

## BULLET DENTS – “PROOF MARKS” OR BATTLE DAMAGE

POR

ALAN WILLIAMS, DAVID EDGE, TONY ATKINS\*

### ABSTRACT - RESUMEN

It is well known that the breastplates of many armours from the later 16<sup>th</sup> century and the 17<sup>th</sup> century bear the hemispherical dents generally known as proof marks. It has been taken as axiomatic that these marks were made in order to demonstrate the armours' effectiveness against firearms.

If however some of these dents are compared with dents which are the result of battle damage, it appears that they were made by energy levels of a different order of magnitude, and offer little guarantee as to the “proof” of the armour.

Como es bien sabido, muchos petos de armaduras de finales del siglo XVI y del XVII tienen abolladuras semiesféricas conocidas como pruebas de arcabuz. Se ha considerado axiomático que estas abolladuras fueron hechas para demostrar la efectividad de las armaduras frente a las armas de fuego.

Sin embargo, si se comparan con otras debidas a daños en combate, parece que fueron producidas por energías de diferente orden o magnitud, al tiempo que ofrecen pocas garantías como “pruebas” de las armaduras.

### KEYWORDS - PALABRAS CLAVE

Firearm. Armour. Bullet dent. Proof mark. Munition.

Arma de fuego. Armadura. Prueba de arcabuz. Munición.

Ffoulkes relates, quoting many examples, how suits of armour were tested with the cross-bow in the 14<sup>th</sup> and 15<sup>th</sup> century and with firearms in the 16<sup>th</sup> century (Ffoulkes, 1912). Some customers did not rely only on tests made by the makers of the armour. The Emperor Maximilian II was recorded as testing his own armour himself “with pistol and arquebus shots” in 1561 (Gamber, 1972). Greenwich armour was apparently expected by Sir Henry Lee, in 1590, to withstand the impact of a pistol bullet, and suffer little more than a dent. Of course, Greenwich armour, like that of Innsbruck, was a high quality product made of steel hardened by quenching and tempering. Large quantities of armour were made in the 17<sup>th</sup> century, especially during the period of the Thirty Years' War, and referred to as “pistol proof”. This was generally armour of modest quality which achieved any success in protection by its thickness. Ffoulkes quotes an account by the Verney family of 1667:

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\* Alan Williams (Visiting Research Fellow in the Department of Engineering at Reading University), David Edge (Head of Conservation at the Wallace Collection, London), Tony Atkins (Professor of Mechanical Engineering at Reading University). The Wallace Collection, Hertford House, Manchester Square, London W1U 3BN, United Kingdom.

“Richard Hals is choosing some armour for his cousin in London; he has tested it with as much powder as will cover the bullet in the palm of his hand...” (Verney wished to have the armour tested again, but the armourer refused) “...it is not the custom of workmen to try their armour after it is faced and filed.”

## FIREARMS

The recent work of Krenn (1990) has given us a very detailed picture of the performance of contemporary firearms. He tested a selection of pistols, and muskets from the very numerous collections of the Graz Zeughaus (Arsenal), on an instrumented Austrian Army firing range, using modern gunpowder. Such powder corresponds to the “corned” powder (of uniform grain size) which displaced “serpentine” powder (of variable grain size) during the 16<sup>th</sup> century. The use of serpentine powder would have reduced the muzzle velocity by about 30 to 40%, and hence the available kinetic energy by up to half (Williams, 2003, 921).

Some of his results included:

- A Nürnberg wheellock pistol of c1620 had a muzzle velocity of 438 m/sec, and a muzzle energy of 917 J.
- A wheellock carbine of 1593 from Suhl had a muzzle velocity of 427 m/sec, a muzzle energy of 988 J, and a bullet velocity at a distance of 8.5 m from the muzzle of 406 m/sec.
- A 17<sup>th</sup> century matchlock arquebus from Styria had a muzzle velocity of 449 m/sec, and a muzzle energy of 1752 J. This velocity diminished to 428 m/sec by 8.5m, and hence the energy diminished to 1592 J. But it was observed that at 100m the bullet still retained enough energy to put a lead bullet (17g) through 1 mm of mild steel sheet. Even more powerful was a 16th century musket (with a 1 m barrel) which had a muzzle velocity of 456 m/sec, and a muzzle energy of 3125 J.

## RESULTS OF EXAMINATION OF BULLET DENTS ON CUIRASSIER’S ARMOURS

There are a series of “three-quarters” cuirassier’s armours dating from the second quarter of the 17<sup>th</sup> century which bear almost identical “proof marks” in very similar positions on the right side of the front of the breastplate, near the central keel, and some of which bear Nürnberg city marks. There is one, now polished bright, in the Wallace Collection, London (A.65) and others, still remaining blackened, in the German Historical Museum, Berlin (DHM), the Bavarian Army Museum, Ingolstadt, and the West Bohemia Museum, Plzeň.

### *Wallace Collection, London (A.65)*

1. The average thickness of the breastplate at the centre is 3.7 mm
 

Left side edge	= 2.8 mm;	Left lower edge	= 2.7 mm
Right side edge	= 3.2 mm;	Right lower edge	= 2.8 mm
Upper edge	= 2.9 mm;	Weight	= 5.2 kg
2. Dent - diameter = 10.3 mm
3. Dent - depth = 3.8 mm
 

Vertical height from neck opening to fauld	= 37.5 cm
Circumferential width from one side to the other	= 48.5 cm
Approximately, surface area	= 1800 cm <sup>3</sup>

The area of the breastplate, and its weight, also suggest an average thickness of 3.7mm, which is close to that determined at the front, where the bullet impact is to be found.

$$\text{Average thickness} = \frac{\text{Weight}}{\text{Area} \times \text{density}} = \frac{5200 \text{ g}}{1800 \text{ cm}^2 \times 7.9 \text{ g. cm}^{-3}} = 0.37 \text{ cm}$$

The microstructure of the breastplate was also determined, and found to consist simply of ferrite and slag, in short, a wrought iron.

Microhardness (100g load) range 112-142; average = 131 VPH.

*Deutsches Historisches Museum, Berlin (DHM 1989/2564/3)*

1. Average thickness of the breastplate = 3,78 mm.
2. Diameter of the dent = 10,69 mm.
3. Depth of the dent = 4,44 mm.

The microstructure of the breastplate was also determined, and also found to consist simply of ferrite and slag (Williams, 2003, 673).

Microhardness (100g load) range 195-236; average = 211 VPH.

It is notably hard for a wrought iron, but etching with Oberhoffer's reagent, which does not deposit copper on high-phosphorus areas, suggests a higher than average phosphorus content.

*Bavarian Army Museum, Ingolstadt (BAM A.11668)*

This armour has a dent exactly in the centre of the breastplate.

1. Average thickness of the breastplate = 3 mm.
2. Diameter of the dent = 11 mm.
3. Depth of the dent = 3.7 mm.

The microstructure of the breastplate has not been determined, but is assumed for the purposes of these calculations also to consist of ferrite and slag.

The microstructure of the breastplate of a very similar armour in the West Bohemia Museum, Plzen, was also determined, and also found to consist simply of ferrite and slag (Williams, 2003, 676). Indeed, it seems that most 17<sup>th</sup> century armour was made merely of iron, and relied on its thickness alone, rather than metallurgical sophistication, to defeat missiles.

Apparently these armours were all intended, or at least purported, to be bullet proof, since they all bear the indentation of a bullet in the centre of the breastplate. Would they have actually resisted the weapons of the performance established by Krenn's experiments? Before attempting to answer this question, it was thought worthwhile to compare the “proof mark” struck on these armours with other dents, some of which from their position were certainly due to battle damage, on armours from the collections of Vienna and Madrid.

*Results of examination of bullet dents on armour in Hofjagd- und Rüstkammer, Vienna, 2004*

Dents are assumed to be circular unless specified otherwise. The dimensions of oval dents have been averaged. The diameter is given first, and then the depth of indentation. The thickness of the breastplate at its front (*in the vicinity of the dents*) was measured with a dial gauge. In Madrid, the thickness was measured with a vernier caliper. Ultrasound was not used here for thickness measurements because of the common occurrence of laminations. Surface hardness, as well as microhardness, is quoted to show that the metallography is representative. Where there is more than one dent, they are labelled ...a, b, c, etc.

Those dents which have diffuse rims are identified as **D**. The calculation of impact energy for such dents is more complex, as discussed below. The presence of a sharp rim to the dent is suggestive of the use of a cast-iron bullet. Indeed, Biringuccio describes in 1540 the making of both *cast iron* and *wrought iron* as materials for bullets (1959: 321). Where a deforming bullet has been used, then the bullet energy must have been *greater* than the figures quoted here, as a part of its kinetic energy was used up in deforming the bullet, as well as deforming the armour.

**A.831.** Armour of Gianettino Doria; North Italy, c.1545.

Extent of dent: 30 x 34 mm, depth 4.7 mm **D**.

Thickness of other parts: breastplate sides 2.6-4.5, av. 3.8 mm.

Breastplate weight: 6.5 kg. Backplate weight: 1.4 kg. & thickness 1.3 mm.

Burgonet weight 2.3 kg. Surface hardness 125-210 VPH.

