Falling weight low velocity ballistic testing and its damage on different type of metals

Düşen ağırlıklı düşük hız balistik testi ve farklı metal türlerindeki hasarı

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Highlights

❖ *The dynamic projectile motion has caused different work hardening property on metallic metarials.*

❖ *The free falling test provided a method of analysing the time required to deform with constant velocity.*

❖ *Springback force can be triggered at the initial projectile force which acts as a part of ballistic property.*

❖ *Results comply with Hollomon's results; the best correlation was found to be with K, strength coefficient.*

Graphical Abstract

The material property such as elastic and plastic response against the falling weight was investigated for low speed impact process; analyzes based on the test results were made with force and reaction time measurements.
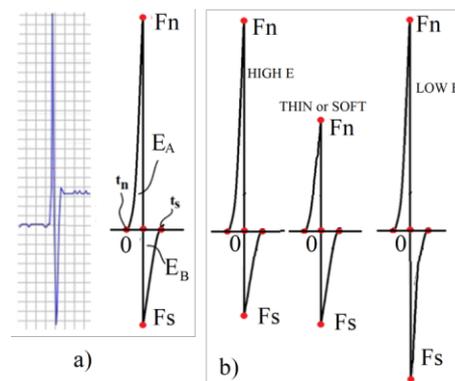

Figure 4. Simplified depiction of impact test result; a) calculation basis and b) a general classification of results

Aim

 The material response and the effect of testing were investigated during the free falling weight ballistic test of different metals to correlate and find a novel method of classification of metals against the falling weight.

Design & Methodology

Low velocity ballistic tests were carried out on four different metallic materials under the same conditions using a 1 Kg of weight to deform the free moving metal plates. The springback response of metals at a constant speed was measured using test jig in terms of force and deformation duration.

Originality

The response of metallic materials against the falling weight was investigated at low speed impact using a test jig that classifies the damage according to ballistic property

Findings

The indent results showed that copper is more prone to impact damage whereas stainless steel and Brass are more resistant. Curves showed different dynamic responses against free falling weigth due to intrinsic properties.

Conclusion

The response time and force for the impact showed that strength coefficient are important parameters and Stainless steel is ballistically durable due to its high matrix hardness and high K value.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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Araştırma Makalesi / Research Article

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ABSTRACT

In this research, the damage mechanism applied by the projectile at the ballistic tip on the samples during the ballistic test of the samples consisting of different materials with the same wall thickness as the ballistic test was attempted to determine. Free falling low velocity ballistic test was performed in order to compare stainless steel, brass, copper, low carbon steel materials with the same wall thickness section. A jig consisting of sensitive force readings was set up and its principles were established. This study showed that the projectile tip creates a deformation zone as well as the state of absorbing the impact on the material which are possible to determine by sensitive measurements. Stainless steel and Brass showed better performance than low C steel and Copper due possibly to low work hardening property. K, strength coefficient, showed a significant correlation with the results.

Keywords: Impact damage, low velocity ballistic, ballistic testing, strength coefficient, ballistic resistance.

Düşen Ağırlıklı Düşük Hız Balistik Testi ve Farklı Metal Türlerindeki Hasarı

ÖZ

Bu araştırmada, balistik test ile aynı et kalınlığına sahip farklı malzemelerden oluşan numunelerin balistik testi sırasında balistik uçta mermi tarafından uygulanan hasar mekanizması belirlenmeye çalışılmıştır. Aynı et kalınlığına sahip paslanmaz çelik, pirinç, bakır, düşük karbonlu çelik malzemeleri karşılaştırmak için serbest düşen düşük hızda balistik test yapılmıştır. Hassas kuvvet okumalarından oluşan bir düzenek kurulmuş ve çalışma prensipleri belirlenmiştir. Bu çalışma, mermi ucunun bir deformasyon bölgesi oluşturduğunun yanı sıra, hassas ölçümlerle belirlenmesi mümkün olan malzeme üzerindeki etkiyi absorbe etme durumunu da göstermiştir. Paslanmaz çelik ve Pirinç, muhtemelen düşük pekleşme özelliği nedeniyle düşük C çelik ve Bakırdan daha iyi performans göstermiştir. Dayanım katsayısı olan K, sonuçlarla anlamlı bir korelasyon göstermiştir.

Anahtar Kelimeler: Darbe hasarı, düşük hız balistiği, balistik test, dayanım katsayısı, balistik dayanım.

