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Low-speed impact on structural integrity of aluminum alloy Al1050

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A B S T R A C T

Low-speed impacts are common occurrences in industries such as aviation, automotive, and marine. Yet they have received relatively little attention compared to medium and high-speed impacts. Understanding the behavior of materials under low-speed impact is crucial for ensuring impact resistance and damage absorption in engineering structures. This study presents an experimental investigation into the low-speed impact behavior of 1050 aluminum alloy plates. Impact tests were conducted using a CEAST 9340 drop-weight testing machine, varying impact energies and temperatures to analyze their effects on the material. The findings highlight the importance of understanding the dynamic response of engineering materials under low-speed impact loading conditions. The insight gained from this study informs the design and optimization of aerospace and automotive structures to enhance their impact resistance and structural integrity. The results of the study indicate an inverse relation between the temperature of the impacted specimen and the maximum contact force.

1. Introduction

Aluminum alloys, renowned for their versatility and applicability across various industries, undergo significant enhancements in physical, mechanical, and chemical properties through alloying. The ability of aluminum alloys to withstand low-velocity impacts is of paramount importance in structural, aeronautical, and automotive applications. The low velocity dynamic impact behavior on Al alloys structures has become a problem that requires immediate attention. In the aviation industry, for the design of aircraft structural components, accidental tool drops during service maintenance must be considered. Furthermore, impact loads of hailstone, bird strike, and debris must be accounted for when designing aircraft structures. The material ability to absorb energy and crashworthiness are important issues in the design cycle. In the past decade, the focus had been in the penetration process of aluminum alloys and the peculiarities that influence perforation. The main objectives of the current study are to consider the low velocity impact behavior of Al alloy 1050 and find correlations between temperature of the alloy, impact energy, contact force, and displacement after impact. Despite their widespread use, the dynamic impact behavior of aluminum alloys under low-velocity conditions remains relatively understudied, and consequently this study aims to address this gap.

Impact tests determine if a material is brittle or ductile by examining the transition temperature from brittle to ductile. They determine the amount of energy absorbed by material during fracture. Below a critical threshold of impact energy, no significant damage occurs, where the impact is elastic, and the impact energy is absorbed. Impact energies above this threshold can compromise the material strength and cause significant damage (Guo et al., 2023a). The effect of impact can cause failure in engineering structures in different ways depending on the failure modes. The failure can be catastrophic (instantaneous) or years after the moment of impact by way of fatigue loading. Low velocity impacts can be classified as impacts with velocity ranging from 1 to 10m/s (Guo et al., 2023b). These impacts are usually simulated experimentally in a lab using drop weight impact instruments. A drop weight test is used to determine a material's capability to resist sudden impact force. That is, the

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amount of energy that it takes to fully break a material specimen and how much energy can the material specimen absorb. Low velocity impact is of particular concern to aerospace structures such as airplanes, which occurs during service and routine maintenance, e.g., dropping a tool on the airplane body or encountering runway debris thrown up and hitting the airplane. This is a huge reason why aerospace structures materials must have considerably high impact resistance. Impact resistance of a material is directly related to its young's modulus. Stiffer materials have less impact resistance and increasing the modulus of elasticity of the material decreases its impact resistance (Guo et al., 2023b). Previous studies revealed that when aluminum alloy plates are impacted with 100J impact energy, the highest energy absorbed at 13kg impact mass. And with increasing mass of impact hammer the material energy absorption decreases.

2. Experimental Study

Low-velocity impacts, typically ranging from 1 to 10 m/s, were simulated in the laboratory using a CEAST 9340 drop hammer impact machine. The CEAST9340 drop hammer allows impacts to be conducted at different temperatures and impact energies with different impact hammer masses (punch mass). The well-known relation between kinetic energy, mass, and velocity $E = \frac{1}{2}mv^2$ can be used to find the desired parameter required for the test machine. The CEAST9340 (**Fig. 1**) allows for impacts at different temperatures and energies, with variations in impact hammer falling height. The experiment carried out in the lab involved impacting 27 Al1050 samples with three impact energies (40J, 80J, 120J) under a variety of temperatures (25°C, 70°C, 100°C) to investigate the impact behavior under low velocity impact.