Metallography: a sample was taken from the turned rim at the top of the breastplate.

The microstructure consists of equiaxed ferrite with some areas of coarse pearlite partly divorced and arranged in bands (corresponding to a carbon content of around 0.1%C overall). There are also a few slag inclusions.

Microhardness (100 g load) range 105-163; average = 135 VPH.

**A.1203.** Armour of Ascanio della Cornia; North Italian, c.1560.

Extent of dent: 15.7 x 3.6 mm **D** Thickness at front 4.9 mm.

Thickness of other parts: breastplate sides 2.1-5.0, av. 4.0 mm. Breastplate weight: 7.8 kg. with tassets 9.7 kg. Backplate weight: 3.9 kg.

Surface hardness of breastplate 142-168 VPH.

Surface hardness of backplate 184-210 VPH.

Metallography: a sample was taken from the turned rim of edge at top of breastplate, in section. The microstructure consists of equiaxed ferrite, with little or no pearlite visible. The carbon content is perhaps 0.1%C. There are also some slag inclusions, and cavities.

Microhardness (100g load); range 178-204; average = 191 VPH.

**A.1043.** Armour of Francesco Duodo; North Italian, c.1570.

Extent of dent: 11.8 x 2.2 mm **D**.

Thickness of other parts: breastplate sides 2.1-3.9, av.2.8 mm.

Breastplate weight: 4.9 kg. incl. tassets.

Metallography: a sample was taken from the upper turned rim. The microstructure consists of ferrite and a little pearlite, corresponding to a steel of about 0.2%C.

Microhardness; range 140-164; average = 152 VPH.

**A.1280.** Armour of Galeazzo Fregoso, Count of Mureto; Italy 1575-80.

Extent of dents:

(a) 18.5 x 2.8 mm **D**.

(b) 18.4 x 2.9 mm **D**.

Thickness of other parts: breastplate sides 3.1 - centre 4.1 mm.

Breastplate weight: 7.0 kg. Helmet weight 4.3 kg. Backplate weight: 9.2 kg.

Metallography: a sample was taken from lower rim of the lower visor of the helmet

The microstructure consists of equiaxed ferrite mixed with varying amounts of rather divorced pearlite areas (corresponding to a carbon content of perhaps 0.3%C overall). There are also a few elongated slag inclusions.

Microhardness (100g load); ranges from 164-279, depending on C%;

Average = 183 VPH.

**A.1656**

Plain infantry armour with marks of Köln and maker WT [helmet] V; with 3 dents as well as dent in helmet. c. 1575.

Extent of dents: (a) 13.2 x 1.9 mm **D**.  
(b) 13.5 x 1.1 mm **D**.  
(c) 14.6 x 1.8 mm.

Thickness of other parts: Breastplate at front: 7.7 mm.

Breastplate weight: 12.3 kg. Backplate weight: 9.2 kg.

Surface hardness = 138-190, av. 173 VPH.

Metallography: a sample was taken from inside the breastplate of A.1656.

The microstructure consists of equiaxed ferrite with varying amounts of pearlite, so that the carbon content fluctuates between 0 and 0.4%C. There are also a few slag inclusions, lumpy in form.

Microhardness (100g load); range 119-153. Average = 134 VPH.

**Burgonet** (apparently made in two parts)

Thickness 2.3-3.8, av.3.1 mm.

Surface hardness 114-210 VPH.

A dent which has become a cup almost detached from the helmet 13.9 x 5.2 mm **D**.

A sample was also taken from the skull of the burgonet of A.1656, near the peak.

The microstructure consists of equiaxed ferrite with a small amount of intergranular pearlite (corresponding to a carbon content of less than 0.2%C). There are also a few slag inclusions.

Microhardness of burgonet; (100g load) range 130-153; average = 142 VPH.

**A.1180.** Armour of Johann Baptist, Freiherr von Thurn und Taxis; Netherlands or Germany, c.1585.

Extent of (a) oval dent: 11.9 x 21.1 x 4.4 mm **D**.

Extent of (b) 2<sup>nd</sup> dent: 8.8 x 1.1 mm.

Breastplate at front 6.0 mm.

Thickness of other parts: breastplate sides 3.0-5.1, av.4.0 mm.

Helmet weight: 6.5 kg.

Breastplate weight: 9.6 kg.

Surface hardness = 160-168 VPH.

Metallography: a sample was taken from the turned rim of the breastplate of A.1180.

The microstructure consists of equiaxed ferrite with a small amount of intergranular pearlite (corresponding to a carbon content of less than 0.1%C). There is a corrosion crack visible, but very few slag inclusions.

Microhardness (100g load) range 174-221; average = 185 VPH.

**A.1487.** Heavy breastplate, gorget and helmet of Cristobal Mondragón (1510-96); North Italian c.1585.

Extent of dents in breastplate:

a) 23 x 27 mm; depth of dent: 2.2 mm **D**.

b) 33 x 31 mm; depth of dent: 5.1 mm.

Thickness of other parts: breastplate at sides 4.4-6.2, av. 5.3 mm.

Breastplate at front = 5.3 mm.

Surface hardness 140-180 VPH.

Extent of dents in morion:

a) 23 mm; depth of dent: 3.2 mm.

b) 13.7 mm; depth of dent: 2.3 mm. Morion weight: 4.4 kg.

Metallography: a sample was taken from the lower rim of the morion at the front.

The microstructure consists of equiaxed ferrite with some areas of somewhat divorced pearlite (corresponding to a carbon content of around 0.3%C). There are also a few slag inclusions, arranged in rows.

Microhardness; range 137-165, average = 145 VPH.

**A.1715** Armour of Franz, Graf von Vandemort; French, c1590.

Extent of dent: 10.7 x 0.7 mm **D**.

Thickness of other parts: right pauldron 1.6 mm, lower back 3.3 mm, cuisses 3.4 mm, breastplate sides 3.6 mm. Breastplate at front: 5.5 mm.

Helmet weight: 6.6 kg.

Metallography: a sample was taken from the lower back plate of A.1715.

The microstructure consists of equiaxed ferrite with numerous areas of pearlite (corresponding to a steel whose carbon content varies between 0.2% and 0.7%C, perhaps 0.5% overall). There are also a few slag inclusions.

Microhardness average = 170 VPH.

**A.1704.** Armour of Cardinal Andreas of Austria; German, late 16<sup>th</sup> c.

Extent of dents: (a) 8.3 x 1.7 mm.

(b) 11.6 x 3.7 mm.

Thickness of breastplate at front = 2.5 mm.

Thickness of other parts: side of breastplate: 2.1 mm.

Backplate 2.0-2.8, average = 2.5 mm.

Dent in backplate 13.2 x 5.1 mm.

Breastplate weight: 6.8 kg. Surface hardness = 168-212 VPH.

Backplate weight 6.6 kg. Surface hardness = 131-140 VPH.

Close helmet wt. 3.2 kg.

Metallography: a sample was taken from the backplate of A.1704.

The microstructure consists of equiaxed ferrite with areas of pearlite (corresponding to a carbon content of around 0.3%C). There are also a few slag inclusions.

Microhardness (100g load) range 202-261, Average = 229 VPH.

**A.1654** A cuirassier's armour for Maurice of Nassau; probably made in the Netherlands about 1610.

Extent of dent, 23.0 x 1.8 mm.

Thickness of breastplate at front = 2.3 mm.

Metallography: A specimen from the neck plate of the helmet was examined in section.

The microstructure consists of ferrite and slag inclusions only.

The microhardness (average) = 179 VPH.

*Results of examination of bullet dents on armour in Madrid, Real Armeria (2005)*

There are 3 examples of siege armour (1600-1650) with severe dents.

**A.427** breastplate has numerous small dents –largest is diameter 9.3 mm, depth 0.8 mm. Thickness ranges from 5.5 to 8.5 mm.

**E.199** Backplate has 2 large dents as well as several smaller ones.

(a) diameter 28 mm. Depth 2.5 mm **D**.

(b) diameter 32.8 mm. Depth 2.5 mm **D**.

Thickness ranges from 7.3 mm to 8.8 mm.



**D.47** warhat, made in 4 pieces. Front damaged.

Thickness = 8.8 mm.

Dents (a) diameter 33 mm. Depth 6.4 mm.

(c) diameter 36.7 mm. Depth 6.5 mm.

Metallography was not carried out upon the last three armours. The average hardness from the microhardness measurements of the armours from Vienna was 168 VPH, so the assumption is made for the sake of this calculation that all three Madrid armours consist only of iron, and their average hardness is 160 VPH.