1. INTRODUCTION

The word "Ballistic" is the acronym for the science that examines the thrust, flight and impact effect of projectiles. In ballistics, together with the weapon, the effect of ballistic and its examination is based on the tools by which the impact is carried out with the projectile, projectile parts or pellets. With the firing, the events until the projectile leaves the gun barrel are called internal ballistics and generally, it is the first muzzle velocity of the fired projectile by producing a flammable substance, especially gas, and using the thrust pressure of a few tons of this gas [1-3]. External ballistics, however, examines the movement of the projectile outside the barrel. One of the problems encountered in the examination of the ballistic impact event is the determination of the speed at which an object can withstand without being damaged, that is, the ballistic speed or critical impact velocity. Factors such as the shape and dimensions of the projectile, the impact velocity and the thickness of the

target also come to the fore in the calculations regarding the ballistic limit [2,3]. The effect of tensile, compression or other stresses that cause damage on the amount of energy required to pierce the armour material are an important tool in analysing the ballistic properties [4-6]. Keeping the amount of collapse to a minimum is provided by spreading the energy to be generated during the impact over a wide area on the target material. A large part of the energy generated by the impact of the projectile is transferred to the surface of the target material

directly in contact as local deformation from kinetic energy and heat. The target absorbs a significant amount of energy by being plastically deformed and damaged [2-4, 7-9]. The kinetic energy of a projectile varies depending on the penetration effect, the projectile mass, the speed of the projectile, the angle of hitting the target and the metallurgical properties of the projectile and armour materials [2-5]. With ballistic protection, it is aimed to minimize the impact resulting from the impact of an object at a certain speed and / or prevent its contact

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with the target. The behaviour of target during the course of deformation is explained by Johnson-Cook treatment of plastic deformation [9, 10] based on torsion test at various temperatures, too. Ballistic studies that are carried out using falling weight puncture test are comparable to actual ammunition tests [3-6] although falling weight experiments are usually carried out for polymer based ballistically proof composites [6, 7]. At low speed ballistics, the deformation analysis is different and relatively easier than high speed ballistic test [6, 7, 11]. One of the most important effects of projectile on metallic materials is the work hardening property. Work hardening becomes active beyond which a metal is strained beyond the flow stress for which an increasing stress is required to produce additional plastic deformation. Due to this process, the metallic material becomes stronger and more difficult to deform. Strain hardening reduces ductility, which increases the chances of brittle failure. Variation of fields of strains in the

specimens was cleaned with alcohol and it was ensured that all specimens were tested using the same conditions. The initial grain structure of 304 Stainless Steel consists of mostly equiaxed austenitic grains with a few annealing twins and the average size of grains is about 64 μm ±8.7 μm. Brass (70/30 quality with grain size of 102 μm ±17 μm) and Copper (grain size of 89 μm ±12 μm) also consists of mostly equiaxed grain but slightly elongated due to rolling and thickness reducing operation. Low carbon steel microstructure was elongated and plain i.e. contained no morphological feature inside the grain. The average grain size of low carbon steel was (73 μm ±15 μm). Hardness of specimens was measured using Shimadzu HMV02 microhardness tester using 100 gr load. Low speed ballistic testing was carried out using a setup consisting of 1 Kg of steel bar mass which was dropped on its own weight with effect of gravity from a height of 2.5m (Figure 1a). Figure 1a shows the force reading schematic consisting of 4 of 50Kg force sensors.

Table 1. Dimensions of the coupon samples used in this study (as received).

Specimens	Dimensions	Thickness (mm)
Low C steel (AISI 1010)	4 (35mmx35mm)	1
Cu (99%)	4 (35mmx35mm)	1
Stainless Steels (304 Quality)	4 (35mmx35mm)	1
Brass (65/35-Alpha Brass)	4 (35mmx35mm)	1

matrix generate dislocations and cross movement up to which the movement is restricted by grain boundaries, pinning obstacles and other dislocation networks and strain fields such as Cottrell atmospheres [12-14].

In this study, a subsonic low velocity free falling weight ballistic test was carried out in order to compare samples of stainless steel, brass, and copper, low carbon steel with the same thickness.