Table 1. Impact Parameters for specimens impacted at different impact energy levels

	Impact parameters impacted at following energy levels		
Impact Energy (J)	40	80	120
Impact Velocity (m/s)	2.57	3.63	4.44
Falling Height (mm)	336	671	1007
Additional Mass (kg)	9	9	9
Total Mass (kg)	12.15	12.15	12.15

Fig. 1. CEAST 9340 drop weight impact machine developed by INSTRON® used in experimental tests

Specimens consisting of square Al1050 plates were securely clamped on a circular fixture and subjected to impact using a hemispherical steel tip. For each temperature and energy, the test is repeated 3 times. The specimens used for the impact test are 100 × 100mm of Al1050. The thickness of the plates is 2 mm +/- 0.2 mm and weighs around 52.6 g +/- 0.5 g. To begin with, the specimens are marked and labelled with the temperature and Energy which will be tested at. This is done to avoid mixing up between the samples and later associate each sample with its impact data saved in the computer terminal which is connected to CEAST 9340. To ensure that the sample is at the desired temperature, the sample is heated for 10 min then impacted.

For the data collection, pictures of the impacted specimens from the impacted and non impacted side are taken. The absorbed energy by the material (J) vs time (ms), the load (N) vs time (ms), and the displacement vs time (ms) are obtained for each impact. The impact velocity, impact mass, and height from which the impact hammer is dropped, are noted for each impact energy. The results of impact data and associated damage profile are recorded.

3. Results and discussion

The maximum energy absorbed in Al alloy 1050 specimens occurs at 120J impact energy, at 25°C, **Fig. 2**. The maximum energy value = 111.7 ± 2.575 J. The trend observed from the results is that with increasing T, the maximum absorbed energy slightly decreases. At 120 J, increasing the temperature from 25 °C to 100 °C, decreases the material absorbed energy by 3.67%. The results observed can be explained by examining the stress - strain curve of al1050 at the tested temperatures. For example, at 100 °C the material loses some of its strength due to decreases in dislocation density because of an increased annihilation. The high temperature enhances dislocation interactions within the material. It is proposed that the strength of al1050 alloy is more affected by dislocation density than the effect of grain size (Wang et al., 2023b). When analysing in terms of stress vs strain curve and strain-rate effect, a relation can be established between impact energy and strain-rate. As the impact energy is increased, the impact velocity is increased, resulting in an increase in strain-rate. The strain-rate can affect the Al1050 properties at elevated temperatures causing softening of the metal. This change in material properties decreases the strength and increases the ductility. Therefore, there is a direct relationship in al1050 between the temperature and ductility. An inverse relationship exists between the strength of al1050 plates and temperature. However, for the strain rate effect to be appreciable in aluminium alloy 1050, the temperature as indicated experimentally should be elevated, higher than 100 °C (Wang et al., 2023c). Thus, the temperature should be higher to cause a significant softening of the metal. The experimental results observed are explained in detail in the upcoming sections.

