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CHARACTERIZATION OF 6061 T651 ALUMINUM PLATES SUBJECTED TO HIGH-VELOCITY IMPACT LOADS

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ABSTRACT

Ballistic response of single or multi-layered metal armor systems subjected to kinetic energy projectiles was investigated in many experimental, theoretical and numerical studies.

In this study, 6061 T651 aluminum plates impacted by 9 mm bullets were investigated. Microstructural investigations have been carried out using optical microscopy. Microhardness values were used to determine the strength behavior of the plates. Influence of the plate thickness and impact velocity on the microstructure has been evaluated. It was concluded from the study that thinner plates are more prone to deformation hardening with high penetration depth values even at low impact velocities while thick plates are more susceptible to thermal softening with less penetration depths. Maximum hardness values were obtained just below the impact zone in both plate thicknesses.

Keywords: AA 6061 T651, Aluminum plates, High velocity impact, Microstructure.

YÜKSEK HIZLI ÇARPMA YÜKLERİNE MARUZ 6061 T651 ALÜMİNYUM LEVHALARIN KARAKTERİZASYONU

ÖZ

Kinetik enerjiye sahip mermilere karşı, tek veya çok katmanlı metal zırh sistemlerinin gösterdiği balistik davranış, çok sayıda deneysel, teorik ve sayısal çalışmayla araştırılmıştır.

Bu çalışmada, 9 mm mermilerle üzerine atış yapılan 6061 T651 alüminyum levhalar incelenmiştir. Mikroyapı incelemesi optik mikroskop kullanılarak gerçekleştirilmiştir. Levhaların mukavemet davranışlarının belirlenmesinde mikrosertlik değerleri kullanılmıştır. Levha kalınlığı ve çarpma hızının mikroyapı üzerindeki etkisi değerlendirilmiştir. Çalışma sonucunda; ince levhaların, düşük çarpma hızlarında bile yüksek nüfuziyet derinliğiyle deformasyon sertleşmesine daha duyarlı olduğu, kalın levhaların ise düşük nüfuziyeti derinliğiyle termal yumuşamaya eğilimli olduğu değerlendirilmiştir. Maksimum sertlik değerleri her iki levha kalınlığında da çarpma bölgesinin hemen altında elde edilmiştir.

Anahtar Kelimeler: AA 6061 T651, Alüminyum levhalar, Yüksek hızlı çarpma, Mikroyapı.

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1. INTRODUCTION

Aluminum plates are widely used in lightweight armor systems as well as aircraft structures, buildings and bridge decks. Impacts or other types of high-speed loading conditions are thus a relevant issue for several of these applications. In these applications, weight of a structure is an important design criterion. For this reason, it is known that aluminum alloys are preferred instead of conventional steel or concrete. Ballistic response of single or multi-layered high strength metals and fabrics subjected to kinetic energy projectiles was investigated in many experimental, theoretical and numerical studies [Borvik et al. 2005]. A great amount of these studies regarding aluminum plates subjected to high velocity impact investigate the behavior of materials under impact load.

Andersen and Dannemann [Andersen et al. 2001] who used two different aluminum alloy (AA6061-T6 and AA7075-T6) of 4.75 mm thickness, studied the ballistic behavior of aluminum alloys.

Borvik *et al.* [2004] investigated the perforation of AA5083-H116 aluminum plates with various thicknesses impacted by conical-nose steel projectiles. Initial and residual velocities of the projectile were measured and impact versus residual velocity curves of the target plates was constructed and the ballistic limit velocity of each target was obtained.

Effect of impactor nose shape on high velocity impact resistance of plates is also under investigation. Many studies are of interest in this phenomenon. Literature studies [Gupta et al. 2006; Gupta et al. 2007; Piekutowski et al. 1999; Forrestal et al. 2000; Warren et al. 2001] show that the effect of projectile nose on the target plates varies with various parameters such as thickness of the target plate, impact velocity of the projectile, target thickness to projectile diameter ratio and nose angle or nose radius of the projectiles.

There is a practical necessity to investigate, describe and predict the behavior and properties of widely used materials such as aluminum alloys subjected to high velocity impact loads. The mechanics of the micromechanisms of failure of these ductile materials are under investigation [Atroshenko et al. 2006; Rosakis et al. 2000]. Atroshenko *et al.* [2006] investigated the behavior of different metals (copper, aluminum, lead, titanium, titanium alloys and different steels) under shock loading. Under uniaxial shock loading on light gas gun pores are seen without fracture and flow lines in the aluminum structure.