### *Results:*

Armour	Dent 2r (mm)	Depth $\delta$ (mm)	Thickness near dent t (mm)	VPH (kg.mm <sup>-2</sup> )	Yield Strength Y (MPa)	r (mm)
A.831	<b>D</b> 32	4.7	4.5	135	441	16.0
A.1203	<b>D</b> 15.7	3.6	4.9	191	625	7.85
A.1043	<b>D</b> 11.8	2.2	2.8	152	497	5.9
A.1280a	<b>D</b> 18.5	2.8	4.1	183	598	9.25
A.1280b	<b>D</b> 18.4	2.9	4.1	183	598	9.2
A.1656a	<b>D</b> 13.2	1.9	7.7	134	438	6.6
A.1656b	<b>D</b> 13.5	1.1	7.7	134	438	6.75
A.1656c	14.6	11.8	7.7	134	438	7.3
A.1656 burgonet	<b>D</b> 13.9	5.2	3.8	142	464	6.95
A.1180a	<b>D</b> 16.5	4.4	6.0	185	605	8.25
A.1180b	8.8	1.1	6.0	185	605	4.4
A.1487a	<b>D</b> 25	2.2	5.3	145	474	12.5
A.1487b	32	5.1	5.3	145	474	16.0
A.1487 Morion - a	23	3.2	5.3	145	474	11.5
A.1487 Morion - b	13.7	2.3	5.3	145	474	6.85
A.1715	<b>D</b> 10.7	0.7	5.5	170	556	5.35
A.1704a	8.3	1.7	2.5	229	749	4.15
A.1704b	11.6	3.7	2.5	229	749	5.8
A.1704 Backplate	13.2	5.1	2.5	229	749	6.6
A.1654	23.0	1.8	2.3	179	585	11.5
RA.A427	9.3	0.8	8.5	(160)	523	4.65
RA.E199a	<b>D</b> 28	2.5	8	(160)	523	14.0
RA.E199b	<b>D</b> 32.8	2.5	8	(160)	523	16.4
RA.D47a	33	6.4	8.8	(160)	523	16.5
RA.D47b	36.7	6.5	8.8	(160)	523	18.35
WC A.65	10.3	3.8	3.7	131	428	5.15
DHM 1989/2564/3	10.7	4.4	3.8	211	690	5.35
BAM A.11668	11	3.7	3.0	(160)	523	5.5

**D** = diffuse rim

VPN in kg/mm<sup>2</sup> can be converted into uniaxial yield strength in MPa (ie MN/m<sup>2</sup> or N/mm<sup>2</sup>) by multiplying by  $(9.8/3) = 3.3$ . Thus 135 VPN becomes  $135 \times 3.3 = 445$  MPa. The 9.8 converts kg to Newtons and the 3 is the approximate factor by which the hardness is a multiple of the unconstrained yield strength.

These derived yield strengths may be compared with experimental results obtained by one of the authors (Williams, 1974) using an extensometer, on fragments of armour from the Tower of London stores, supplied by the late Russell Robinson. (assumes 6.88 kPa = 1 psi).

		C	VPH	psi	MPa
Italy	c1520	0.4%	153	18 500	127
Germany	c1550	0.1%	120	27 800	191
England	c1520	0.5%	138	29 200	201
Italy	c1580	0.2%	170	42 900	295
Germany	c1520	0.6%	241	66 000	454
England	c1620	0.2%	170	80 100	551

All these had ferrite/pearlite or ferrite/carbide microstructures. The derived results are somewhat higher, probably due to the lower slag content of modern steels, but not unrealistically so.

Instrumented impact tests were also carried out by one of the authors on 2 mm wrought iron plates. It was found that they would be penetrated by a spherical steel projectile with 900 J of energy or a lead one with 1500 J of energy (Williams, 2003: 942). These energies would be well within the range of muzzle energies offered by an arquebus in Krenn's tests.

Other tests have been carried out with a target of modern mild steel sheet (3.2 mm thick). 20 mm ball-bearings were used, as well as 20 mm lead balls, as projectiles. The results of an impact of a hard steel ball-bearing (used to mimic a cast-iron bullet) are shown from front (Fig.8) and rear (fig.9). It will be observed that a sharp rim has formed, and a hemisphere of target metal is almost detached.

The results of several impacts on lead bullets (at muzzle velocities ranging from 127 m.sec<sup>-1</sup> to 181 m.sec<sup>-1</sup>) are also shown from the front in Fig. 10, and the side in Fig. 11.

#### ESTIMATION OF ENERGY INVOLVED IN PRODUCTION OF A DENT AND THE RESULTING SIZE OF A DENT

The production of a permanent dent in armour means that irreversible plastic work has been done in its formation. That work is imparted by loss of kinetic energy of the bullet.

The bottom regions of an impression conform to the shape of the bullet and, in some cases that profile is carried through to the surface of the armour to produce a sharp rim between indent and (undeformed) surface. Thus a spherical bullet may produce an indentation that is part of a sphere impressed upon the original surface of the armour where all the permanent deformation is localized into the spherical dent.



In other cases, however, the deformation spreads into the original surface around the dent thus producing an impression with a more diffuse rim in which there is reversed curvature. The difference in shape of the dent is probably due to the fact that lead bullets undergo considerable distortion.

Idealized versions of the two cases are shown in Figures 1 & 2, and practical examples from armours in Figures 12.

In both cases, the energy required to form the impression, is obtained from:

“(plastic work required per volume) x (volume permanently deformed)”

where the plastic work per volume is given by

(the yield strength of the armour) x (the plastic strain imposed in dent formation)

The yield strength  $Y$  is inferred from the hardness, using

$$Y \text{ (MPa)} = (10/3) \text{VPN (kg/mm}^2\text{)}$$

(we are ignoring work hardening for simplicity, so  $Y$  is constant).

The plastic strain is obtained from measurements of the permanent indentation compared with the original size of the region of armour that formed the dent. Owing to the different geometries of the two types of dent described above, different methods of calculation are employed in the two cases, but the principle is the same.

#### (i) *Sharp Rims* (Figure 1)

The dent has depth  $\delta$  below the original surface of the armour. The dent has spherical radius  $\rho$ . The circular rim in the plane of the original sheet has radius  $r$ .

Geometry gives

$$\delta (2r - \delta) = r^2$$

$$\rho = (r^2 + \delta^2) / 2\delta$$

$$\sin\theta = r/\rho; \theta = \sin^{-1} (r/\rho)$$

The dent has been formed by biaxial stretching and thinning of the surface under the bullet. Each principal biaxial strain is given by

$$\varepsilon = (2\rho\theta - 2r)/2r$$

and the effective (3-dimensional) plastic strain for dent formation is twice each biaxial strain value, ie

$$\varepsilon_{\text{effective}} = 2\varepsilon = 2(2\rho\theta - 2r)/2r = 2(\rho\theta - r)/r$$

The plastic work per volume is thus

$$2Y(\rho\theta - r)/r$$

The volume  $V$  of the original armour formed into the dent is

$$V = \pi r^2 t$$

where  $t$  is the *undeformed* thickness of the armour plate (not the thinned metal in the permanent indentation).

The energy  $E_{\text{sharp rim}}$  required to form an indent having a sharp rim is thus

$$\begin{aligned} E_{\text{sharp rim}} &= [2Y(\rho\theta - r)/r] [\pi r^2 t] \\ &= [2Y(\rho\theta - r)] [\pi r t] \end{aligned}$$

(ii) *Diffuse Rims* (Figure 2)

We assume that the 'reverse radius' has the same magnitude as the spherical bullet radius to which the bottom of the indent conforms, i.e. is  $r$ . The depth of the bottom of the indent is again  $\delta$  below the original surface of the armour. The diameter of the whole indentation is  $D$ .

From continuity of curvature

$$\delta = 2r (1 - \cos\alpha)$$

and

$$D = 2r \tan \alpha + 2(r - \delta) \tan\alpha$$

where  $\alpha$  is defined in the figure.

Whence

$$D = 4r \sin\alpha$$

By dividing, it follows that

$$(\delta/D) = (1 - \cos\alpha) / \sin\alpha$$

From the measured  $\delta$  and  $D$ ,  $\alpha$  may be found from this equation. Then  $r$  follows, using  $D = 4r \sin\alpha$ .

The total length of the double curve profile beneath the ball is given by  $4r\alpha$ . Its original length was  $4r\sin\alpha$ , so the extension is  $4r(\alpha - \sin\alpha)$  and the tensile surface strain is  $[(\alpha - \sin\alpha)/\sin\alpha]$ . Because the dent is formed in biaxial tension, the effective plastic strain is  $2[(\alpha - \sin\alpha)/\sin\alpha]$  as above. The work done per volume of material plastically deformed is  $2Y[(\alpha - \sin\alpha)/\sin\alpha]$ .

The volume affected is  $(\pi D^2/4)t$  where  $t$  is the undeformed (original) thickness of the armour. The work required is therefore

$$Y[(\alpha - \sin\alpha)/\sin\alpha] (\pi D^2/2)t$$

*Calculations (i): sharp rims*

Armour	Work (J)
A.1656 c	246
A.1180 b	18
A.1487 morion a	106
A.1487 morion b	54
A.1704 a	21
A.1704 b	91
A.1704 backplate	161
A.1654	18.4
RA. A427	12
RA.D47 a	700
RA.D47 b	731
WC A.65	77
DHM 1989/2564	163
BAM A.11668	75

*Calculations (ii): diffuse rims*

Armour	Work (J)
A.831	746
A.1203	330
A.1043	42
A.1280 a	190
A.1280 b	202
A.1656 a	86
A.1656 b	30
A.1656 burgonet	344
A.1180 a	611
A.1487 a	162
A.1715	8.6
RA.E199 a	391
RA. E199 b	460

## DISCUSSION

So, whatever the form of the dent, when the results are calculated, there are 12 impacts of less than 100 J, 7 impacts in the region of 100 - 300 J, 4 impacts in the region of 300 - 600 J and 4 impacts of over 600 J.

