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(Review Article)

A critical analysis of collision dynamics pertaining to aluminum micro particles on aluminium 6061 alloy substrate in cold spray additive manufacturing process

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Abstract

Cold spray (CS) is a form of additive manufacturing process, involving the accumulation of ductile metal micro particles to create new surface coatings or free-standing structures. Metallic particles are accelerated through a gas stream, experience a high-strain-rate microscopic ballistic collisions against a target substrate. It yields tremendous amounts of kinetic energy from extreme plastic deformation of the particles and substrate. In this paper, the dynamic behavior of aluminium micro-particles during the collision is analysed using micro-ballistic method. Aluminum 6061 alloy particles, approximately 20 µm in diameter, impact and rebound off aluminum 6061 alloy substrate target surface over a broad range of surrounding temperatures and impact velocities. This, in turn, can provide insight into the underlying material science behind the cold spray process.

Keywords: Cold spray (CS); Substrate; Impact velocity; Rebound velocity; Restitution; Temperature

1 Introduction

Additive manufacturing techniques have been an area of great interest to industry and researchers alike. The use of metals in additive manufacturing has proven to be challenging since only a few methods are able to substantiate results, such as selective laser or electron beam melting [1].[1].

1.1 Cold Spray Process

Cold spray (CS) is a solid-state deposition technique which utilizes supersonic impacts of micro particles (10-100 µm in diameter) to build up coatings and/or free-standing structures. The high velocity impact results in severe plastic deformation and bonding of the particle to the substrate and/or previously deposited particles. An advantage of CS is that deposition and bonding is achieved over short interaction times at temperatures lower than materials' melting point. At comparatively low temperatures, CS is able to avoid the consequences of high temperature material modification including oxidation, residual thermal stresses, and unfavorable structural changes in powder material caused by melting and re-solidification. Ang et al. compared various thermal spray techniques in terms of the particle impact velocity and process temperature. Figure 1 shows that the temperature of CS is far less than other thermal spray techniques, while still achieving the high velocities necessary for particle deposition.

As a result of the high impact speeds, the particles-substrates interaction time is short, on the order of 10 ns. The low process temperature also allows for the structures within the materials to be preserved without significant recrystallization. Additionally, it has been discovered by Thevamaran et al. that the lack of recrystallization present in this process has the potential to yield nano-scale grain gradients throughout the resulting structure, which can prove to be advantageous when precise control over the bulk properties is desired [2-4]. CS is beneficial when compared to other additive manufacturing techniques and thermal spray processes by leveraging the advantage produced by the large

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plastic deformation. As opposed to thermal energy, which would cause significant changes in the original material, CS used kinetic energy to achieve particle deposition [5].CS was first invented over three decades ago at the Institute of Theoretical and Applied Mechanics in Novosibirsk, Russia [6,7].

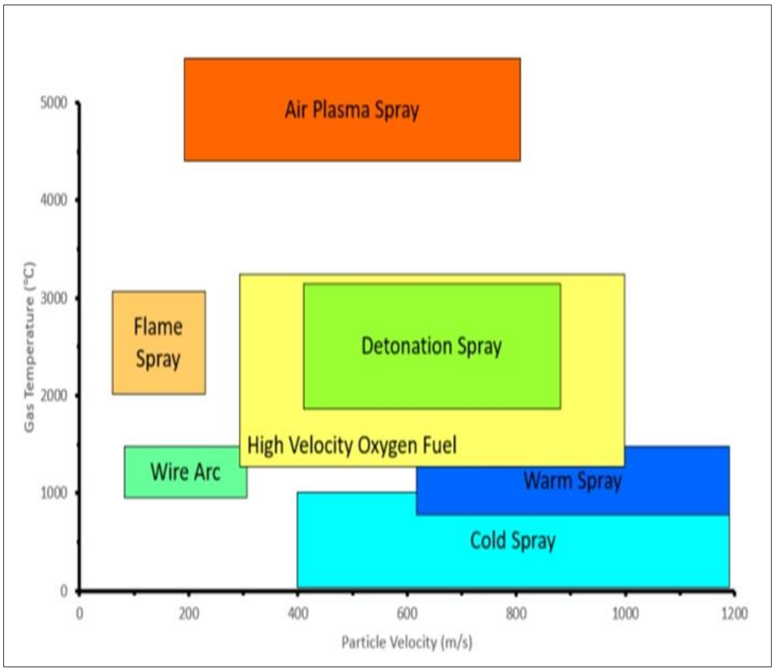

Figure 1 Classification of various thermal spray processes as the impact velocity relates to gas propellant temperature [1].