Dynamic deformation behavior of metallic materials at high strain rates has been studied and reported in the literature. Material deformation at high strain-rates is a much complex phenomenon that involves localized adiabatic heating with the associated thermal softening leading to extreme localization of strain along certain narrow bands called adiabatic shear bands (ASB). Owolabi *et al.* [2006] investigated the effects of particulate reinforcement on the phenomenon of adiabatic heating leading to strain localization in Aluminum 6061-T6 alloy under high velocity impact.

The dynamic compression failure and ballistic penetration characteristics of conventional tungsten alloys similar in strength were investigated with a symmetric Taylor test technique. Results of this study reinforce the argument that shear band formation is a failure mechanism associated with the erosion process for conventional tungsten alloys [Couque et al. 2007].

Martinez *et al.* [2007] studied target plugs facilitated by horizontal and vertical ASBs and cracks occurred in finite Ti–6Al–4V targets impacted by blunt, steel projectiles impacting at velocities ranging from 633 to 1027 m/s.

Karamış [2007] examined the tribological events taking place when a high-velocity projectile hits a SiC particulate reinforced AA 5083 composite material.

In the study by Hayun *et al.* [2010], the dynamic high-strain-rate behavior of boron carbide-based composites with similar phase composition yet different microstructural features, namely, amount of residual silicon, average grain size and morphology of the SiC particles, were investigated as a function of the planar impact strength.

In this study, 6061 T651 aluminum plates impacted by 9 mm bullets were investigated. Microstructural investigations have been carried out using optical microscopy. Microhardness values were used to determine the localized mechanical properties alteration under impact area. Influence of the plate thickness and impact velocity on the microstructure have been evaluated.

2. EXPERIMENTAL PROCEDURE

2.1 Sample Alloys

6061 T651 aluminum alloys of two different thicknesses were used in the study. Alloys' compositions and specimen configurations are shown in Table 1 and Table 2, respectively. Alloy chemical composition measured with SEM / EDX device.

2.2 Impact Tests

In experiments, FMJ (Full Metal Jacket) Parabellum bullets which are produced by MKEK (Mechanical and Chemical Industry Corporation) of 9 mm diameter and 19 mm length were used (Figure 1). Bullets consist of a brass (CuZn36) cup and lead-antimony alloyed core. Weight and barrel exiting velocity of the bullets are 8±0.075 g and 370±10 m/s, respectively.

The distance between the target plate of 250x250 mm dimensions and the shooting system was 5 meters. All shots were normal to target plates. Oehler Research optical ballistic devices (Model 55 photoelectric screens and Model 35P chronograph) were used for the velocity measurements. After impact tests, penetration depths including plate bending in front face and bulgings on back face of the target plate were measured with the help of 3D-CMM (Three Dimensional Coordinate Measurement Machine).

2.3 Specimen Preparation

Following impact, flat rectangular samples of 20x20 mm in dimensions were cut from the center of the impact zone of the target plates by using Electric Discharge Wire Cutting (EDWC) technique as shown in Figure 2.

2.4 Metallographic Examination

For metallographic studies and microhardness tests, the specimens were mounted on epoxy, then they were grinded with 320, 500, 800, 1200 and 2500 grit SiC papers respectively. The polishing procedure was completed in two steps, rough polishing with 3 µm diamond and final polishing with 0,05 µm alumina solutions.

After polishing, specimens were etched with a keller water reagent consisting of vol.%2 HF. Specimens were washed with ethyl alcohol to finish the etching procedure and dried with blow dryer to protect the original etched microstructure. Specimens were also cleaned using water between each grinding and polishing step.

Metallographic specimens were characterized using optical microscope at magnifications between 50 and 500x.

Five different zones in specimens were inspected using optical microscope. As shown in Figure 3,"A" is assigned to define the zone away from the impact region whereas "B" is the zone near the crater walls and "C", "D" and "E" are selected through the impact direction.

2.5 Hardness Testing

Microhardness readings may be related to other mechanical properties such as elastic modulus, which could be needed for micromechanical modeling purposes and therefore hardness may be used as a method to estimate the ballistic resistance behavior of the 6061 T651 aluminum plates.