It may well be argued that in a battle or siege where a large mass of soldiers were firing at varying ranges, the distribution of bullet velocities would be more or less random. The results obtained by Krenn (with corned powder: pistol 900 J, arquebus 1750 J, musket 3000 J) would have represented absolute maxima. At any distance from the muzzle, the velocity of the ball would be reduced by air friction, and so the energy available would be reduced, and if uncorned (serpentine) powder was used, the muzzle velocity might be reduced still further. So the range of maximum energies encountered might then have ranged, hypothetically, from pistol bullets at 400 - 500 J to musket balls offering 1000 - 2000 J.

The impacts of energy around 300 - 600 J could then plausibly have been made in combat at fairly close quarters, and those of lesser energy at greater distances.

However, the “proof” marks seem to have been the result of bullets with only some 75 - 160 J. Even allowing for the use of serpentine powder, the impact of a pistol bullet at the ranges employed for “proofing” should have corresponded to an energy of at least 500 J.

What can be deduced from this? These energies are of a different order of magnitude to the likely impact of even a pistol bullet at short range. Of course, it has to be remembered that the person doing the proving was frequently the person selling the armour, and the temptation to undercharge the pistol fired must have been considerable. If the bullet possessed only half its customary muzzle velocity, it would deliver only a quarter of its customary impact energy, and yet the pistol would sound with a satisfying report.

It may be concluded that “proof marks” do not prove anything about the armour’s likely performance.

*Acknowledgements*

The authors would like to thank the director of the Hofjagd- und Rüstkammer, Vienna, Dr. Christian Beaufort-Spontin, for permission to examine the armours in his collection, and his colleagues, Dr. Matthias Pfaffenbichler and Dr. Christa Angermann. They would also like to record their thanks to Dr. Gerhard Quaas (Berlin) and Dr. Ernst Aichner (Ingolstadt) for their co-operation with this study, and also to the late Russell Robinson, who did so much to inspire this research.

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Figure 3. Wallace Collection, London, armour A.65.



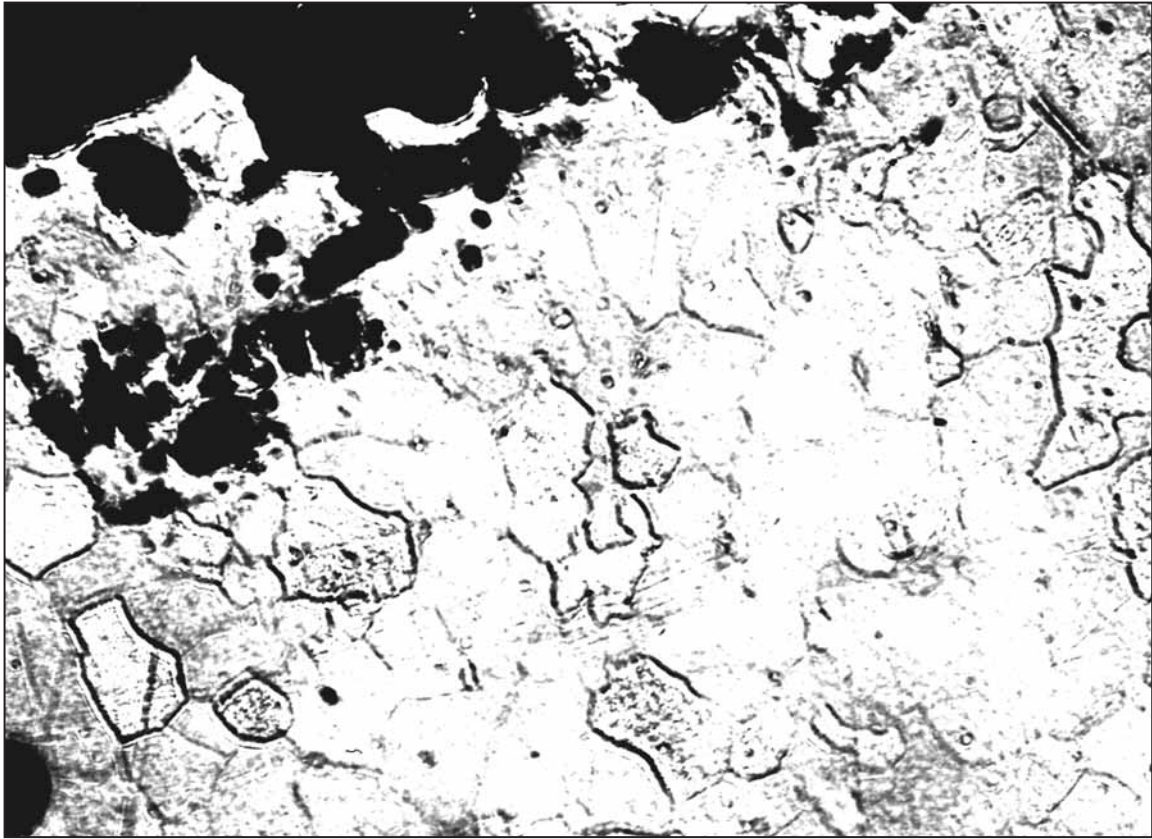


Figure 4. Microstructure of A65: ferrite and slag. This is a wrought iron (0%C).  
(Scale bars are 50 microns in every case).

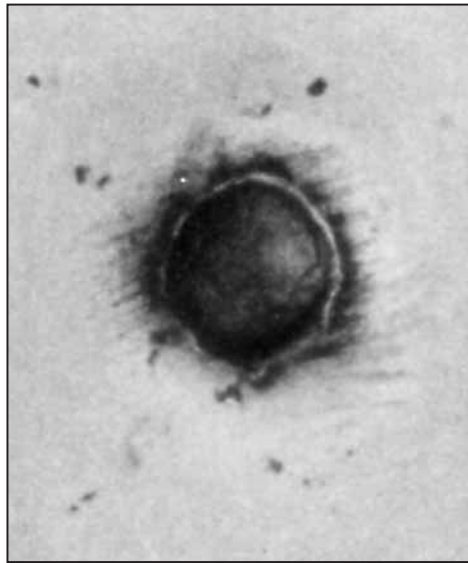


Figure 5. Closeup of dent in A65.



Figure 6. Berlin, DHM (1989/2564/3), armour.

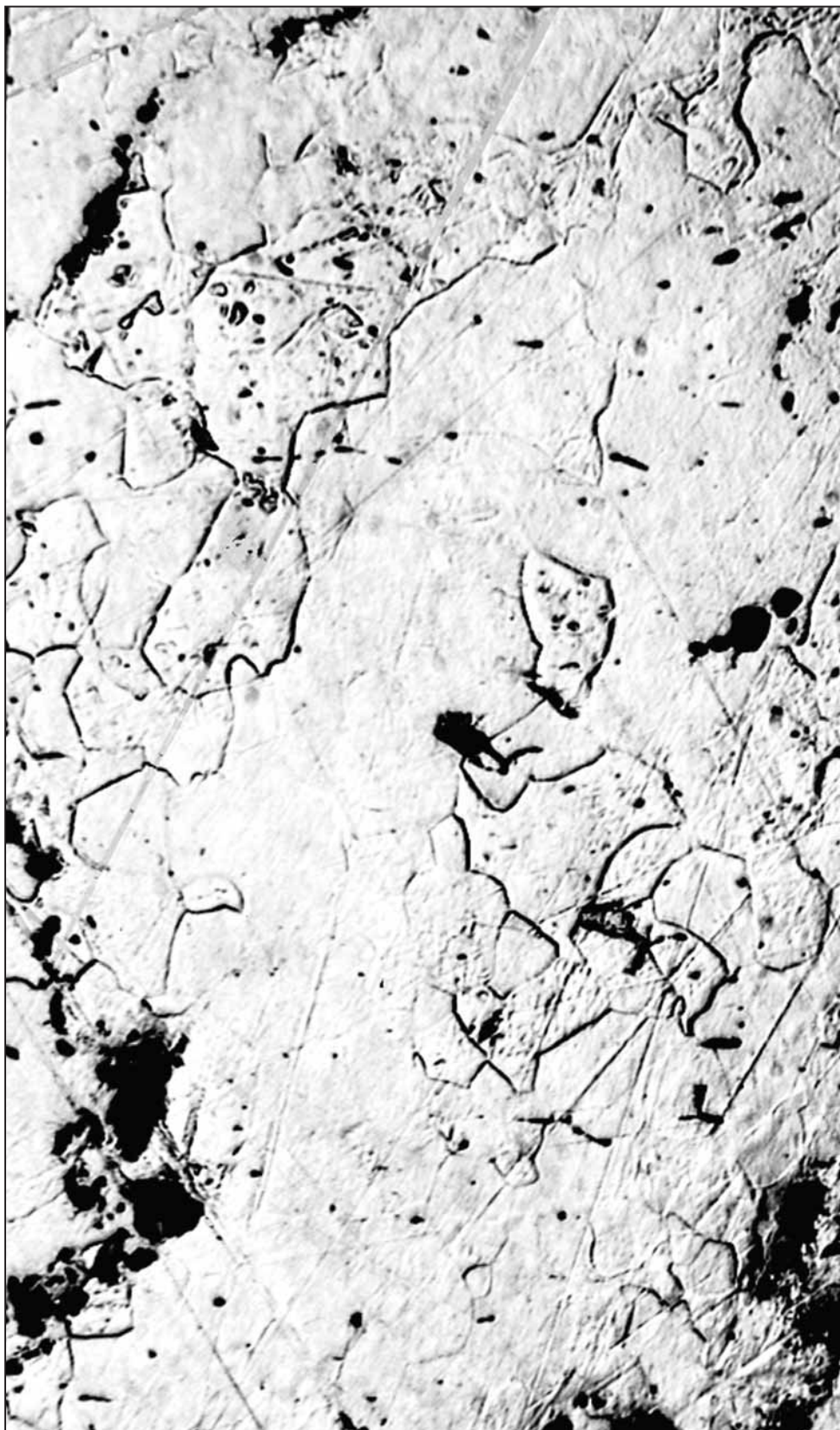


Figure 7. Microstructure of DHM 1989/2564: ferrite and slag.