Serious developments in CS were not seen until the 1990’s [8]. This method has been growing in popularity not only in industry, but also in the academic community, with a large number of publications being produced in the last two decades; in order to understand the physical phenomena occurring in this process [5,9-11]. The understanding of this topic requires the incorporation of many fields of research, including fluid dynamics, solid mechanics, and material science. Although CS has been leveraged for decades, the governing material science behind how this process works is not fully established. In this additive method, various ductile metals are deposited on a substrate well below their melting temperature. Figure 2 shows a sketch of apparatus which is put to use in Cold Spray additive manufacturing process.

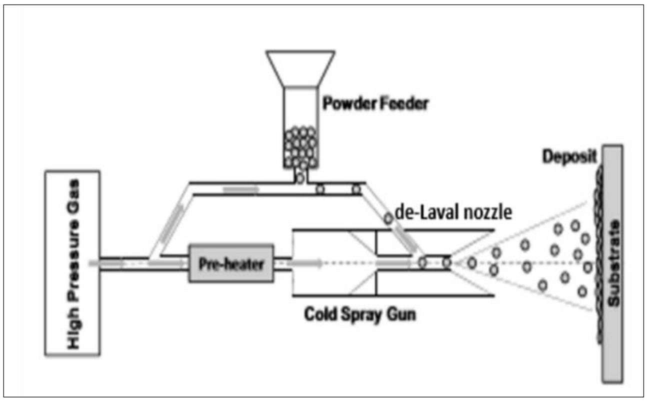

Figure 2 Schematics of the main components of a typical cold-spray apparatus

Powders, containing micro particles 10-100 µm in diameter depending on the material used, are sprayed through a converging-diverging de Laval nozzle at high speeds using a pressurized carrier gas, usually nitrogen or sometimes helium, at a rate of 10^5-10^7 particles per second. The temperature of the electrically heated gas can reach up to 1,000 °C depending on the desired particle speed. However, the temperature of the particles on impact ranges from 20-800 °C, depending on many factors such as the gas, nozzle design and heat capacity of the material [12]. Particles then impact the selected surface or substrate, applying the desired coating or structure. At these high deposition rates and velocities, it is challenging to observe individual particle collisions. Obviously, there is a large amount of variation between the impact parameters of each individual particle.

It has been well studied that if the impact velocity exceeds a specific critical value, the energy will be enough to induce severe enough plastic deformation resulting in the bonding of the particle to the target, which can either be a fresh surface or particles that had previously been deposited. This critical velocity is related to successful bonding and depends most significantly on the thermomechanical properties of the particle and substrate materials, but is also a function of particle size, initial temperature and melting temperature [13-16]. It is understood that if the energy required for bonding exceeds the elastic energy stored in the particle upon deformation on impact the particle can bond to the surface. Otherwise, the particle is reflected off the surface [17]. The visco-plastic deformation experienced leads to two key phenomena of CS; sequential compaction of deposited layers into a solid and metallurgical bonding between the particles and substrate over a large fraction that interfaces. Both are required to have a dense and strong resultant structure. If the powder is not efficiently compacted by subsequent impacts, the resultant will be highly porous. Furthermore, if there is poor bonding at the particle-substrate and particle-particle interfaces, the resultant structure will have low strength [18]. In order to improve CS deposition, the deformation process must be understood. Various hypotheses have been introduced as to the fundamental material science behind the bonding mechanisms such as material inter locking by interface instability, cohesive bonding, adiabatic shear instabilities, and local melting [18,19-21]. Material interlocking is achieved through the compaction of subsequent layers of material. This happens when the particle-substrate collision creates a crater that physically holds the particle in place.. Even if earlier particle impacts do not have good adhesion to the impact surface, following impacts will improve that adhesion through repeated impacts, creating a stronger bulk material [22].