Microhardness evaluation was performed by measuring the vickers hardness over the polished impacted samples using HVS 1000 (Bulut Makina) device with weight of 50 g. Five microhardness values for each sample at 1 mm intervals in the impact direction have been obtained. No.5 values are average of the four values obtained at out of the impact zone. This procedure is illustrated in Figure 4.

3. RESULTS AND DISCUSSION

3.1 Ballistic Performance

As an indication of ballistic performance of plates, penetration depth values versus projectile velocity with exponential trend lines are shown in Figure 5.

As a result of higher areal density, 8 mm plates have better performance in same projectile velocities. Thinner plates are more susceptible to deformation with increasing projectile velocity.

3.2 Metallography

Microstructures obtained away from the impacted zone are shown in Figure 6. The initial microstructure typically consists of elongated grains parallel to the rolling direction and black, elliptic Mg_2Si particles that most common intermetallic phase in 6XXX series alloys.

Table 1. Composition of sample alloys (wt.%)

	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
Standart comp.	95.8~98.6	0.04~0.35	0.15~0.4	0-0.7	0.8~1.2	0-0.15	0.4~0.8	0-0.15	0.25
Measured comp.	98,1	0.12	0.15	-	1.1	-	0.5	-	-

Table 2. Specimen configurations

test no	plate thickness (mm)	impact velocity (m/s)
5-7	6.35	359
5-6		367
5-5		378
6-7	8.00	368
6-5		376
6-6		379