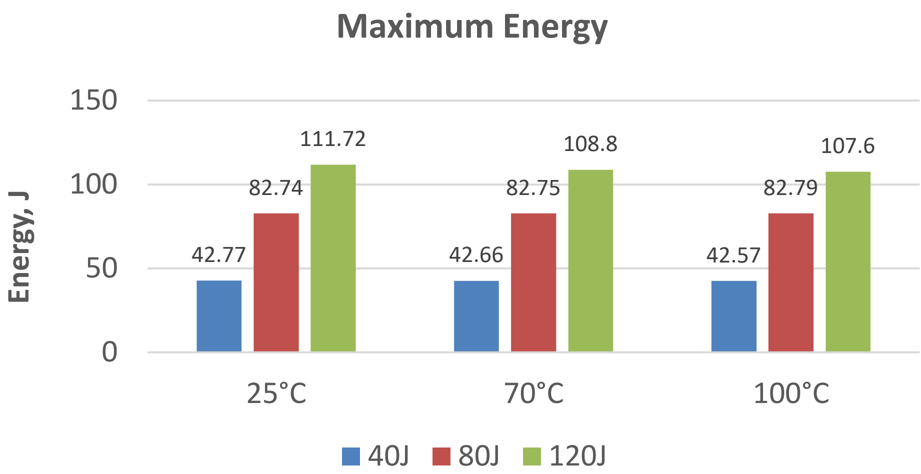


Fig. 2. Maximum absorbed energy at 40J, 80J and 120J impact energy at 25°C, 70°C and 100°C

The maximum displacement with respect to temperature for each impact energy is obtained as seen in Fig. 3. The maximum displacement equals 48.28 ± 5.43 mm which occurs at 25 °C and 120 J impact energy. Further inspection and analysis of the data reveals that increasing the temperature of the specimens from 25 °C to 100 °C decreases the displacement by 10.7%. The lowest displacement in the material happens at 40 J of impact energy which is expected since it is the lowest case of impact energy used in the experiment. With increasing impact energy, the velocity of the falling hammer increases, and increases the strain-rate and consequently the displacement in the material at the point of impact increases. The results in **Fig. 2** can be explained in terms of stress – strain curve of Al alloy 1050. As the impact energy is increased, the impact velocity increases and strain-rate increases with increasing stress in the material, hence going higher up in the stress-strain curve of al1050. This results in a plastic deformation beyond the yield strength of the material. As can be seen from **Fig. 2** for example, increasing impact energy at 25°C from 40J to 120J, increases the displacement by 46.7%. As discussed previously, the strain-rate is higher when the impact energy is higher since the impact velocity is increased. Also, the strain-rate effect in al1050 is higher at elevated temperatures (Wang et al., 2023c). The change in displacement with altering the temperature is more appreciable at the 120 J impact cases. There is a direct relation between ductility of Al1050 and temperature while there is an inverse relation between strength of Al1050 and temperature (Wang et al., 2023a), the overall result is dependent on these factors. higher ductility material allows for better absorption of impact energy. Whereas higher strength in the material allows for less displacement in the material. Considering the effects of all the mentioned parameters in terms of stress – strain curves help understand the influence on impact displacement results. At 120J as we increase the temperature, the displacement decreases, but not considerably. This is because the temperature is not elevated enough for the strain-rate effect to be prominent and to have significant effect in displacement. The error bar at 25 °C and 120J is higher than other cases could be due to friction observed in the impact machine when unloading.