Figure 8. Cuirassier armours at Ingolstadt.



Figure 9. Results of spherical steel bullets striking mild steel plate: from front.

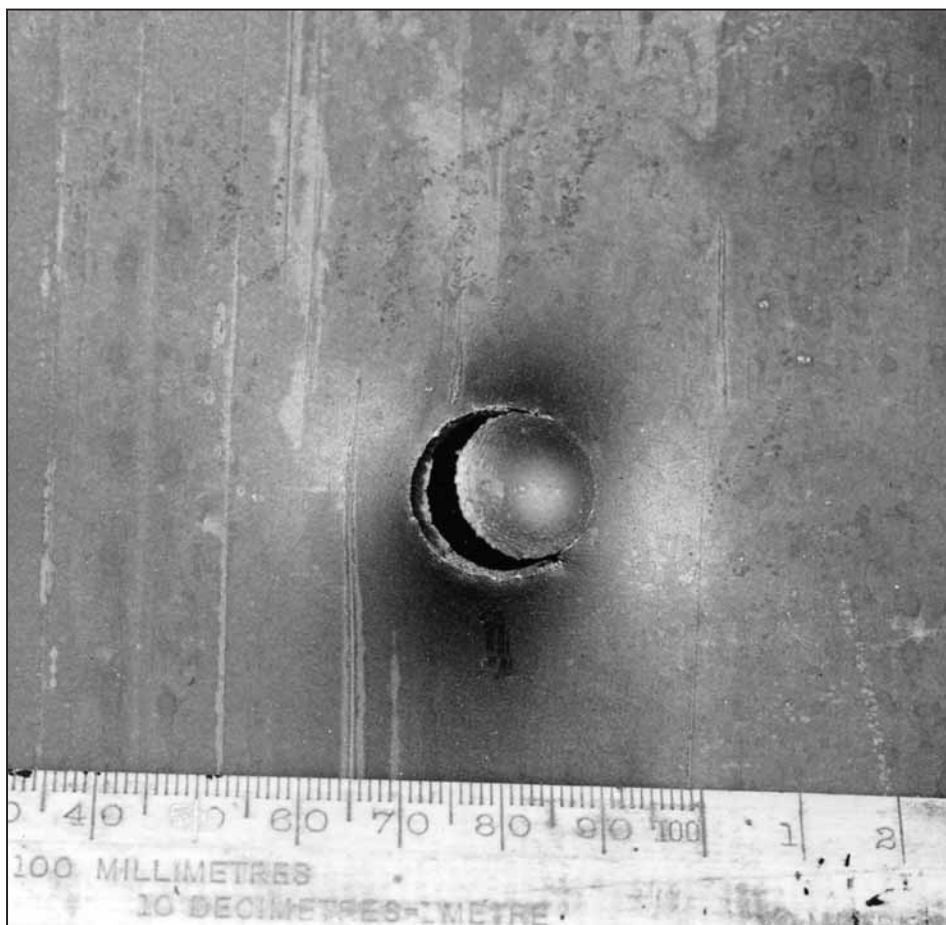


Figure 10. Results of spherical steel bullets striking mild steel plate: from rear.

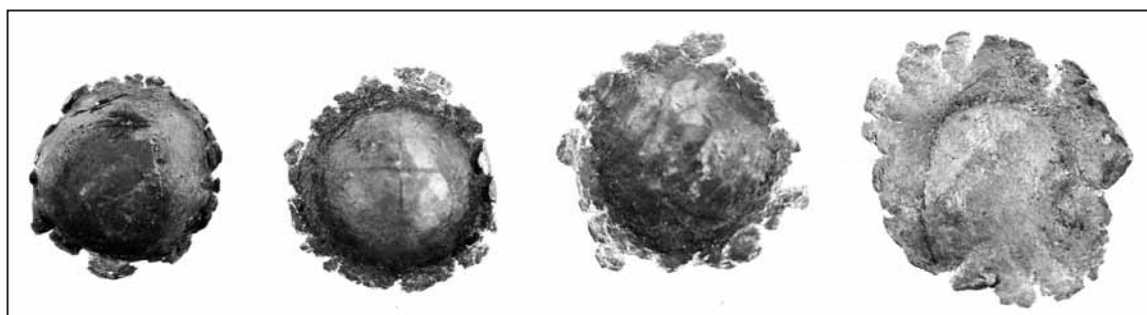


Figure 11. Results of impact on lead bullets: from front.

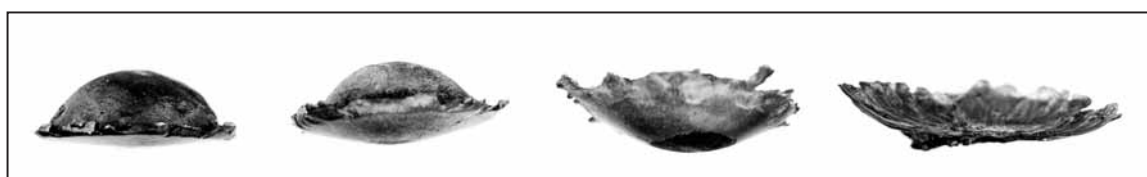


Figure 12. Results of impact on lead bullets: from side.



Figure 13. HJR, Vienna, A. 831.





Figure 14. Closeup of A. 831.

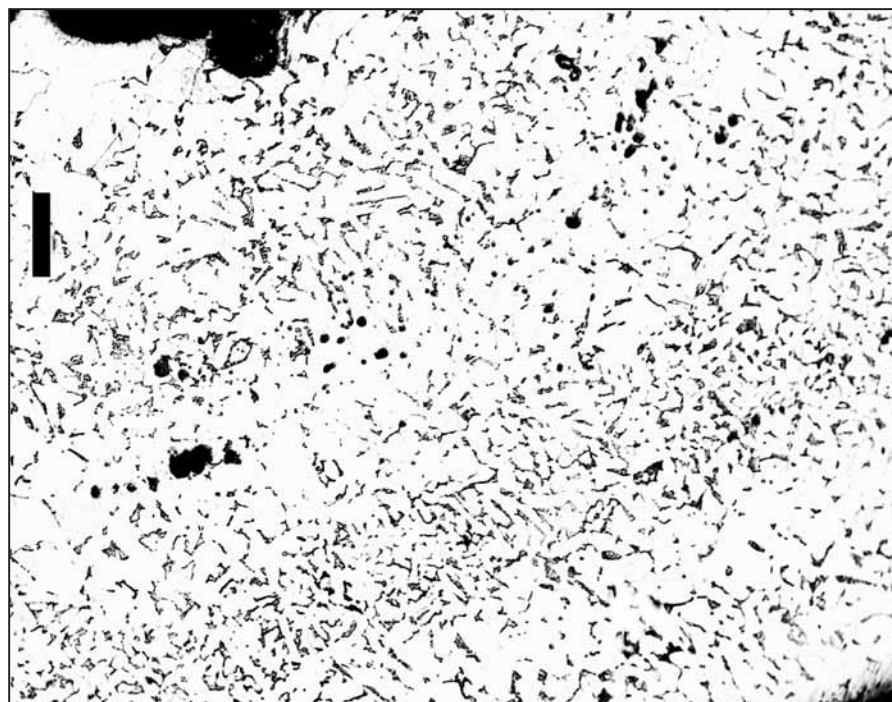


Figure 15.  
A.831  
Microstructure:  
ferrite, a little  
pearlite, and slag.  
This is a low-  
carbon steel  
(0.1% - 0.2%C).



Figure 16. HJR, Vienna, A.1203.



Figure 17. Closeup of A.1203.