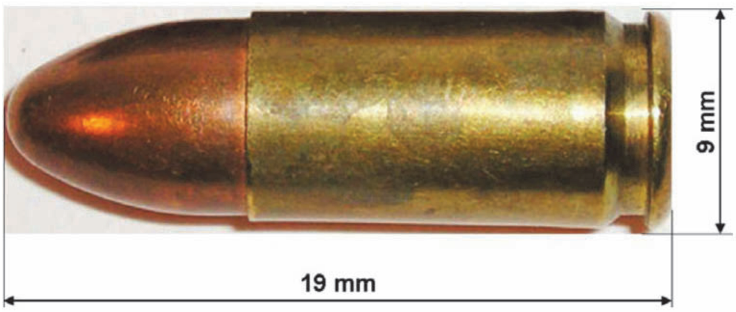


Figure 1. Bullet used in tests

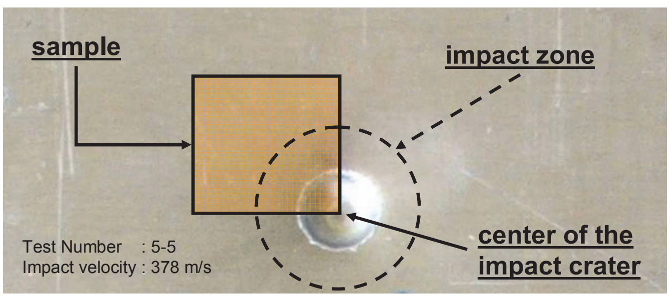


Figure 2. Sample cutting from impacted plate

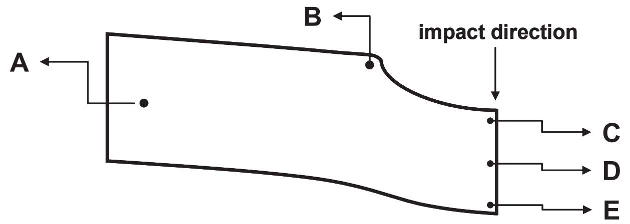


Figure 3. Characterization procedure

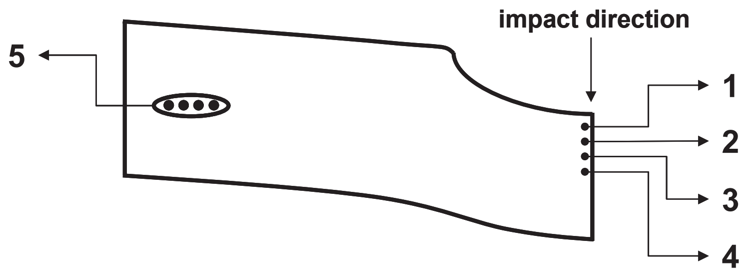


Figure 4. Microhardness measurement procedure

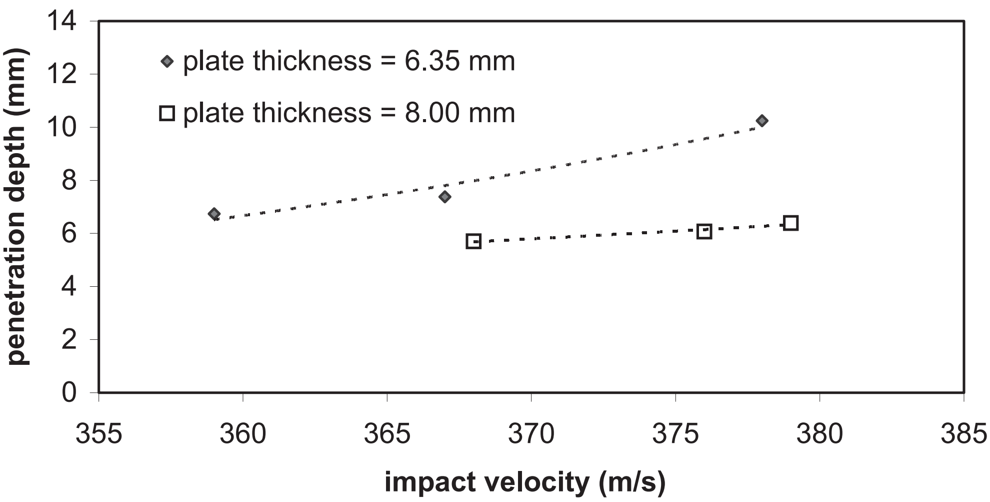
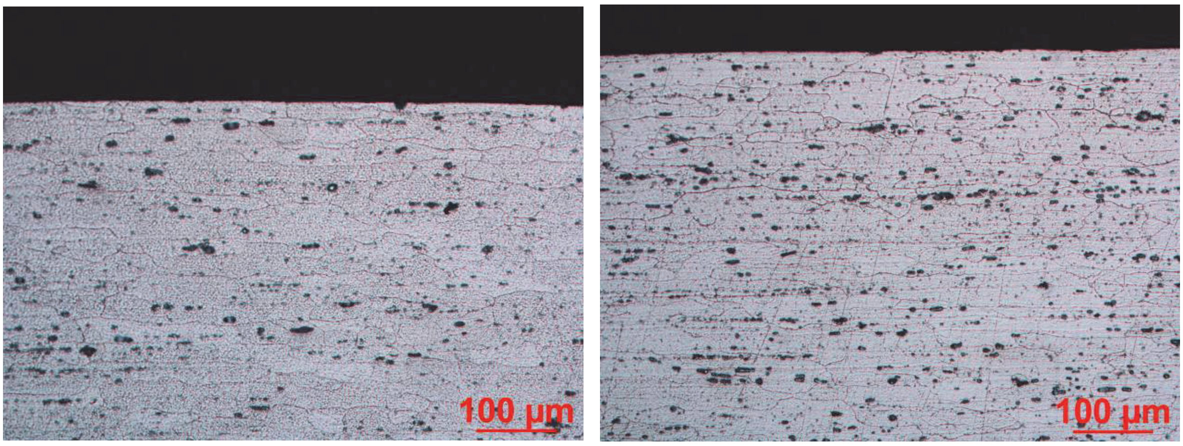


Figure 5. Penetration depth values in front faces of the plates

It can be easily seen from figures that grains sited out of the impact zone keep their original sizes and forms and there is no deformation effect in this region because of the nature of the high strain rate loading such as high velocity impact.

A projectile striking a target effectively distributes its initial kinetic energy between itself as a deforming and eroding body and the deforming and eroding target, as well as the energy required to separate a plug from the rear of a target with finite thickness. For small projectiles at high velocity, the penetration into the target may be only a small crater which scales with the projectile diameter; while the projectile is fragmented or eroded, leaving some fractional mass in the cratered target. The crater is formed by target material flowing along a narrow zone at the crater wall, usually in the solid state [Martinez et al. 2007].