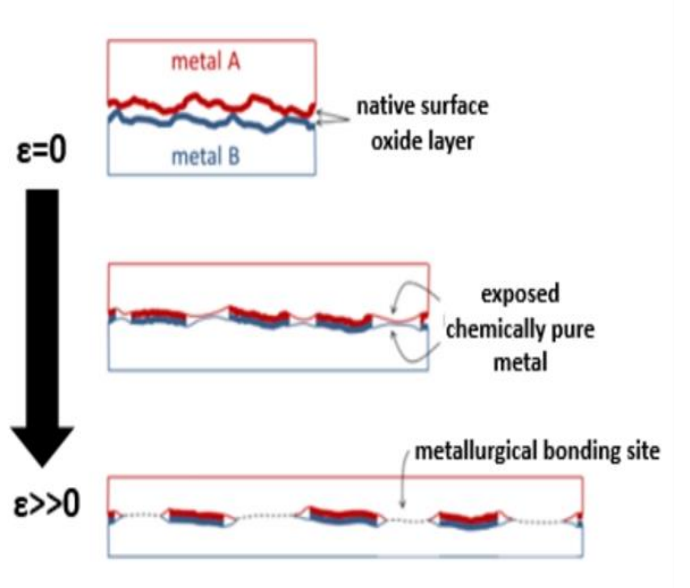

Figure 3 Schematics of interfacial area between two metal surfaces in a high-strain-rate collision

Under adiabatic conditions, as opposed to isothermal, the plastic strain energy is dissipated. As heat increases during deformation, the temperature rise causes the material to soften. It is easier for softened material to deform and produce heat. As a result, the rate of strain hardening decreases and the flow stress reaches a maximum then decreases with increasing plastic strain. In a real non-uniform material however, variations in stress, strain, temperature, and microstructure may be present.

1.2 Materials For Cold Spraying

There is great interest in using thermal spraying to fabricate coatings and structures with unique functional properties by using many different material powders. To this end, cold spraying has been used to accelerate and bond a wide variety of metals, like copper or high strength metals like titanium [20, 22]. It also has the ability to bond particles to substrates of dissimilar metals [11]. Polycrystalline Aluminum 606l T6 alloy (AA6061) is a common material in many fields, including defense and aerospace applications. AA6061 is comprised of 97.5% aluminum and other traceable elements and will be the topic of this study and work closely related.

Objective of research

The prime objective of the research is to study and analyse the dependence of the high-strain rate single particle impacts on the environment's temperature by performing impacts at various elevated temperatures and observing the change in the dynamic response. By elevating the temperature of AA6061, the material will soften allowing for increased movement or destruction of dislocation within the micro particles. However, thermal softening will be in competition with strain-rate hardening. Therefore, the extent of the temperatures effect needs to be determined. Temperature increases during impact could lead the material to surpassing the melting temperature in a high temperature environment. It is hypothesized that there will be increased plastic deformation or flow of material during impacts. Also, there will be increased bonding ability resulting from the increase in flow of material, this will be in the form of a lower bonding critical velocity.

2 Methodology

In this research, in-situ observations of micro particle impacts and rebounds were recorded using the α-LIPIT system. This capability has proven to be useful in augmenting computational simulations and understanding the complex high-strain-rate dynamics of these collisions. In these experiments micro particles approximately 20 μm in diameter of AA6061 are accelerated at a wide range of velocities and impacted upon a target substrate. To examine different aspects of the impact phenomenon a mirror polished AA6061 substrate was used as target. The impact and rebound velocities are then captured by the α-LIPIT system and recorded. With this information, an understanding of the energy dissipation and deformation during impact is gained. Unique to this research, a heating chamber has been added to the α-LIPIT in order to capture and observe data about collisions at an elevated temperature.

3 Results and discussion

On elevating the temperature has many different effects on ductile metals like AA6061 are seen like:

- Material softening,
- Formation of higher energy system, closer to the melting temperature,
- Increase in surface oxidation at very high temperatures [23,24].

The following are the results of the α-LIPIT experiments performed at elevated temperatures with AA6061 microparticles impacting on AA6061 target substrate. The rebound velocities for collisions at room temperature can be seen in tabular and graphical form as:

Table 1 Variation of Impact Velocity (Vi) and Rebound Velocity (Vr) at 25 ˚C

Impact Velocity (V_i)	**Rebound Velocity (V_r)**
25	13
50	14
150	18
200	21
300	21
400	21
500	22
550	23
600	24
700	26
800	26
900	24
950	23