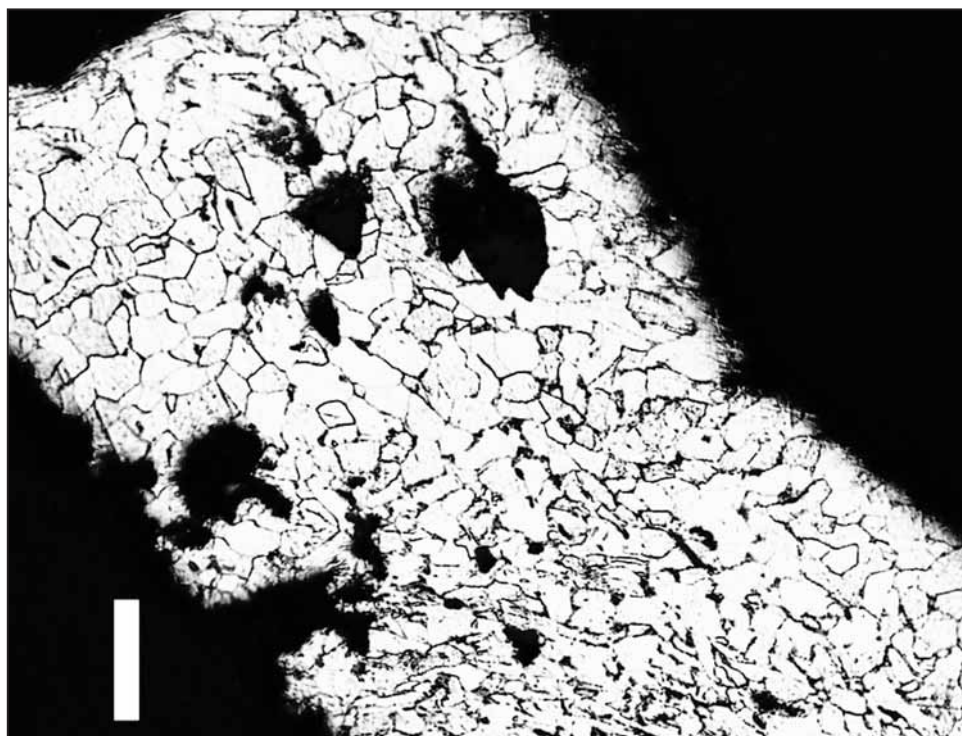


Figure 18. A.1203 Microstructure: ferrite and slag.





Figure 19. HJR, Vienna, A. 1043

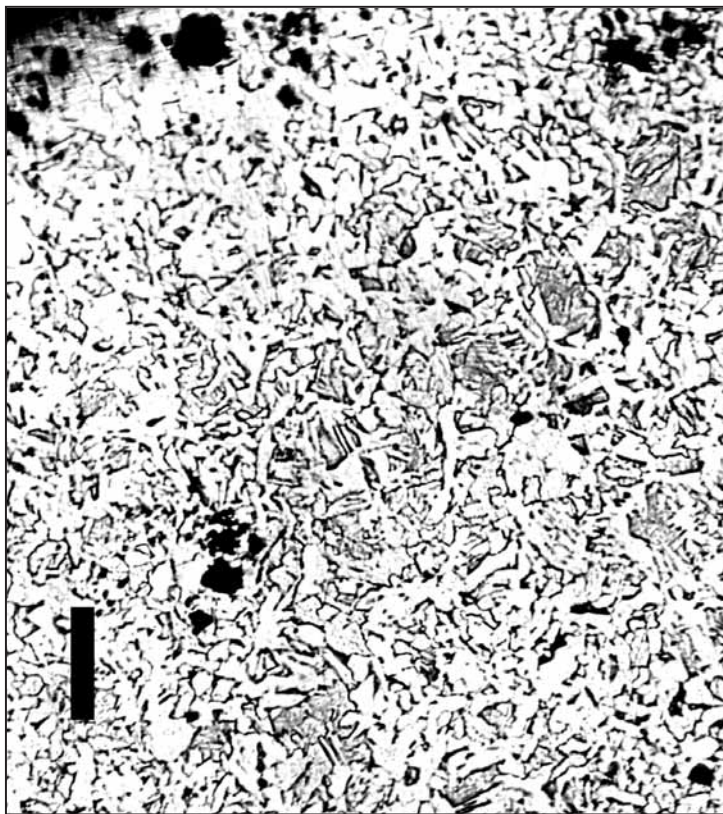


Figure 20. A. 1043 Microstructure: ferrite, a little pearlite, and slag. This is a low-carbon steel ( $\sim 0.2\%C$ ).



Figure 21. HJR, Vienna, A. 1280.



Figure 22. Closeup of A. 1280.

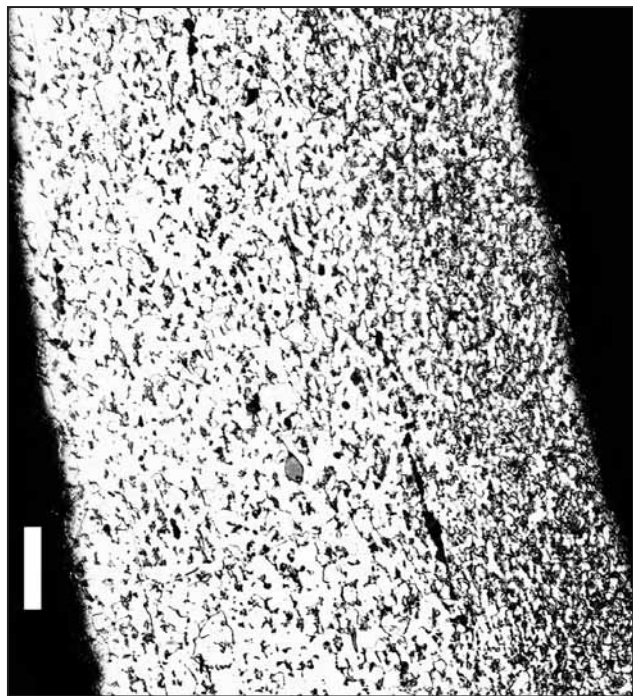


Figure 23. A. 1280 Microstructure: ferrite, a little pearlite, and slag. This is a low-carbon steel (0.2% - 0.3%C).



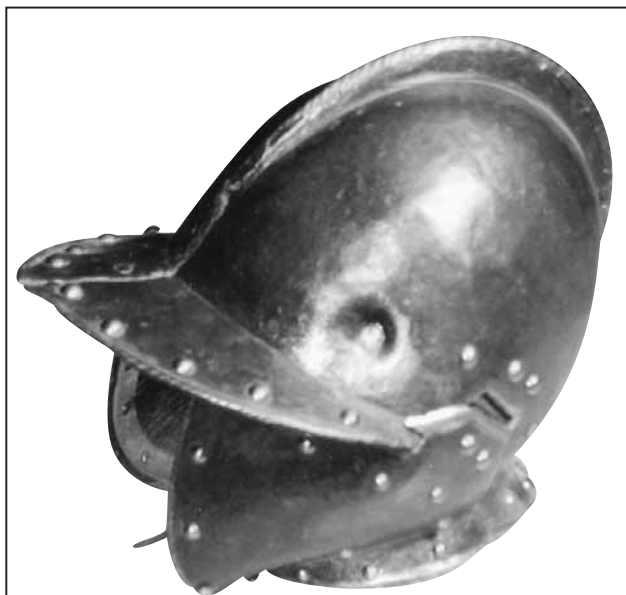


Figure 24. Burgonet of A. 1656.

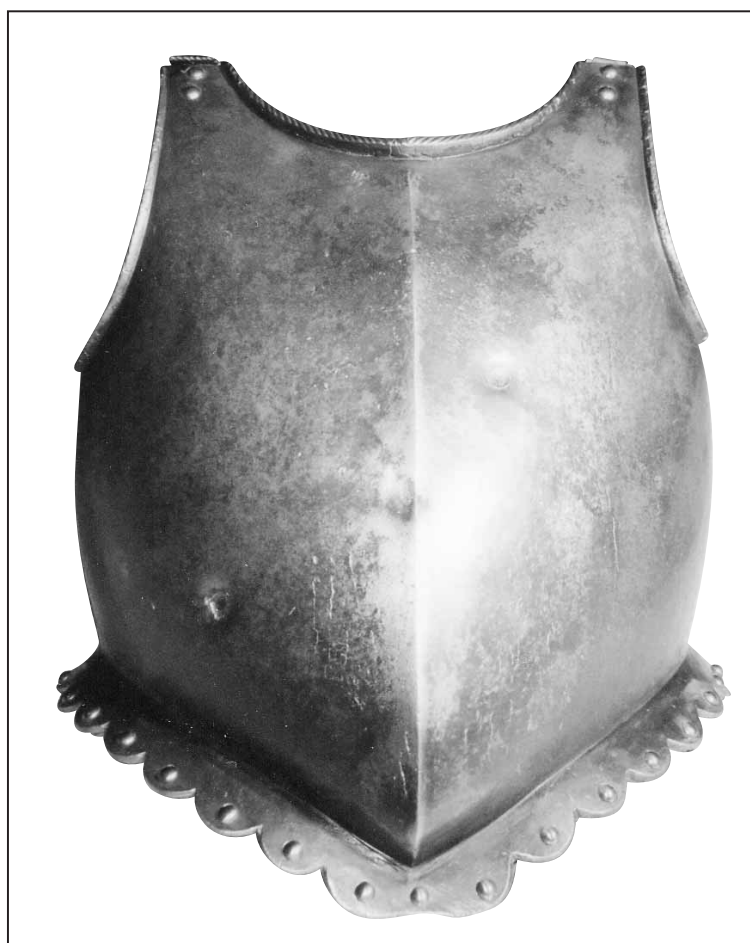


Figure 25. HJR, Vienna, A. 1656.





