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Experimental investigation of the impact wear

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Abstract – Impact wear can be defined as the wear of a solid surface due to percussion, which is a repetitive exposure to dynamic contact by another solid body. It has not been studied as extensive as other wear mechanisms and the information on causes and actual data is quite scarce. In the present work an experimental wear tester is designed and used to study the impact wear phenomenon experimentally. It creates the consecutive impacts between balls and flat plate. The different ball sizes (up to 30 mm), impact velocities (up to 6 m.s^{-1}) and impact angle ($10°-80°$) can be tried by tester. The mass loss of plate is measured as the wear parameter. These measurements for different specimens revealed some aspects of their wearing behaviors. The obtained results could be helpful in optimal practical designs and explanation of some phenomena associated with impact wear.

Key words: Impact wear / hardness / mining / wear testing

Nomenclature

m	Ball mass
f_r	Reflected force (due to wheel-ball impact)
f_d	Deformation force (due to wheel-ball impact)
e	Coefficient of restitution
I	Ball mass moment of inertia
ω_1	Wheel angular velocity before impact
ω_2	Wheel angular velocity after impact
v	Ball velocity
H_{o1}, H_{o2}	Angular momentum before and after Wheel-ball impact
R_1	Radius in which wheel-ball impact occurs

1 Introduction

Industrial machinery components may subject to the mechanical impacts during their useful life. While component stresses safely remain under the yield point, practical usefulness of the machine element depends on its resistance to fatigue and wear. Fatigue may be virtually eliminated by maintaining the part under the endurance limit but wear phenomena apparently persist even at low stress levels. In many mechanical devices impact wear poses a severe problem to the useful life of components which are otherwise carefully designed for performance in the elastic range. Since preventive measures are mandatory, a basic understanding of the wear process and the factors influencing it must be sought. Very little engineering information has been established in this area [1]. Studies [2–4] revealed that the normal load and relative velocity of contact points are the main causes of the mechanical wear. Steady state wear mechanisms have been solved theoretically for the different wearing geometries but the compound impact wear evaluation is so complicated [5]. Becausse the impact phenomenon study is a complicated process, studying its wear behavior is a hard work. Several parameters may affect the impact behavior of materials. There are several theories for describing the impact. The most convenient model includes the Hertz relations which are limited in the elastic deformations. Mindlin [6] improved the Hertz theory for the case that the plastic deformation occurs. Researchers [7–9] theoretically and experimentally analyzed the variation of the tangential and normal forces due to impact of a ball on the flat plate.

Empirical models have been proposed to evaluate the wear rate in different modes of erosion due to solid particle interactions [10–14]. Talia et al. [15] established a theoretical analysis based on a new laboratory technique for solid micro- particle erosion. They could evaluate the effect of particle velocity components (normal and tangential) on the wear rate in micro-particle scales. Since many parameters affect the impact wear, generalizing the results of one case to other ones is rarely reliable and so each wearing case should be studied separately. Our case study is

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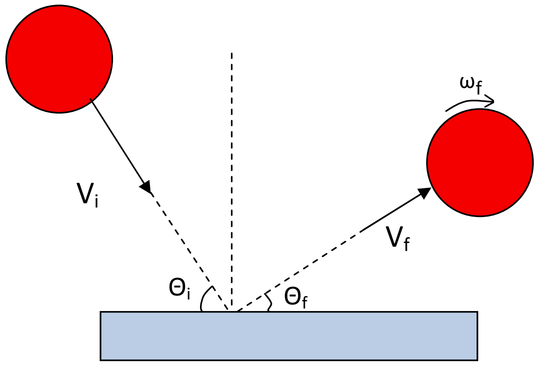

Fig. 1. Schematic of the ball impact on a flat plate.

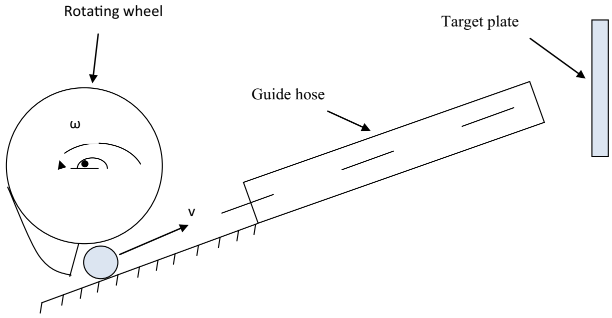

Fig. 2. Schematic of the rotating wheel, ball path and impacted plate position.