2. EXPERIMENTAL PROCEDURES

Test samples were prepared in accordance with the dimensions in Table 1. The slicing process was carried out mechanically without using any heat input in order to preserve the initial as-received condition of the specimens. After slicing process, the surfaces of

Plates of metals were not fixed. Force readings scanning speed was analog signal and 16 MHz, which gives a resolution of min 0.001ms. The sensor response time is less than 1.5 ms max. A hardened projectile tip (48 HRc) was used (Figure 1b) for the testing. An average projectile velocity of 6.2 m/s was achieved but the velocity at time of contact was measured from impact tests. The depths of indents resulting from the impact test were measured using a digital calliper. The setup for the testing is shown in Figure 1a, an Arduino based data logger was used to record the signals from velocity sensors and force measurements (upto 50 Kg) and output was saved on a computer. The digitised data were analysed for the exact measurements of force on the sensors and the velocity of projectile.
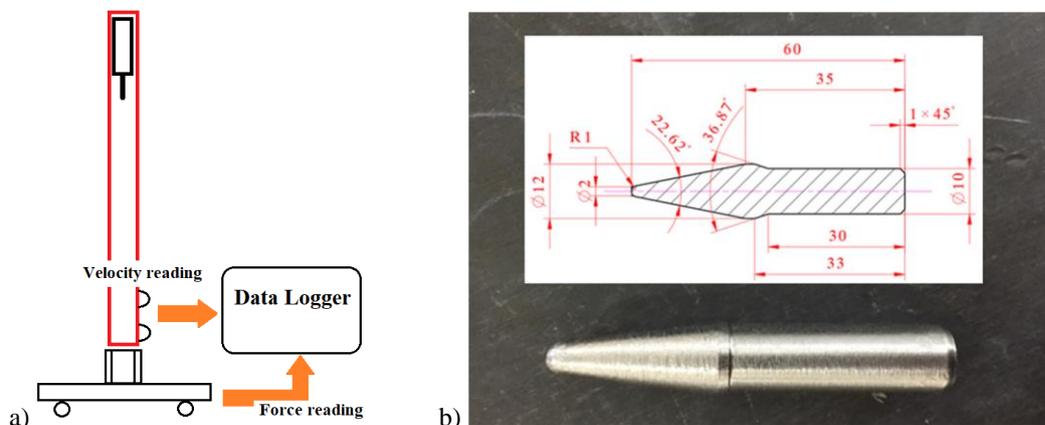

Figure 1. a) Principle of data collection and b) the technical drawing of the projectile.