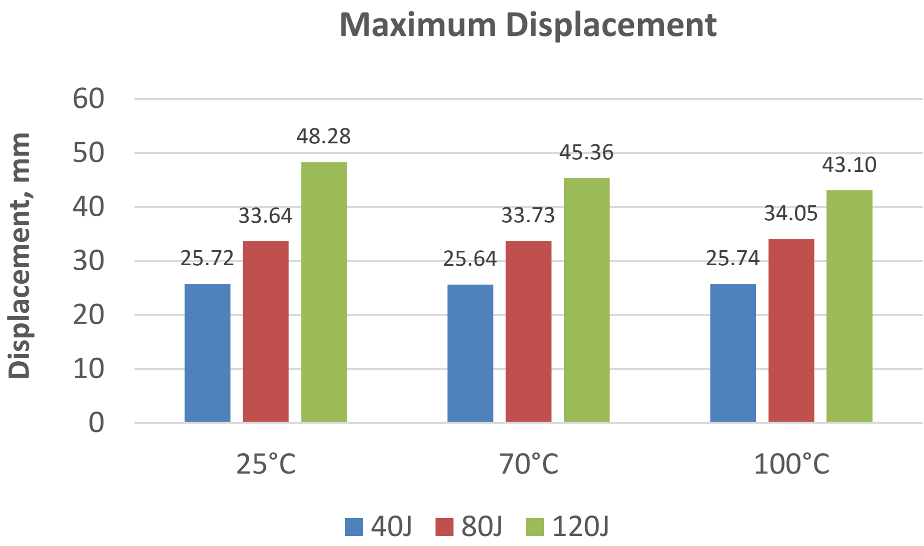
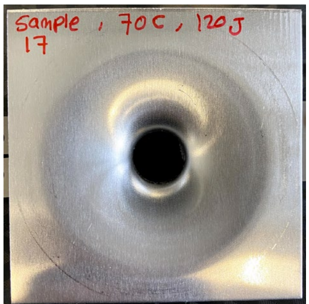
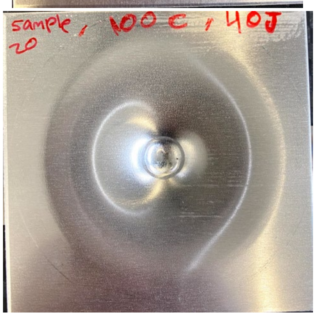
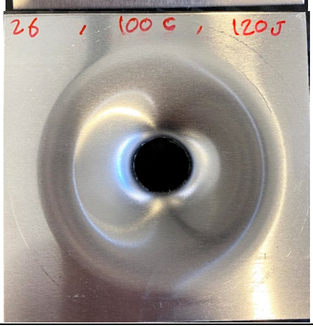


Fig. 3. Maximum displacement after impact at 40J, 80J, 120J impact energy at 25°C, 70°C,100°C

Table 2. Comparison of physical damage on the impacted side (top view) between the specimens

Energy (J)/Temperature (°C)	40	80	120
25			
70			
100			

There is a direct relation between the impact energy and the intensity of the damage observed on the specimen because of the impact. **Table 2** illustrates the results of the impact on the Al aluminium 1050 alloy. There are two sides of the sheets, one is the site where impact took place, and the other is the non-impacted site. The damage is on the impacted side of the specimen which is where the impact took place. For each respective impact energy, the shapes of the damage or deformation exhibit a similar failure pattern.

At 40 J of impact energy the specimen experiences indentation which is a plastic irreversible deformation. This happens since the impact stress is greater than the yield strength of Al1050. From 80J, the specimens start to experience fractures. The fracture occurs because of the high impact energy such that the material is unable to withstand the amount of impact force. At 120J impact energy, the specimens completely break, and penetration occurs as apparent in pictures in the table above. On a larger scale, the perforation seems to be the same regardless of the temperature. However, thorough examination of the impacted specimens shows that the fracture is wider in the case of higher temperatures. From column 2 (80 J) at 25°C, the fracture in the plate is quite thinner but as there is an increase in the temperature from 25°C – 100°C, the Al alloy plate loses strength, and the resulting fracture or crack is wider (increase in crack diameter). From these observations, a relation can be established when analysing specimens at higher impact energy levels. In column 3 (120 J) the crack diameter is higher because of a further increase in the impact energy.