the wear of mill liners due to the impacts of mill charge (ball and ore). For this aim a new impact wear tester is designed, and as the elementary steps, the wear behavior of some materials is investigated. Experimental procedure is such that a flat plate is impacted consecutively by the steel balls and its worn mass is measured after a number of impacts. The results could be used to have the optimal designs where the impact wear occurs. The advantage of the present work compared to other researches of the field is free impacts of ball on specimen. The other impact experiments include impacts that the impactor doesn't collide the specimen freely. The impactor is often a hammer [2,3], or mass spring [16] which includes the arm force effects during impact. They are not free impact of a ball on the specimen. Some researchers [1,17] stated that the experimental data on real impact wear are so scarce. Another advantage is the macro ball impacts. Many experiments of this field include the impact of a flow of small shots of sizes of 200 μm [18] or 5 mm [9]. Here the experiments are performed with the ball sizes of 25 mm.

2 Impact

Impact of mechanical elements conjugates with transferring the high level forces due to small periods of time and causes the mass loss of elements. However the impact is a complicated process to be completely analyzed [19] but at least it can be said that the response of bodies depends on the impact initial conditions and material properties. In the case of the impact of a ball and a flat plate, as schematically illustrated in Figure 1, the ball impacts the plate by the initial velocity v_i at the angle θ_i and leaves it by the final velocity v_f and the angular speed ω_f at the angle θ_f. Impact studies generally include the attempts of providing the procedures to determine the material responses and final impact parameters [6–9]. Mass loss of impacting bodies is one of devastating effects of the impact phenomena and makes the elements away of their normal performance so it would be obviously desirable to accommodate the level of impact wear. For this aim, the influence of impact parameters and material properties on the wear intensity should be studied. It requires the incorporation of the contact and wear theories and will be obviously a complicated process. A simple and reliable way is using the empirical apparatus. Some machines have been manufactured for this aim [2,16,20–22] and, here a new wear tester is designed to study some aspects of impact wear.

3 Experimental apparatus

As mentioned, theoretical analysis of the impact wear is rather complicated and may not give the reliable results. So, the empirical apparatus would help us to study the process reliability. As a part of a tumbling mill performance study (in Sarcheshme copper complex) we were to explore the effect of particle impacts on the wear of mill liners. To obtain the experimental data for our case a tester is designed such that the balls get the required velocity and impact the specimen (a flat plate) consecutively. The balls are positioned in front of the rotating wheel, get the velocity, move through an inclined hose toward the specimen and impact it. After that, they fall in the ball container to repeat the process. The schematic of the rotating wheel, ball path and specimen are illustrated in Figure 2 and an image of the impact apparatus is illustrated in Figure 3. A 25 mm ball is illustrated in this figure to show the real size of machine. The specimen can be positioned in different angles in front of the ball path.

At a special value of the wheel rotational speed, a special value of ball velocity is achieved. The ball velocity is evaluated using the dynamic relations of motion. Assuming the conservation of angular momentum during the wheelball impact, and using the definition of coefficient of restitution, the following relations could be written.

$$H_{o1} = H_{o2} \tag{1}$$

$$\bar{I}\omega_1 = \bar{I}\omega_2 + mvR_1 \tag{2}$$

$$e = \frac{\int f_r \mathrm{d}t}{\int f_d \mathrm{d}t} = \frac{m(v - v_0)}{m(v_0 - 0)} \tag{3}$$

$$e = \frac{\int M_r \mathrm{d}t}{\int M_d \mathrm{d}t} = \frac{\bar{I}(\omega_2 - \omega_0)}{\bar{I}(\omega_0 - \omega_1)} \tag{4}$$

$$v = \frac{\bar{I}R_1\omega_1(1+e)}{\bar{I} + mR_1^2} \tag{5}$$

Table 1. Material properties of the specimens.

Conventional name	Material	Modulus of elasticity	Hardness	Dimensions
A	steel (annealed)	210 GPa	160 HB	$3 \times 4 \times 1$ cm
B	brass	110 GPa	180	$3 \times 4 \times 1$ cm
C	copper	110 GPa	140	$3 \times 4 \times 1$ cm
D	steel	210 GPa	250	$3 \times 4 \times 1$ cm

Fig. 3. Impact wear tester.

where f_r and f_d are the interactive forces between ball and wheel during the reflection and deformation periods respectively. Other parameters are defined in nomenclature. The coefficient of restitution is obtained by drop of balls on disk from a specified height and measuring the restitution height. Performing this experiment, for ball and disk collisions, gives the average value 0.5 for this coefficient. It doesn't highly change in the range of our required velocities. Evaluating the ball velocity by measuring the distances of ball movement in horizontal and vertical directions confirms the relations of equations (1)−(5) by an error of about 3%.