3. RESULTS AND DISCUSSION

3.1. Low Velocity Ballistic Testing Results

Ballistic test results are given in Figure 2 below. It was observed that the Brass and Copper coupons were the most affected as a result of the impact and ended with a rupture in the middle of the plate. However, this perforation of the plate was not observed in stainless steel and low carbon steel coupons. Therefore, it can be concurred that there may be a relationship between the degree of perforation in the specimens and the modulus of elasticity and the strain coefficient. During the hardened projectile engaging the surface of the coupon, there is a sudden dynamic deformation process or work hardening at the point where the projectile tip touches. With the effect of the speed of the projectile, a large part of its energy is spent on the deformation of the metallic plate, and it causes high tensile stresses resulting in a work hardening or strain hardening with the effect of the projectile impact. The high deformation rate causes an increase in dislocation density generation at the beginning of projectile contact and it is multiplied significantly, which leads to the tangling of dislocations with time and applied force. Dislocation density in all specimens, especially Brass and Stainless Steel should increase and a saturation point or a large amount of tangle of dislocations should be rapidly reached due to partly intermetallic constituents present in the matrix as in Brass (CuZn- CsCl prototype) and high number of alloying elements related to matrix hardening as in Stainless Steel [15-17]. Annihilation effect on dislocations is not generously expected since the deformation takes place at room temperature but it should be very limited. With low amount of deformation, the activation of slip planes is not fully accomplished because of many reasons such as the magnitude of applied force, grain orientation etc.., but, in the case of highly deformed metal, the dislocations are almost fully activated and failure limit is usually reached. For this reason, there will be a limited amount of slip planes that are active and ready to glide on close packed planes [16, 18, 19]. Work hardening causes a formation of cracks as a result of dislocation tangle formation and hence, without the possibility of dislocation formation, either highly deformed and hard layer forms or a crack occurs ahead of moving projectile tip. At this stage, the frictional forces between the tip of the projectile and surrounding surface on the target plate are to be omitted.
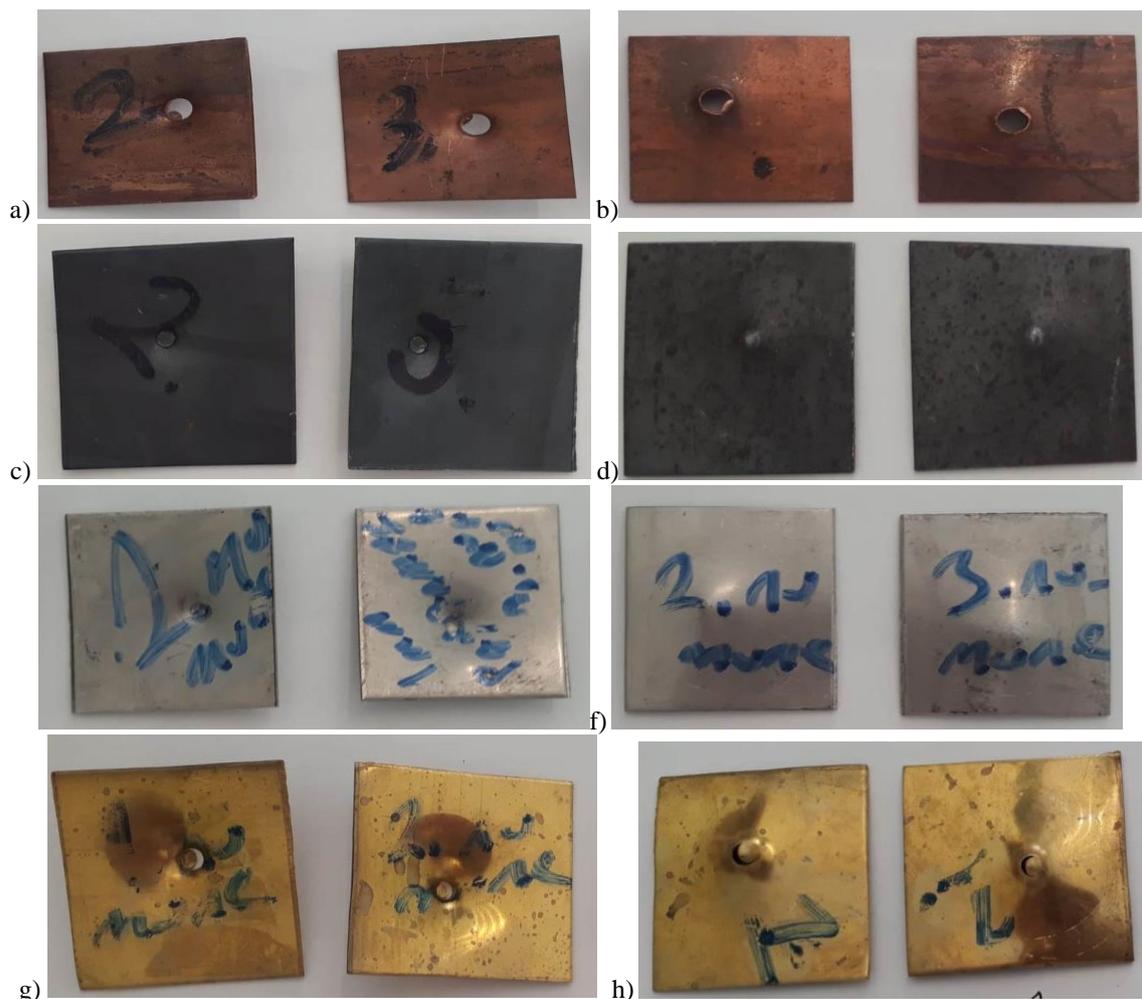

Figure 2. Front and back views of a, b) Copper, c, d) low carbon steel, e, f) Stainless Steel and g, h) Brass samples after the test; front (left) and back (right) view.

Since the thicknesses in each sample are the same and the projectile tip diameter is the same, the width of the zone subject to deformation remains the same. However, during deformation, the material of the same size is subjected to deformation hardening with the exceeding of the yield point, and the materials that harden more easily and have a low elasticity modulus are more easily damaged. In this study, AISI 304 Stainless Steel, Brass and Copper are F.C.C. and Low C steel is B.C.C. structure. Intrinsically, FCC structures contain lower number of slip planes compared to BCC crystals. FCC crystal having 12 slip planes or glide systems are more malleable due to close packed (111) planes but BCC crystal having 48 slip systems are not as malleable due to less number of close packed system that can be easily activated upon load [12, 17-19, 23, 24]. However, as the C content is lowered the steel becomes softer naturally [20].