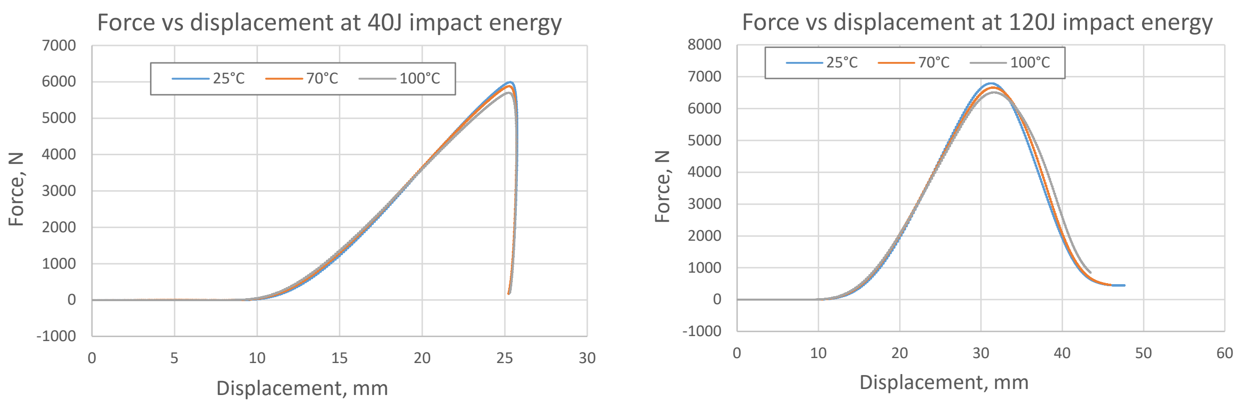


Fig. 4. F-D Curve obtained at 40J, 80J, 120J impact energy respectively for 25°C, 70°C, 100°C

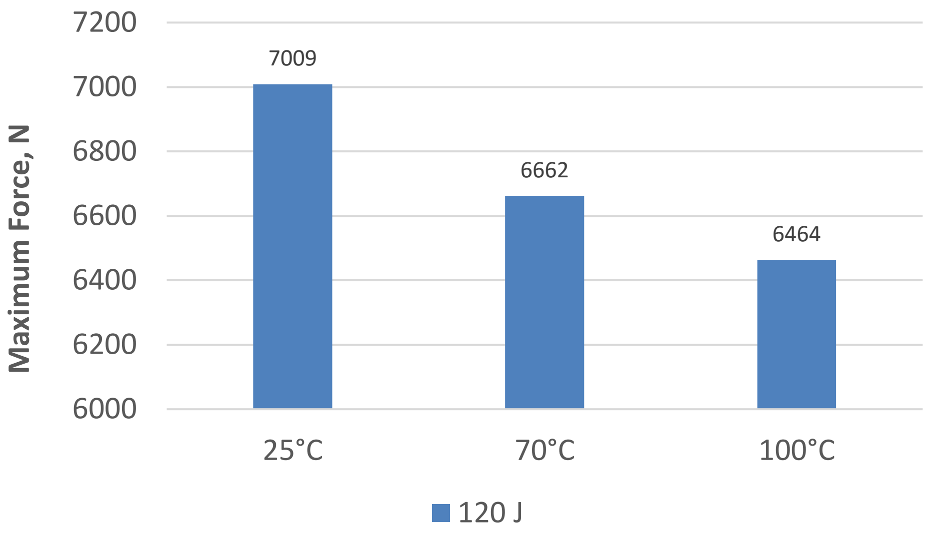


Fig. 5. Maximum force the specimens experienced at 120 J of impact energy at 25°C, 70°C and 100°C

There is no abrupt load drop in the first section of the F–d curve, **Fig. 4**. Rather, when the load is increased, the specimen's tangent stiffness progressively increases. High frequency oscillations of low amplitude, indicating probable material failures, are typically observed in the F–d trend only when the contact force is 80–90% of the maximum force. Finally, beyond the maximum load, the force rapidly drops to a value extremely close to zero, showing that penetration requires very little energy. At low impact energy such as 40J, the force vs displacement curve exhibits a backward curve behavior as seen in **Fig. 4**. This is due to the measurement given by the displacement sensor in the impact machine.

The first elastic phase in the aluminum 1050 is interrupted by a sharp reduction in the contact force, which is followed by similar occurrences as the load increases, until the maximum force is achieved. Although the load continues to oscillate significantly as the displacement increases beyond the point of maximum force, the Force – displacement curve gradually approaches the point of penetration (zero load) which is beyond the point of greatest force. The first load decrease is caused by delamination propagation, whereas near the maximum load, a substantial reinforcing damage is generated. The perforation and penetration processes of the plate are primarily responsible for the gradual decrease in load beyond the maximum (Resnyansky, 2021). Of course, plate failure and penetration have a significant impact on the material's energy absorption capability. Further investigation reveals that an increase in temperature has an inverse relation on the strength of the aluminum alloy 1050. Similarly, with the case of 120 J impact energy, it can be seen that the alloy follows a very similar pattern in terms of decrease in strength with increasing temperature.