4 Specimens

Experiments were conducted with balls made of AISI 52 100 steel (nominal chemical composition of 1.04 wt.% C, 0.35 wt.% Mn, 0.25 wt.% Si, 1.45 wt.% Cr, bal. Fe), which presented a diameter of 25 mm. Different specimens are used to investigate the effect of various parameters on the impact wear. The specimens are selected such that the effect of parameters such as hardness, number of impacts and impact angle can be investigated. Two different hardness alloy AISI H10 steel plates (nominal chemical composition of 0.81 wt.% Si, 0.42 wt.% Zr, 0.26 wt.% S, 0.19 wt.% V, 0.65 wt.% Cr, 1.68 wt.% Mn, 0.46 wt.% Ni, bal. Fe), gilding brass (5 percent Zn) and copper plates are used for this aim. The reason of such selection is that the steel elements are subjected to the impact wear in industrial machinery. Brass and copper bushes are used as the seals and so subject to wear. They are listed in Table 1 and conventional names appropriated to them. All specimens have machined surfaces.

The specimens are dehumidified by use of the ultrasonic drier before and after tests to have the reliable measurements. Impacting elements are heat-treated chromium-steel balls of 600 HB hardness, they are hard enough compared to the specimens to be considered rigid.

5 Test results

Impact process causes surface pitting during the initial impacts until the surface is hardened enough and more pitting doesn't happen. After a number of impacts (which wear is not measurable) the worn mass is measured.

Collision angle of ball is an important parameter in the impact wear process. It has been shown that for a given velocity and ball size, there is a collision angle that maximizes the wear rate. It may be because that the shear impact energy and sliding duration maximize in this impact angle. This angle has been reported near 20−30° [9,16,18]. The present experiments also confirm this as illustrated in Figure 4.

Test results also uphold that the material hardness highly affects the wear intensity. Variation of the worn mass with respect to the material hardness is illustrated in Figure 5. However these data are of different materials but we can see that the wear intensity increases as the materials softened. Effect of hardness is different at the different impact angles and is more evident at the impact angle of 30 degrees.

Plastic deformation occurs in plates due to ball impacts. It makes the work hardening to happen on their surfaces and so the wear rate may decrease as the impact number increases (Fig. 6). Comparison of the wearing behavior of materials A and D in Figure 7 reveals that the harder materials less hardened due to impacts.

Figure 8 illustrates the surface of materials A, B and C after 600 impacts at the impact angle of 30 degrees. Craters are evident on plate surfaces which reveal the plastic deformation before wear. Observation of the subsurface morphologies revealed that a larger amount of plastic deformation occurred on the wear surface. This is described as a forging and normal extrusion mechanism, producing deep surface pits that contribute to the erosion process. Therefore, it can be concluded that the normal impact energy defines the level of deformation and forging mechanism and increases as the impact angle increases.

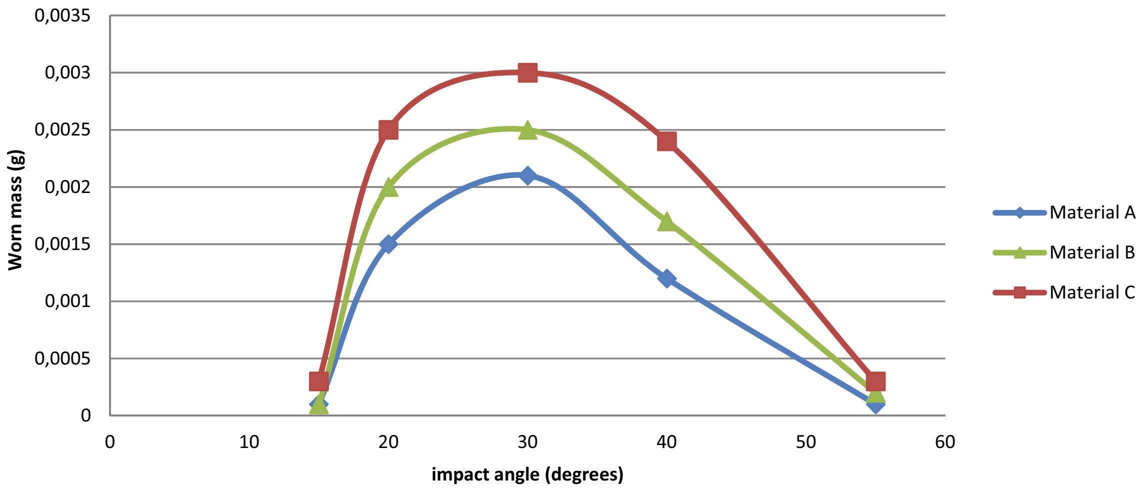

Fig. 4. Variation of the worn mass versus the impact angle for materials A, B and C due to 600 impacts.