Average velocity is not included in the calculation since it includes the acceleration process due to gravity from the beginning. The ballistic test that resulted in a puncture in copper target is shown in Figure 2a and b and Figure 2g and h, and as a result of the impact force measurement of stainless steel given in Figure 2c and d and Figure 2e and f, ended with high back reflection and less deformation. The springback zone increases in proportion to the amount of deformation. It was observed that the projectile tip, which showed a free fall, fell independent of its own weight only with the effect of gravity with an impact velocity of approximately 16.4 m/s at the point of impact.

The data obtained in this study (Figure 2 and Table 1) showed that the impact effect of the projectile when it engaged with the target varied according to the mechanical properties and hardness of the target material. The ballistic resistance of the target material is
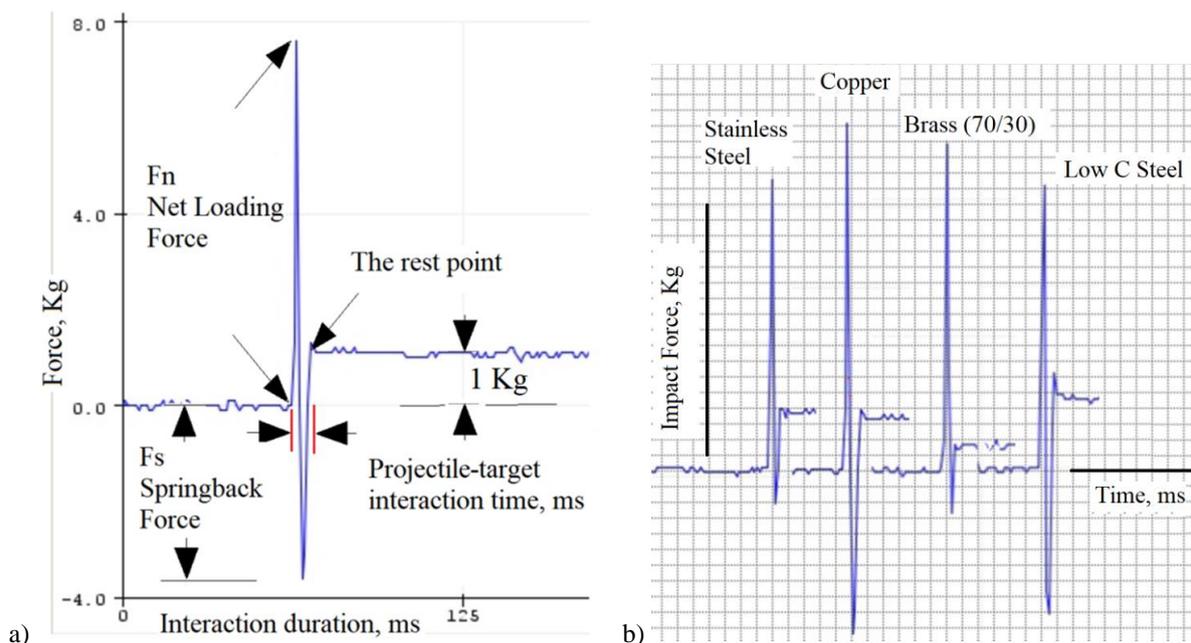

Figure 3. a) Impact force and analysis result showing impact duration and b) material responses

3.2. Force and Reaction Time Measurements and Analysis of the Process

In order to compare samples of stainless steel, brass, copper, low carbon steel materials with the same cross-section, a low speed ballistic test was carried out at the speed of free fall of 1 Kg steel mass. After impact force measurements and impact damage, the reaction force formation with the effect of springback of 1 Kg object is given in Figure 3. The ballistic impact zone and the area of measurement of the reaction force are clearly visible. Typically, the impact damping effect varies in proportion to the mass and or stiffness i.e. modulus of elasticity of the material [25]. The hard matrix is expected to absorb the impact and reduce the damage, with an effect similar to wear resistance.