Craters occurred in the 6061 T651 aluminum plates are shown in Figure 7. Also extremely deformed shapes of grains through the crater walls in Figure 7 and general material flow under impact area in Figure 8 can be observed.



a) b)

Figure 6. Microstructure of the plates with different thickness at the initial state (away from the imact zone)

a) test number 5-6 (plate thickness = 6.35 mm, impact velocity = 367 m/s, 200x)
b) test number 6-7 (plate thickness = 8 mm, impact velocity = 368 m/s, 200x)

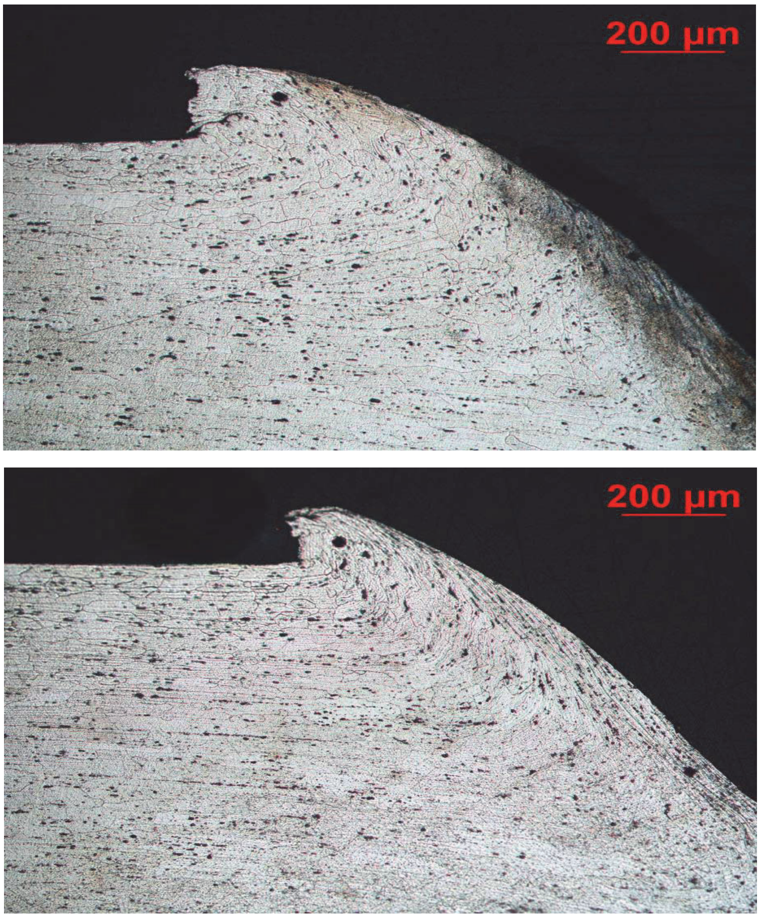


Figure 7. Microstructure of deformed plates, crater's view from B-zone

a) test number 5-6 (plate thickness = 6.35 mm, impact velocity = 367 m/s, 100x)
b) test number 6-7 (plate thickness = 8 mm, impact velocity = 368 m/s, 100x)

