in Table 1:

Deformation Degree: $\eta = \left(1 - \frac{D_2}{D_1}\right) \cdot 100$

Shear Stress: $\tau = \left(\frac{F_c}{\pi \cdot d \cdot L}\right)$

D_1: Jacket outer diameter before forging
D_2: Jacket outer diameter after forging
d: Core diameter
W_G: Width of the grooves
N_G: Number of grooves on a core test sample
L: Length of a core test sample
Fc : Compression force

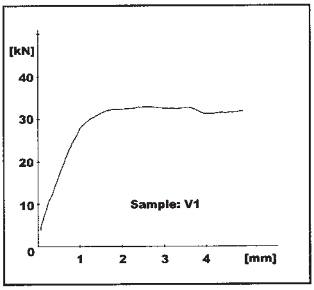


Figure 7. Compressive strength vs time.

The push-out is adjusted to 0.5 mm/min. Fig. 7 shows the force behaviour when pushing out the core sample according to test sample V1 as mentioned in Table 1. The other test samples show higher values of τ.

Microscopic Assessment

The optical observation on the longitudinal section of the sample is an important point. Gaps between core (bright area) and sleeve (dark area) would indicate a poor forging quality. Fig. 8 presents the perfect joint by forging.

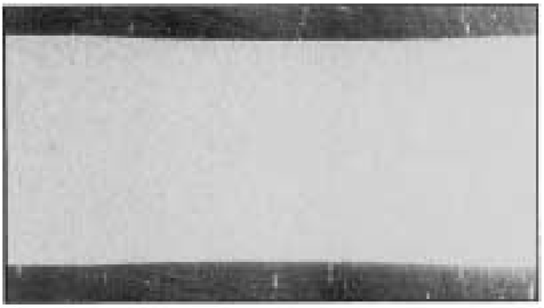


Figure 8. Longitudinal section through the groove.

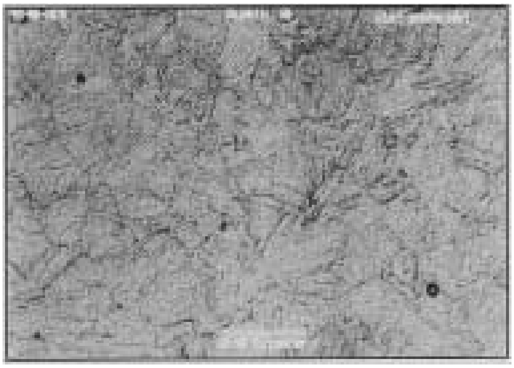


Figure 9A. Material structure before forging.

After the thermal treatment micrographs of the jacket material were made and compared with its former condition (Fig. 9A, 9B and 9C). It is visible that the material structure of the jacket is becoming finer.

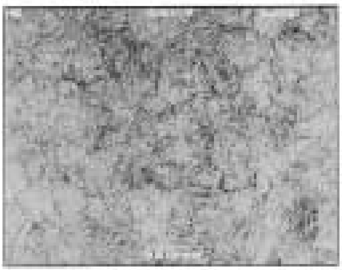


Figure 9B.
Material structure after forging is getting finer than before.

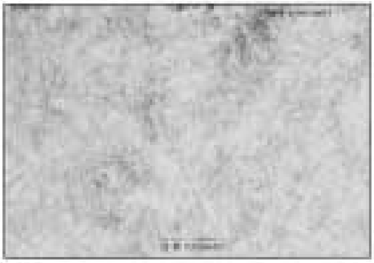


Figure 9C.
Material structure after forging and thermal treatment.

Firing Test

During the firing test the measured gas pressures ranged from 4500 to 5000 bar. The muzzle velocities were 1550 to 1600 m/s. Problems due to insufficient joint between the core and the jacket did not occur. The ballistic performance of these jacketed penetrators seems to be satisfactory too. Fig. 10 shows the complete ammunition.