The velocity at the moment of impact can be calculated with the information received from the velocity sensor.

determined by the amount of force that is absorbed by the material [2, 3, 8]. It can be proposed that the springback force in relation to the material impact strength for this type of experiment is given as:

$$Ʊ = \frac{Fs}{Fn} \tag{1}$$

Failback strength coefficient (Ʊ), is therefore, can be described as net springback force (Fs) upto the rest point (Rp) divided by the net load applied (Fn). Weight of projectile should be deduced from the total springback force readings since the projectile sits upon the specimen after the specimen is ballistically damaged.

The springback force is mostly determined by stored elastic behaviour during the sheet metal forming or high modulus of elasticity of new type of steels such as DC04 steels [26]. The correlation between material properties

and impact response given in Table 2 as a measure of correlation by Elasticity modulus (E), the work hardening coefficient (n) and strength coefficient (K) as given in Hollomon's equation. The relationship between the strain calculated during true stress-strain curve, stress and strength coefficient, K, is given in Hollomon's equation [12, 18].

$$\sigma p = K\epsilon_p^n \tag{2}$$

where ϵ_p is plastic strain, K is strength coefficient and n is work hardening coefficient. This equation states that plastic strain is a dominant factor in as the deformation starts on atomic planes, the fast moving glide process takes place at low n values but as the n value increases the dislocations interact intensely and further movement of dislocations are prevented and elastic forces are more prevailed. As is also shown in Johnson-Cook model [9], von-Misses and in Hollomon's model[10, 12, 18], the strain is dominant factor and the whole behaviour of plate deformation is dependent on how this strain is applied onto the surface of the target. However in this study, the results appear to be meaningful with Hollomon's results

i.e. the best correlation was found to be with K, strength coefficient. The deformation capacity can be correlated by K, strength coefficient and it closely fits with springback strength coefficient. Here plane stress conditions are valid due to thin material. As given in Hollomon's equation the critical stress is reached when there is sufficient amount of extension, i.e. strain that is equal to 1, then plastic deformation is inevitably active mechanism in deforming the material.

Figure 4 shows an example of an impact test result and categorized slicing of the curves as a basis for calculations. As given in Equation 1 that, Fn is the force at the time of impact, Fs is the springback force following the tip of projectile engaging the target surface. The reaction time, tn, is the time between the projectile tip touching the surface and beginning to deform the metal at an initial force of Fn. This duration is also an indication of how fast the load is transferred to the plate. As seen in Table 1 that the total duration is given in ms; this is the difference between tn and ts values. If the time between 0 and tn is taken out of total time, it can be seen that the total deformation time is relatively fast. The springback

Table 2. Impact force, springback force and the average indent depth results showing impact duration and material responses [21, 20, 10, 15, 22, 23]

|	Copper	Low C Steel	Brass	Stainless Steel
Net Force, Fn (Kg)	7.3	6.8	6,6	6.8
Springback Force, Fs (Kg)	-3.4	-3.25	-0,88	-0.73
The average indent depth (mm)	5.025	4.825	4.48	4.23
Failback Strength Coefficient, ℧	**0.46**	**0.48**	**0.13**	**0.107**
Elasticity Modulus, GPa	117	200	102	192
Work Hardening Coeff., n	0.54	0.26	0.49	0.45
Strength Coefficient, K	**315**	**530**	**900**	**1275**
Interaction duration (ms)	**8.3**	**7.2**	**6.6**	**4.2**
Hardness, HV	**68**	**152**	**96**	**229**
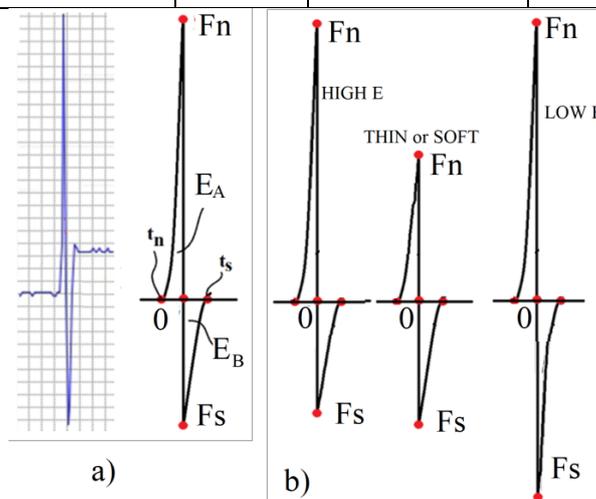
Figure 4. Simplified depiction of impact test result; a) calculation basis and b) a general classification of results