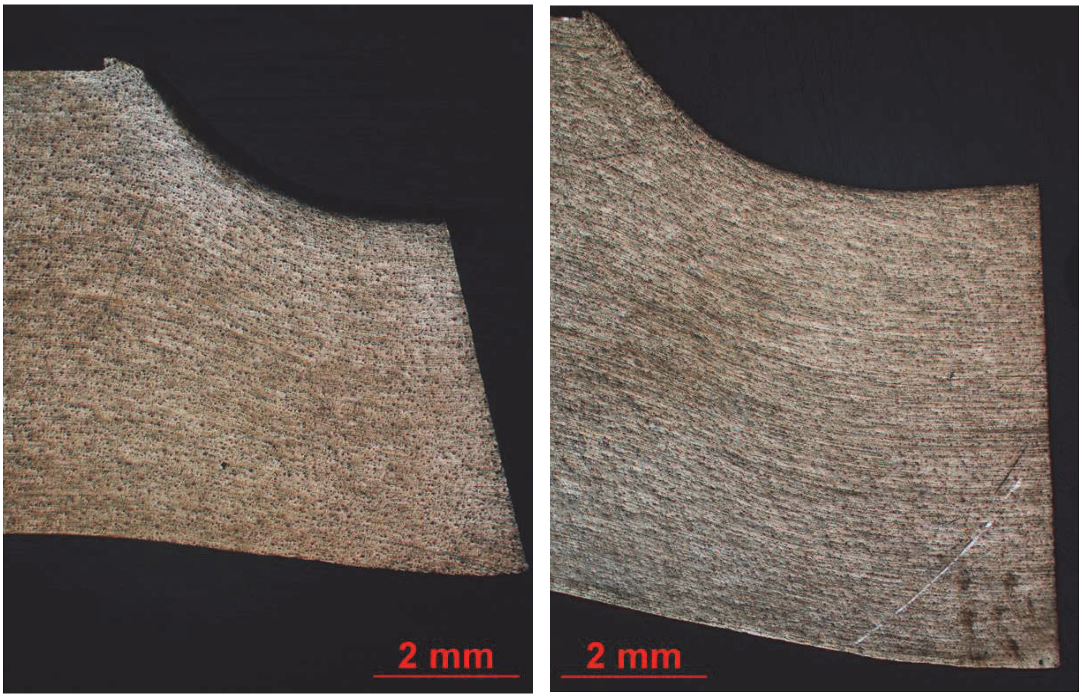


Figure 8. General material flow microstructure of deformed plates.

a) test number 5-6 (plate thickness = 6.35 mm, impact velocity = 367 m/s, 15x)
b) test number 6-7 (plate thickness = 8 mm, impact velocity = 368 m/s, 15x)

Adiabatic shear bands (ASB) are observed near the crater wall. These bands indicate high strain rate and localized heat generation near crater wall [Jena et al. 2010]. As a result of thermo-mechanical instabilities in ASB regions, cracks occurred in 6,35 mm deformed plates. One of these bands with crack can be shown in Figure 9.

3.3 Microhardness

Microhardness values taken from samples using 50 g weight are shown in Figure 10 and Figure 11.

Microhardness measurements were also performed for two samples at semi lateral 45^0 angles with impact direction. The results could be shown in Figure 12.

Hardness values are affected by two competitive phenomena; deformation hardening and thermal softening. 8 mm plate with 368 m/s projectile velocity has lowest deformation values and thermal softening overcomes deformation hardening then tends to decrease in hardness. All other plates tend to increase in hardness. Higher projectile velocities cause increasing hardness. Maximum hardness values are obtained just below the hitting area where deformation of materials is high. Semi lateral hardness values are similarly high at hitting area (point 1) but lower relative to impact direction values at a distance from hitting area because of less material flow in this region.

4. CONCLUSIONS

It was concluded from the study that thinner plates are more prone to deformation hardening with high penetration depth values even at low impact velocities while thick plates are more susceptible to thermal softening with less penetration depths. Maximum hardness values were obtained just below the impact zone in both plate thicknesses. Hardness values are also proportion with projectile velocity.

Adiabatic shear bands has been observed in both plate thickness but only thin plates has cracks in these regions. It can be thought that ASB induced cracks is an earlier indication of plug separation or perforation.

Thick plates show better performance with low penetration depth and less microstructural instabilities (ASB induced cracks). This performance is attributed to higher areal densities of thick plates.

Figure 9.ASB (adiabatic shear band) in test number 5-7 (plate thickness = 6.35 mm, impact velocity = 359 m/s, 50x)

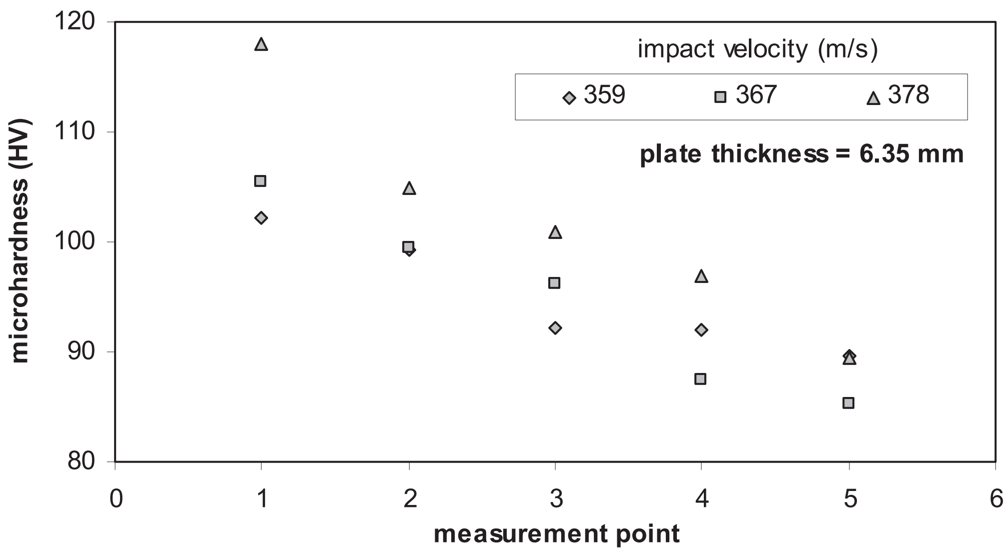


Figure 10. Microhardness values taken from samples of 6.35 mm in thickness (test numbers 5-5, 5-6 and 5-7)