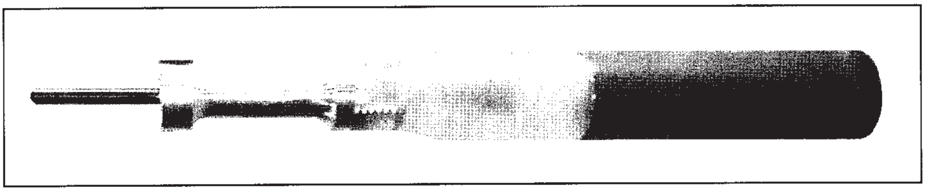


Figure 10. Round ready to fire.

BUILD-UP WELDING

Further investigations concerned stiffening the slender tungsten core by build-up steel welds in view of increasing shear load transfer. The experiences published in [5] were very helpful for our research.

Initially the weldability of sintered tungsten was proved using a cheap austenitic welding wire. A hard metallic compound was formed, its strength was confirmed by pushout tests. The tungsten surface was melted and an undercut existed like those of build-up welds on steel shafts. A sharp line separated the weld and the sintered tungsten. Individual tungsten particles were washed into the weld.

Three different brands of maraging welding wire were available, two flux cored wires and a solid one. Non-aged build-up weld samples using flux cored wires partially showed extensive separations in the boundary layer. To find the reason for this phenomenon the pure weld metals were tested. The non-aged solid wire metal proved to be ductile with 12.5% elongation at break and 50% area reduction whereas the flux cored wire metals always exhibited brittle ruptures. Moreover the tensile strength was very low, a mere 970 MPa. Ageing improved this considerably, after one hour of heat treat-ment this value reached 1400 MPa. However elongation at break and area reduction scattered unacceptably.

So far in the maraging steel tests the transferred welding heat had not been taken into consideration. As shown in Table 2 monitoring the interpass temperatures reduced the scatter of the tenacity values.

sample	yield strength $R_{p0.2}$	tensile strength R_m	elongation at break A_5	area reduction Z
solid wire	1315 MPa	1540 MPa	10.5 %	29 %

Table 2. Tensile tests of pure weld metals with controlled interpass temperatures and ageing (mean values of 4 samples)

Both controlling the interpass temperatures and an appropriate welding process allow the design of jacketed projectiles suitable for very high gas pressures. Multiple firings proved the ability of build-up welded jackets to withstand both the acceleration forces in the barrel and the deceleration forces in a spaced armour target (Fig. 10).

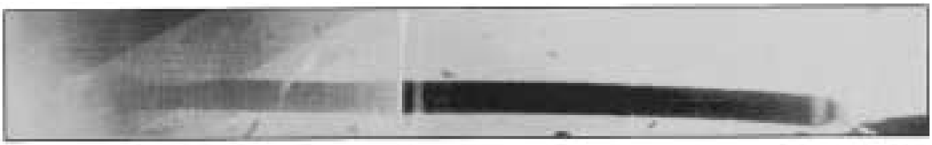


Figure 10. Big caliber L/D = 46 steel-jacketed tungsten rod after penetration of 2x25 mm RHA / 30° double skirt. X-Ray by GR FA26 Thun.

CONCLUSIONS

Three methods for joining core and jacket of slender KE projectiles were investigated both analytically and experimentally.

Jacketed penetrators of L/D = 40 were produced with all three methods and fired. These investigations and tests lead to the following conclusions:

- The shrinking/bonding joint does not achieve the values mentioned in the literature. With about 15 MPa shear strength they are far below the prospected 40 MPa. A test firing with 38 mm calibre shows a clear failure at 4000 bar projectile base pressure.
- The joints applied with the radial forging technique performed well in test firing with 38 and 140 mm calibre up to 4000 bar. Failures (see Fig. 1) occured occasionally.
- Build-up weld joints were produced in the full scale calibres only (120 / 140 mm), these resisted base pressures of more than 5000 bar without failure.

From the metallurgical point of view the favourite method would be forging. Its suitability for highest pressures of > 6000 bar has yet to be proved. Further investigations in this respect are planned.

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