Figure 26. A. 1656 Microstructure: ferrite, a little pearlite, and slag. This is a low-carbon steel (~0.1%C).



Figure 27. HJR, Vienna, A. 1180.





Figure 28. Closeup of A. 1180.

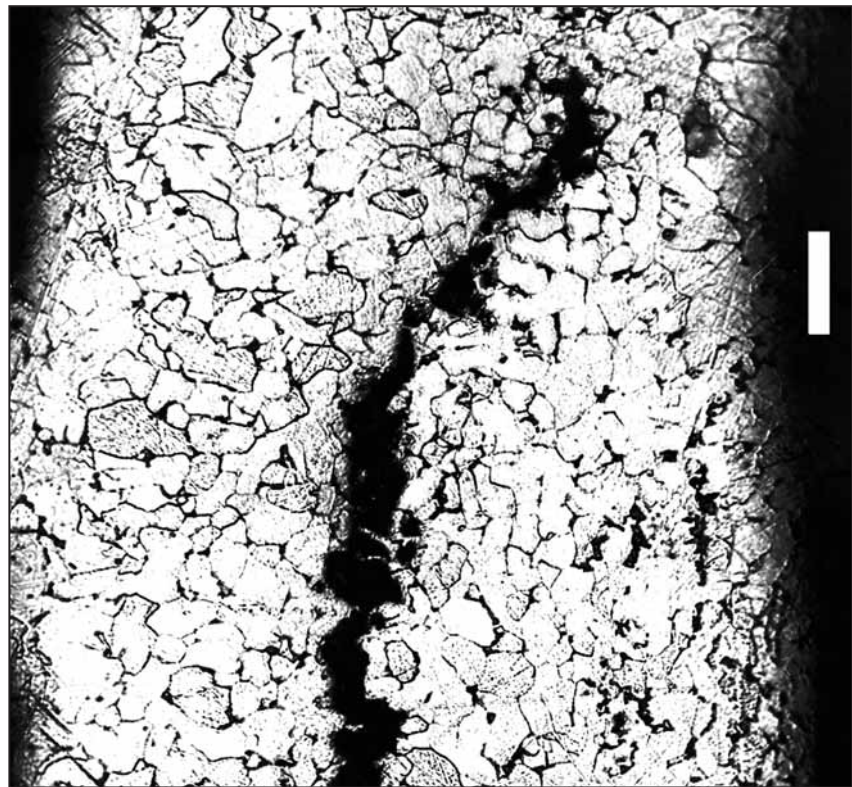


Figure 29. A. 1180  
Microstructure: ferrite  
and slag.



Figure 30. HJR, Vienna, A. 1487.

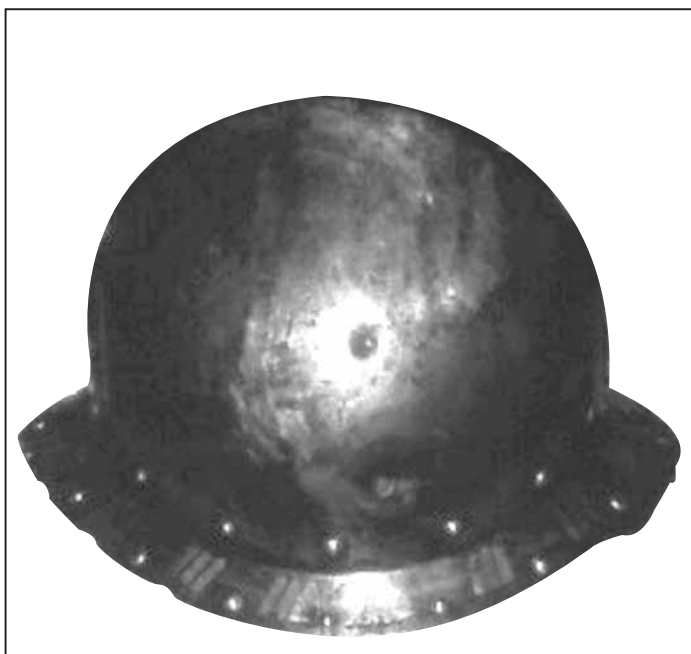


Figure 31. Morion of A. 1487.

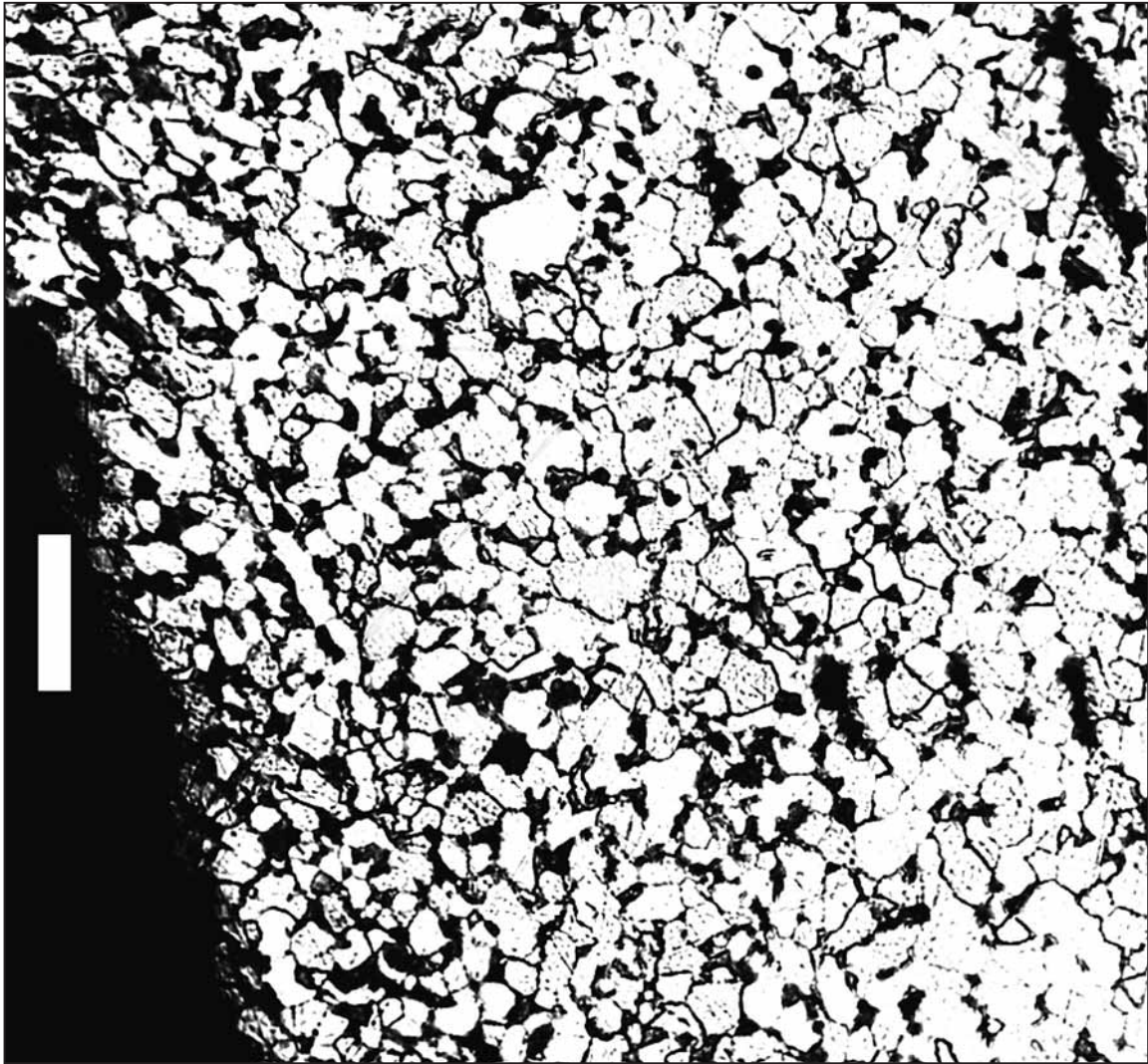


Figure 32. A. 1487 Microstructure: ferrite, a little pearlite, and slag. This is a low-carbon steel (0.1%-0.2%C).





Figure 33. HJR, Vienna, A. 1715.