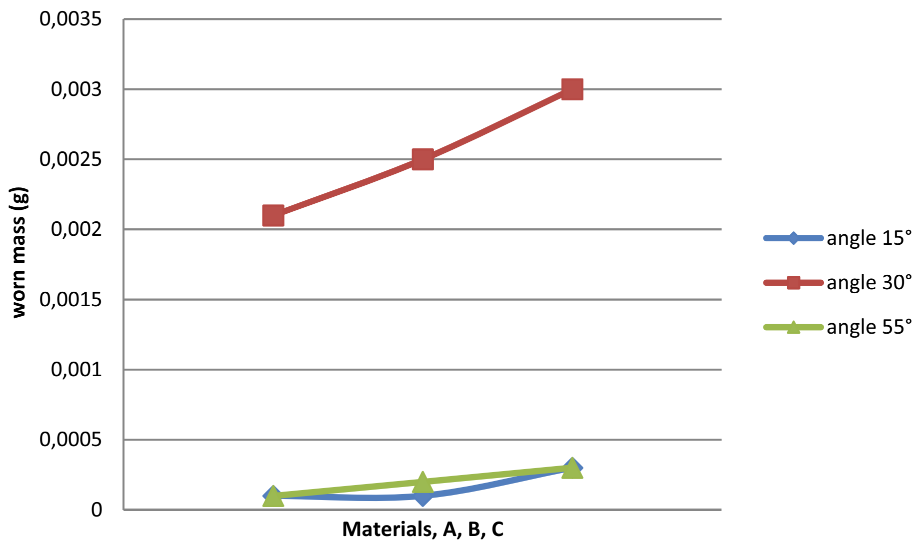

Fig. 5. Variation of the worn mass versus the material hardness due to 600 impacts.

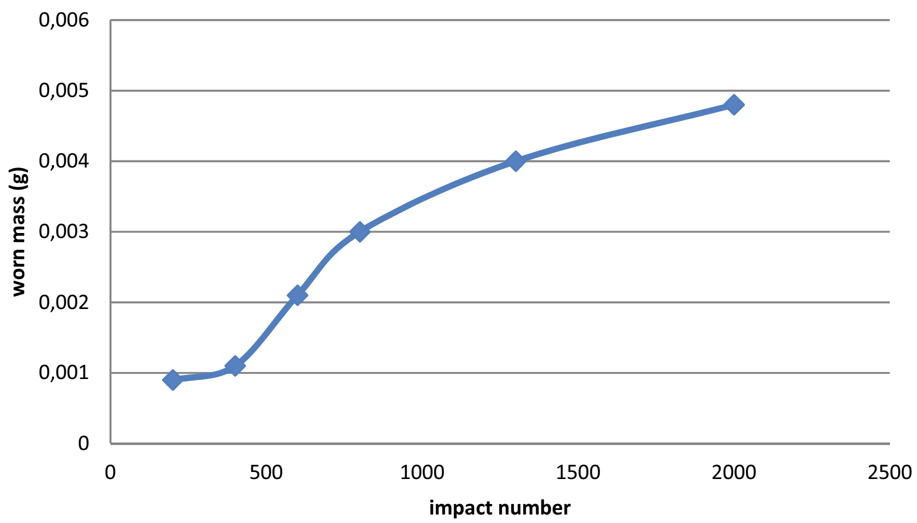

Fig. 6. Variation of the worn mass versus the number of impact for material A.