time, ts, is the resilience against the deformation of plate in response to projectile, Fs is the reaction force against the deformation of target at a projectile velocity of *v*. In this study, the *v* is fairly constant. As can be seen in Figure 3 and Figure 4 that there are four elements to be considered, Fn, tn, Fs and ts. The experiments showed that, the Fn is not always the same, although, the initial speed was same for all experiments. The inequality in the initial force is believed to be related how fast the metal undergoes work hardening process and hence the type of materials. Here, the second part of the curve, B is more appealing and Fs is comparable to Fn. The difference in Fn and Fs is not proportional and unreliable due to many reasons such as grain size, heat treatment history etc.., hence, this requires another approach, which is the comparison of the first half of the curve to the second half of the curve. Let A is the area of the first half of the curve and B is the second half of the curve; this can be written as a general assumption from the results obtained so far; $A \neq B$, $Fn > Fs$ and $tn \neq ts$. These assumptions are valid when the target material is resistant to change its shape or resilient to deformation. As shown in Figure 3 and Figure 4 that, there are two different areas in impact responses diagram. Two different regions can be divided into two distinct regions, which would allow the comparison of the areas A and B in terms of energy balance. Therefore,

$$dA = F.dt \tag{3}$$

If integrated, then it becomes,

$$\int dA = F \int dt \rightarrow A = \frac{F.t^2}{2} \tag{4}$$

For A and B, also ts and tn, this equation is valid and approximate solution for an hypothetical situation. If the impact energy of the projectile, i.e. the area of A, is consumed by the second half of the curve, there would be similar values, however, the results showed that this equation is invalid since Fn and Fs values are incompatible with each other because area comparison of Fn and Fs with tn and ts do not match in terms of energy. The theoretical principles about the energy comparison and displacement that were laid out by Warnet and Reed [11] also cannot be fully employed here since their specimens were fixed unlike of the situation here in this study. Although, the relationship between F and m in connection with v and t can be a good guide it does not connect the impact absorbance i.e. deformation to type of materials in their treatment of testing. In this study, it is possible that elastic strain, ε_{EL} and plastic strain ε_{PL} components are in a forced equilibrium such that as the matrix hardness increases, the elastic component becomes a dominant factor and plastic deformation is limited. This requires more research to be conducted. Hence the best comparison for the curves is the ratio of Fs/Fn. In other cases, such as soft materials i.e. paper or very thin target materials, would not obey this assumption since there is not enough body to resist the advancement of projectile tip. The second assumption is to outweigh the incompabilities in reading, the ratios are

employed i.e. $\frac{Fs}{Fn}$ and $\frac{ts}{tn}$. However, ts can be used to evaluate the damage processing and the effect of mechanical properties together with well established metallurgical principles. In this case, tn is rather ineffective compared to ts parameter but a response time is obtained with respect to deformation. As oppose to tn, ts is a determining factor in reviewing the damage. The higher the ts value, the lower the resistance against advancing projectile front, as can be seen in Figure 2 and 3. It can be assumed that, if Fs < Fn, which is a common case, it is the indication of low work hardenable material, if Fs<<Fn the work hardening is very active process. On the other hand, if Fs≈ Fn, the material is either very thin or relatively soft with no work hardening property.

4. CONCLUSIONS

As a result of low speed impact ballistic experiment on Copper, low C steel, stainless steel and brass, following outcomes can be drawn:

Under a constant projectile velocity, and changing parameter of material, the free falling test provided a method of analysing the time required to deform, in some cases, perforate the metal plate.

Testing of metal plates provided a way to understand how the force time graphs works such that the force transferred to plate trigger the springback force in response to initial force by which ballistic property can be partly identified.

It is also possible to suggest that mechanism of damage due to projectile at low velocity is dependent on crystallographic and structural properties.

The mechanism of damage was investigated by the effect of Fn and Fs on different materials. It is concluded that Stainless Steel is ballistically resistant due to its high K value and high matrix hardness.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Şükrü TALAŞ: Wrote the manuscript and setup the testing jig.

MİLAT KUL: Analyzed the results.

Mustafa YAZAR: Performed the experiments and analyzed the results.

Hilal KIR: Helped with experiments and analyzes of the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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