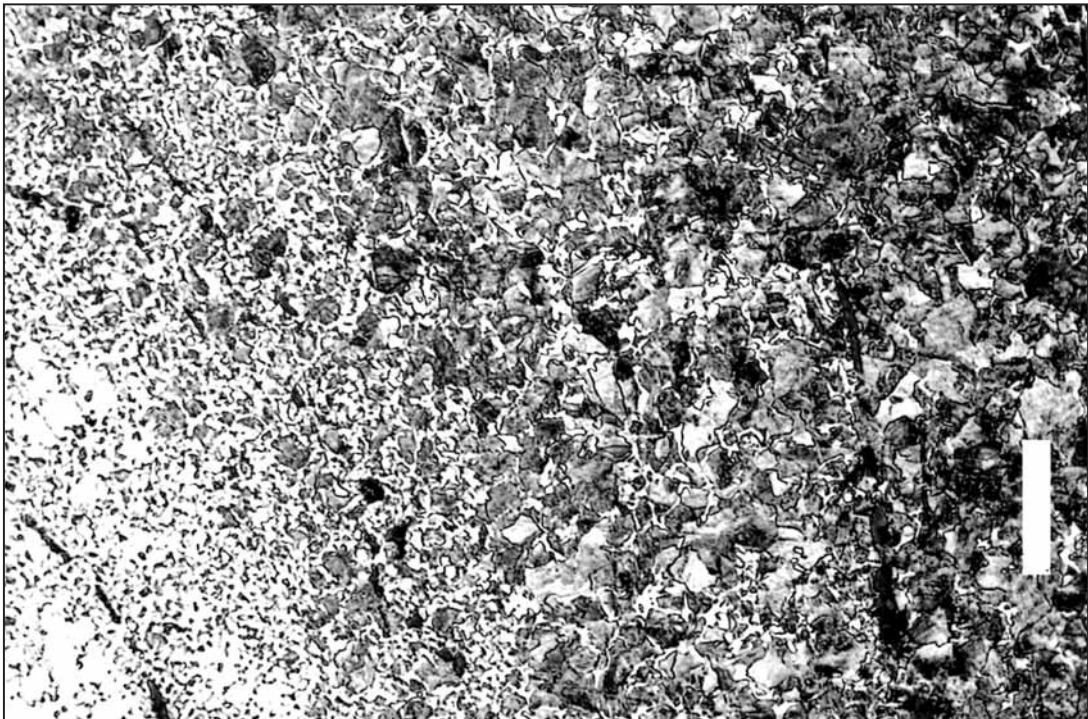


Figure 34. A. 1715 Microstructure: ferrite, pearlite, and slag. This is a medium-carbon steel ( $\sim 0.5\%C$ ).





Figure 35. Breastplate of HJR, Vienna, A. 1704.



Figure 36. Backplate of A. 1704.

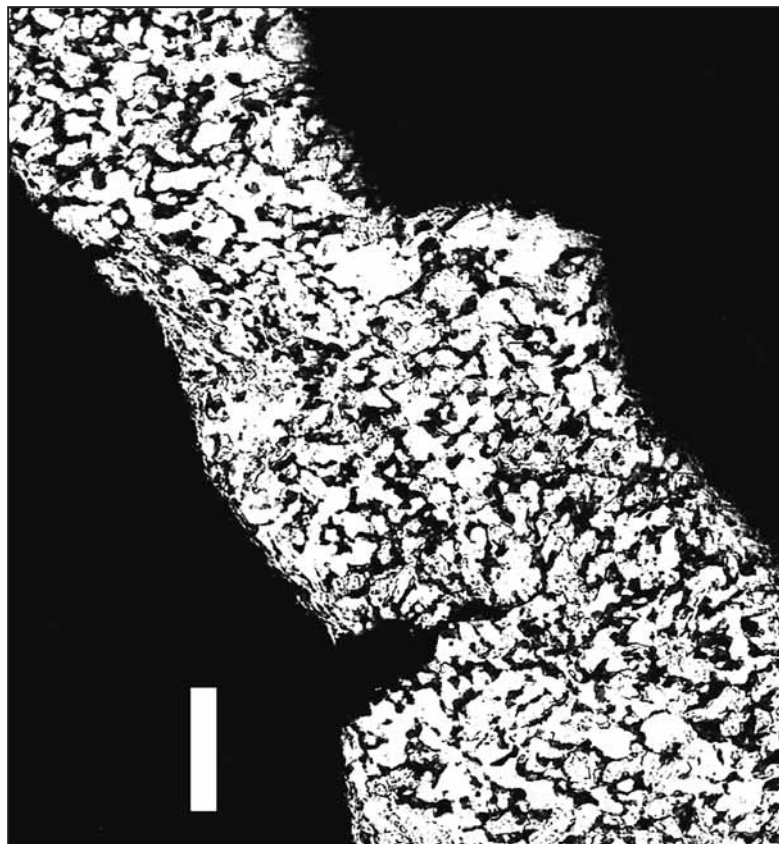


Figure 37. A. 1704 Microstructure: ferrite, a little pearlite, and slag.  
This is a low-carbon steel ( $\sim 0.2\%C$ ).



Figure 38. HJR, Vienna, A. 1654.

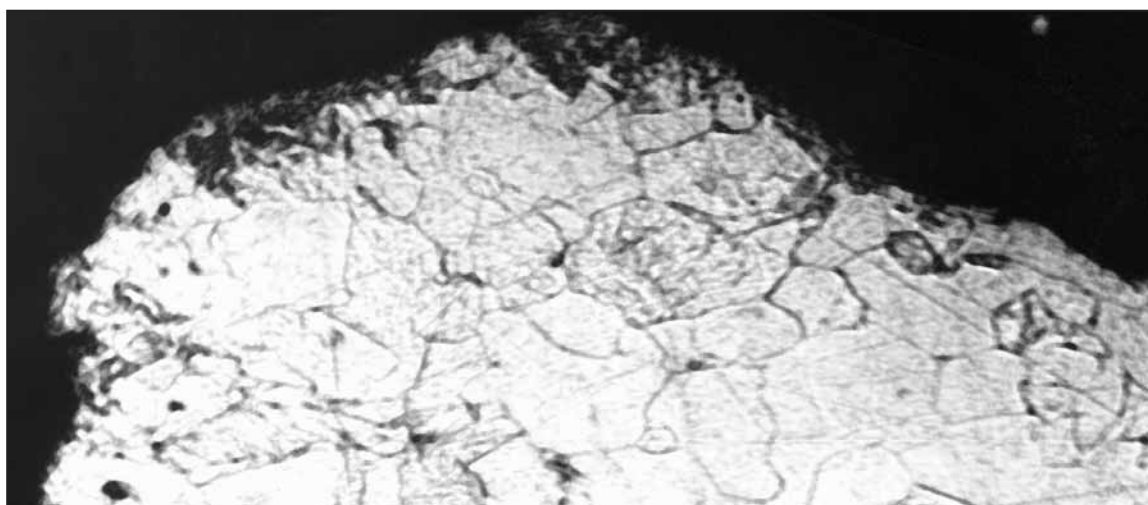


Figure 39. A. 1654 Microstructure: ferrite and slag.

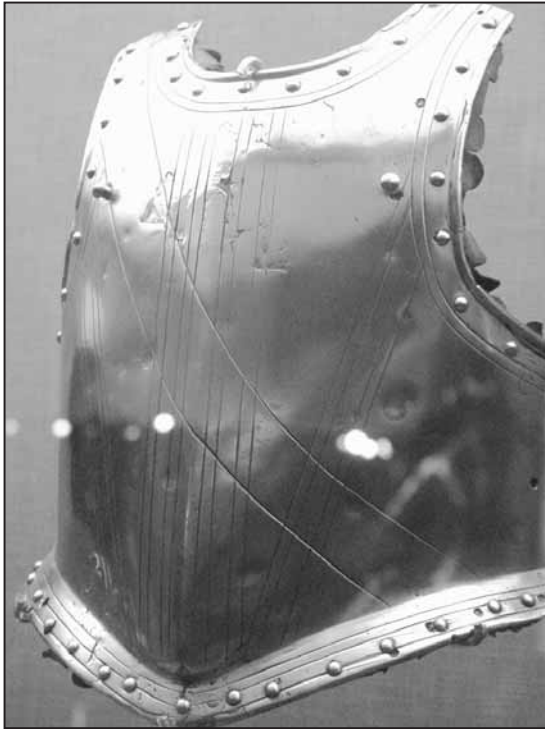


Figure 40. RA, Madrid, A. 427.

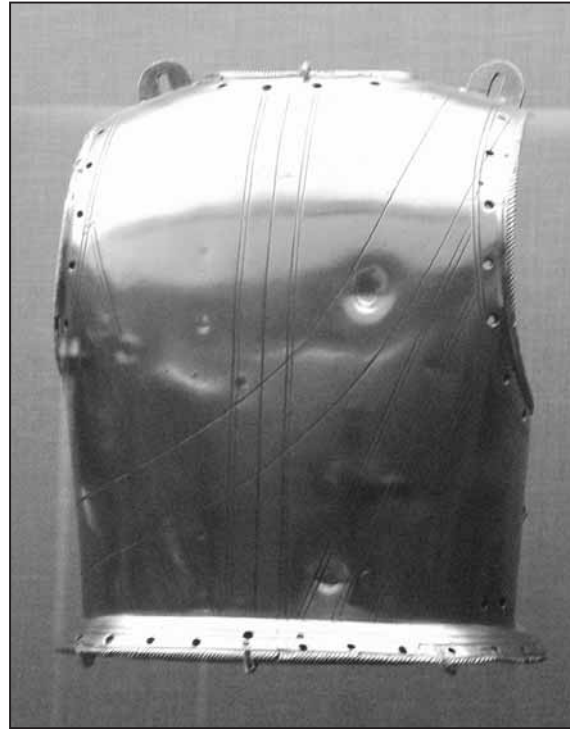


Figure 41. RA, Madrid, E199.



Figure 42. RA, Madrid, D47.