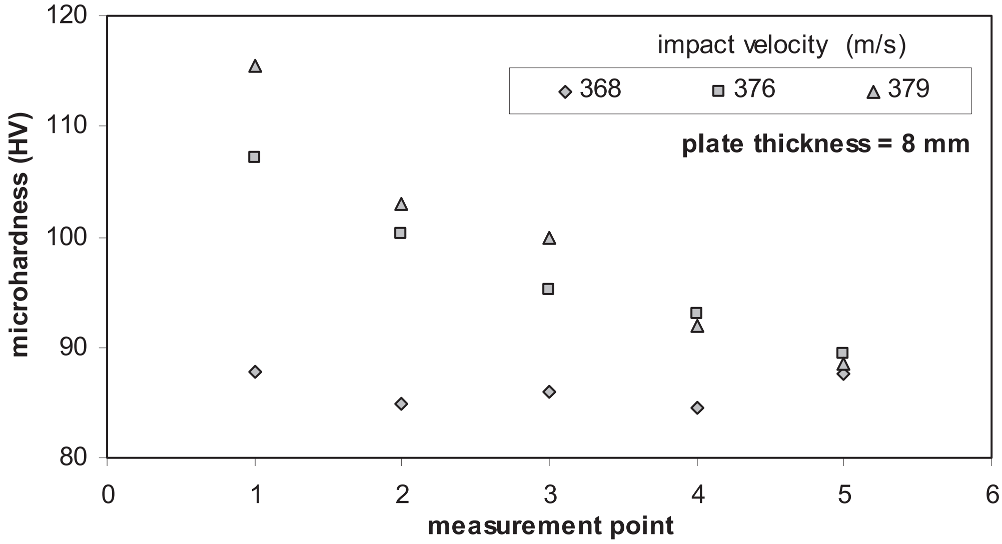


Figure 11. Microhardness values taken from samples of 8.00 mm in thickness (test numbers 6-5, 6-6 and 6-7)

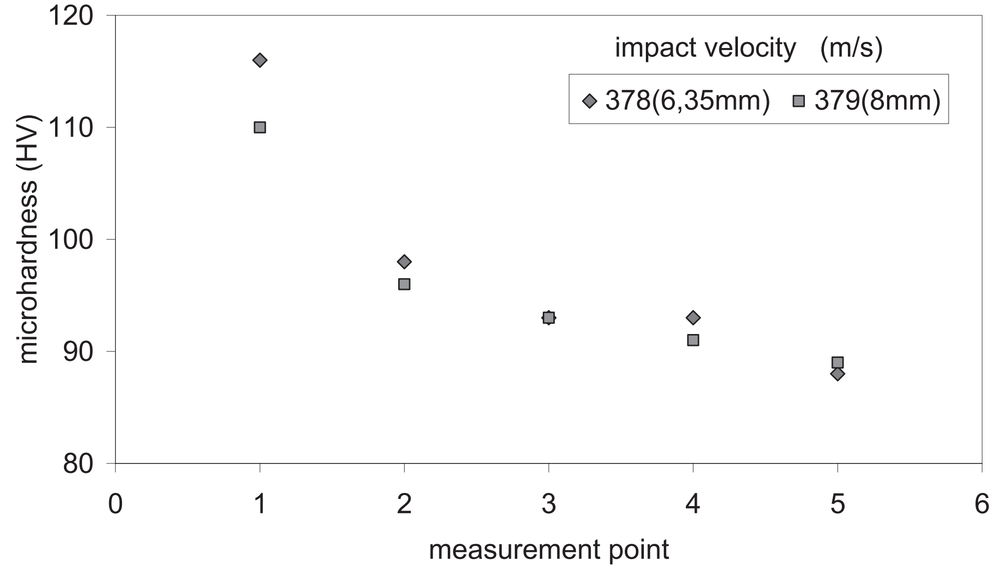


Figure 12. Microhardness values taken from samples at semi lateral direction (test numbers 5-5 and 6-6)

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