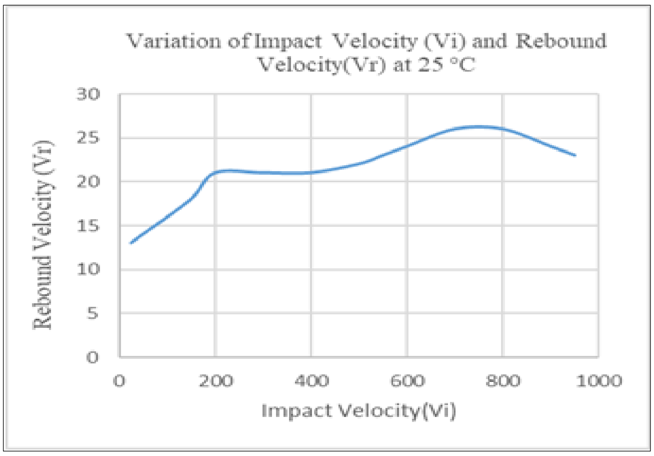

Figure 4 Impact Velocity (V_i) and Rebound Velocity (V_r) at 25 ˚C

Table 2 Variation of Impact Velocity (V_i) and Rebound Velocity (V_r) at 100⁰C

Impact Velocity (V_i)	**Rebound Velocity (V_r)**
100	14
150	16
200	18
250	20
300	21
350	22
400	22
500	18
550	20
600	22
700	25
800	27
850	26

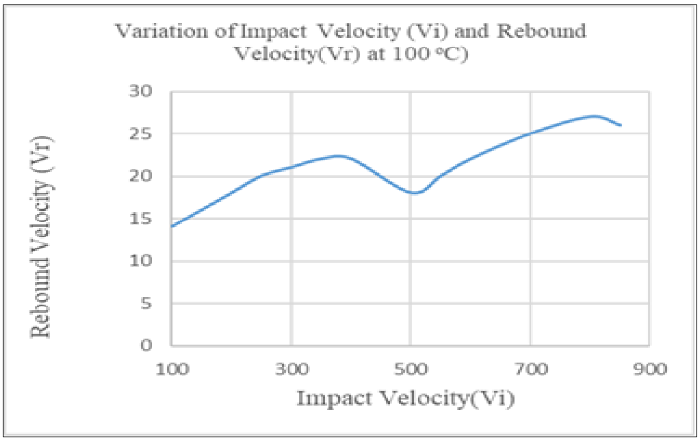

Figure 5 Impact Velocity (V_i) and Rebound Velocity (V_r) at 100 ˚C

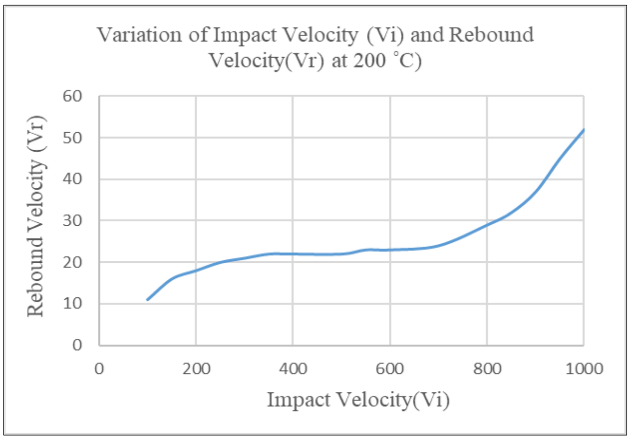

Figure 6 Impact Velocity (V_i) and Rebound Velocity (V_r) at 200 °C

Table 3 Variation of Impact Velocity (V_i) and Rebound Velocity (V_r) at 200 °C

Impact Velocity (V_i)	**Rebound Velocity (V_r)**
100	11
150	16
200	18
250	20
300	21
350	22
400	22
500	22
550	23
600	23
700	24
800	29
850	32
900	37
950	45
1000	52

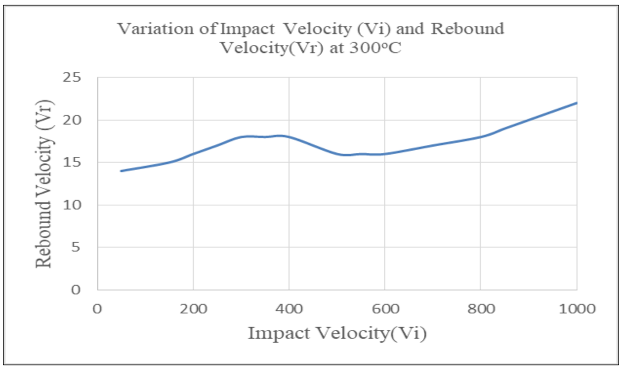

Figure 7 Impact Velocity (V_i) and Rebound Velocity (V_r) at 300 °C

Table 4 Variation of Impact Velocity (V_i) and Rebound Velocity (V_r) at 300 ˚C

Impact Velocity (Vi)	Rebound Velocity (Vr)
50	14
150	15
200	16
250	17
300	18
350	18
400	18
500	16
550	16
600	16
700	17
800	18
850	19
900	20
950	21
1000	22