The impactor's falling height and velocity have a significant impact on the findings; specimens struck with greater velocity and height suffer more force and deflection until failure, and consequently absorb more energy from the impact. From the maximum energy graphs, it can clearly be seen that the absorbed energy value at 25 °C is greater than the other impacts conducted at different temperature and impact energy levels. The reason for that is Aluminum alloys become weaker as the service temperature rises. Under tensile stress, thick particles readily fracture. The alloy's strength decreases as a result the temperature rises. The strength-giving precipitates ripen by over-aging at temperatures over 1500°C, resulting in a loss of strength. The density of the aluminum decreases and the impact forces are now able to crack the aluminum alloy surface (Li et al., 2023a; Li et al., 2023b). In the figures below, a pattern can clearly be seen, which is a direct relation between the Maximum force, displacement and the energy absorbed by the Aluminum alloy 1050 and the temperature of the system. i.e., Aluminum Sheet. Similarly, the maximum force is also observed at the lowest temperature of 25°C. Because the alloy will start losing its strength as the temperature starts to increase. Max force occurs at 25°C and equals 7009 ± 194.1 N as seen in the maximum bar chart (**Fig. 5**).

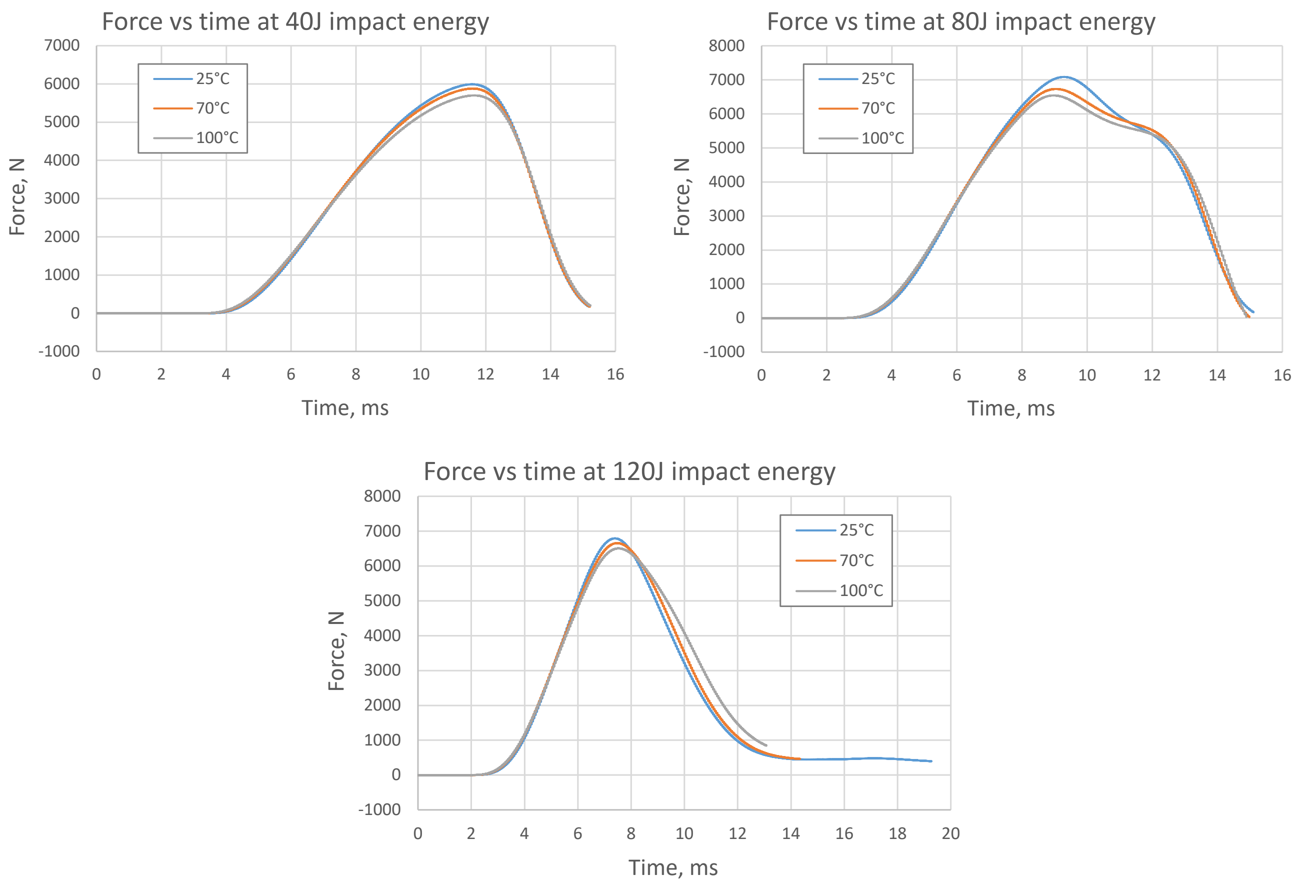


Fig. 6. F-t curve obtained at 40J, 80J, 120J impact energy respectively for 25°C, 70°C, 100°C

The experimental results indicated two main failure behaviors of the aluminum alloy impacted sheets. The failure is governed by impact parameters such as impact energy and temperature of the specimen; the perforation of the al1050 plates was made possible by high impact energies used in the experiment. In the cases where the palates were not penetrated, it is observed that the impact force is to some extent symmetrical in the loading and unloading variation. The variation in resultant contact force can be attributed to a phenomenon that is observed in the unloading called inertia and friction. Of course, as there is an increase in the impact velocity and impact height, the maximum impact force increases. It is well observed from the force vs time graphs (**Fig. 6**), that when penetration of the plates happens, there is an abrupt drop of contact force. This indicates strongly that the Al plates are severely damaged at that point.