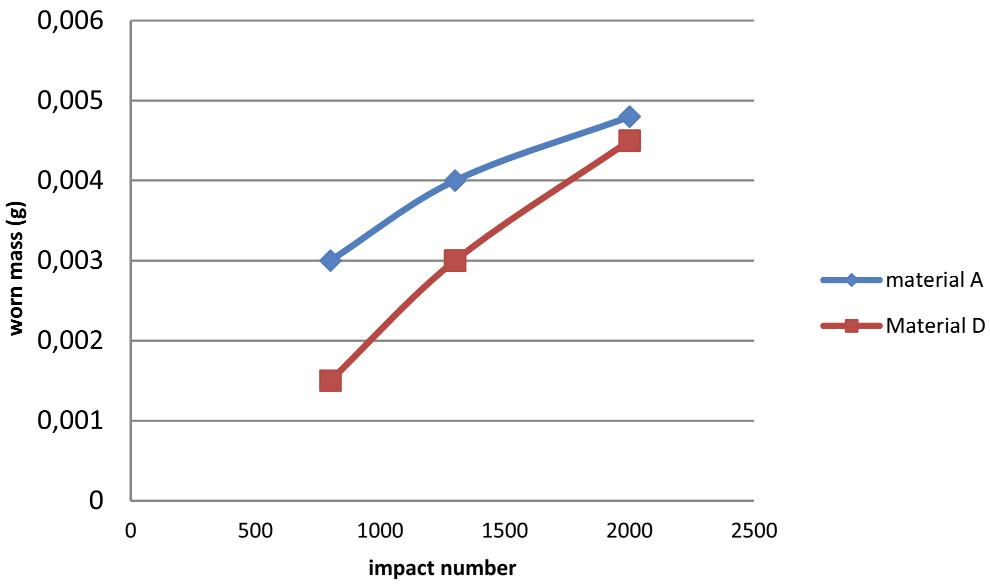

Fig. 7. Comparison of the wear of materials *A* and *D*.

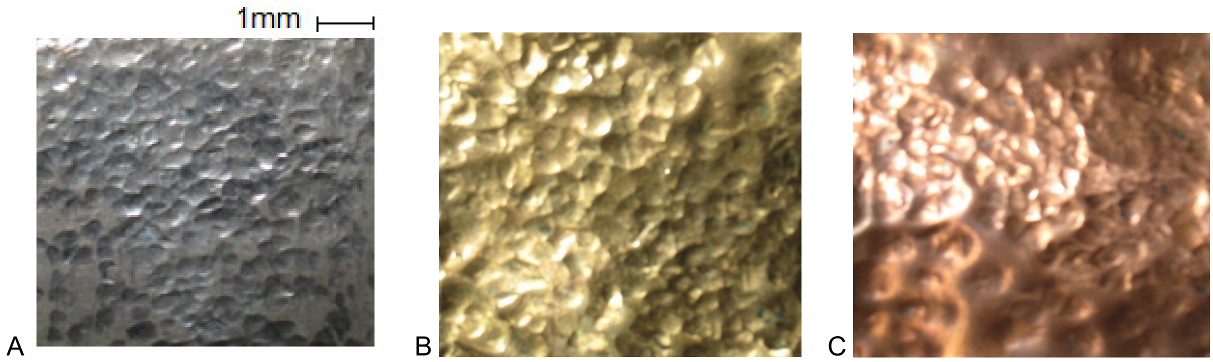

Fig. 8. Images of specimen surfaces after 600 impacts at 30 degrees impact angle.

6 Results and discussion

Impact wear investigation of the mill liners using an impact wear tester is of interest. Different plates are impacted consecutively by balls and the worn mass is measured after a number of impacts. Obtained data well describe some aspects of the impact wear. Effect of parameters such as the impact angle, material hardness and number of impacts is investigated. The maximum wear occurs at the impact angle of 30 degrees which is in agreement with the reported results and is because of increment the shear impact energy and sliding duration. Based on scanning electron micrographs of the eroded specimens, it has been stated that the most dominant material removal made in mechanical erosion is cutting together with cracking happened at 20–30° [23]. Similar examinations have revealed that on the span of collision angle 60−80° the major mechanism is the deformation of the surface by particle impacts. Material hardness highly affects the wear intensity. The plastic deformation occurs due to impacts and so the wear rate decreases due to the hardening behavior. Since the hardness is proportional to the yield strength the hardness increases due to the plastic deformation which increases the material strength. The experimental results show that the wear rate decreases as the impact number increases as a result of strain hardening. The hardening behavior and other effective parameters are currently studied in more details by authors.

7 Conclusions

The experimental study of the impact wear due to impacts of macro ball sizes is of interest. A new impact wear tester is designed. It enables us to simulate the ball impacts on a flat plate as the wearing specimen and eliminates the lack of data in the field of impact wear due to real free impacts. The effect of impact angle, material type and impact number on the impact wear are investigated. It is seen that the impact wear maximizes at the impact angle of 30° which is in agreement with the reported results. As the impact number increases the wear rate decreases as a result of material hardening. The micro-images of material surfaces after impact reveal that the plastic craters, as the forging process, and mass loss in the form of mechanical wear are two governing processes of the mechanical impacts.

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