The behavior of the Aluminum 1050 under different temperatures and impact energies were analyzed in **Fig. 6**. Each of the conditions at their respective impact energy and temperature is analyzed separately. It can clearly be seen that with the increase in temperature of the Aluminum Alloy 1050, the maximum value of the stress decreases drastically. It can be said that the alloy sheet has undergone plastic deformation at a lower value of maximum force because of the increase in temperature (Li et al., 2023b; Li et al., 2023c). As demonstrated under the same impact energy, the peak loads of those aluminum 1050 impacted panels are the greatest, while those having a higher temperature are the lowest. This implies that the aluminum alloy's characteristics, notably its yield stress, have a significant effect on the impact response of this alloy material. Therefore, it suggests that the impact resistance can be improved by increasing yield strength of the aluminum alloy.

4. Conclusion

An experimental approach is used to study the low-velocity impact behavior and subsequent damage condition of aluminum Al1050 alloy in this paper. Low-velocity impact tests are conducted to explore the influences of various parameters, such as falling height, impact velocity, the impact load, sheet temperature, failure mode and energy absorption. All the samples deformed plastically where the material is deformed permanently. This type of deformation occurred because the aluminum alloy (Al1050) specimens were subjected to impact stress that exceeds the elastic limit (yield strength) and caused it to elongate and in most of the cases fracture. One of the major findings is that the increase in temperature has an inverse relation with the maximum impact contact force. Greater impact energy resulted in a greater crack in the sheet surface and in most cases the object penetrated right through the sheet. A direct relation concluded is that if the impact energy is less and the temperature is low, the alloy performs in the best way possible. The aims and objectives of the project have been sufficiently met. The low-speed impact tests on Al alloy specimens have been successfully conducted. The damage seen in the impact plates has been categorized. Finally, the effect of impact parameters on the energy, displacement, and contact force have been evaluated. The suggested future work on this research area is to employ numerical modelling to confirm the experimental results. Furthermore, build solid FEA models that can predict the low velocity impact behavior of various types of Al alloys.

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