Table 5 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 25 ˚C

Impact Velocity (V_i)	Coefficient of restitution (e)
50	0.22
100	0.21
200	0.16
250	0.15
300	0.12
400	0.07
500	0.06
600	0.05
700	0.045
750	0.05
800	0.055
850	0.06
850	0.06
900	0.07

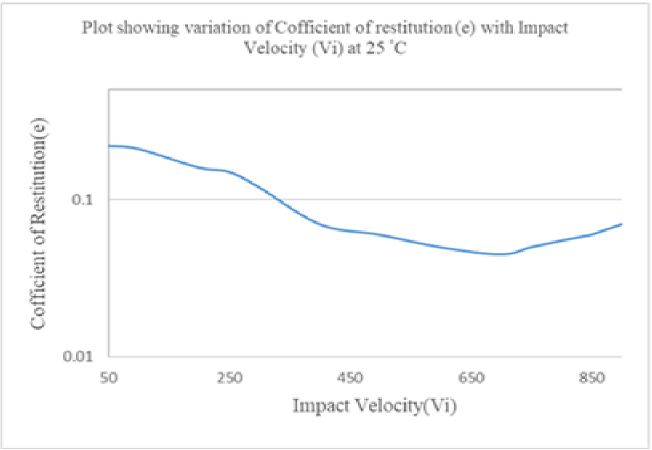

Figure 8 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 25^0C

Table 6 Variation of Impact velocity (Vi) and Coefficient of restitution (e) at 1000C

Impact Velocity (V_i)	Coefficient of restitution (e)
50	0.23
150	0.21
200	0.18
300	0.13
400	0.09
500	0.08
600	0.075
700	0.08
800	0.08
900	0.075
1000	0.075

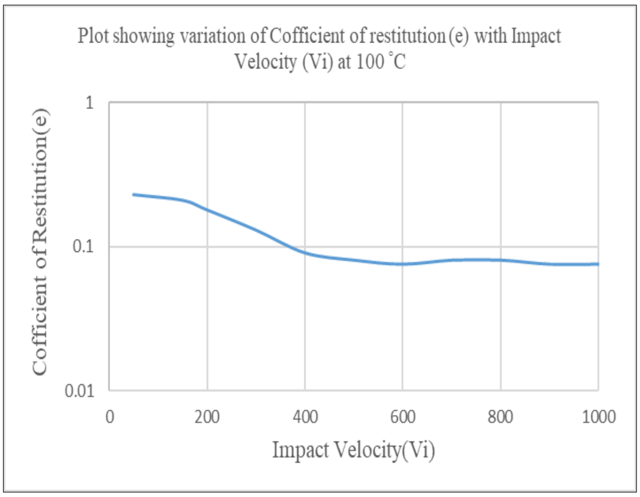

Figure 9 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 100 ˚C

Table 7 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 200 ˚C

Impact Velocity (V_i)	**Coefficient of restitution (e)**
50	0.21
100	0.2
200	0.19
300	0.17
400	0.14
500	0.09
600	0.08
700	0.07
800	0.065
850	0.06

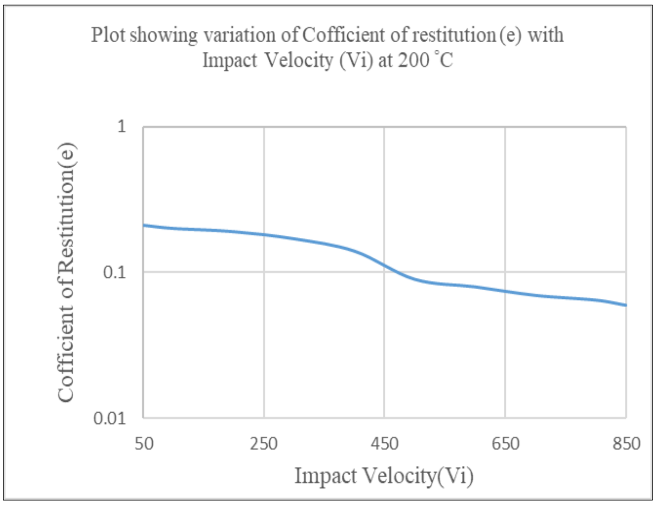

Figure 10 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 200 ˚C

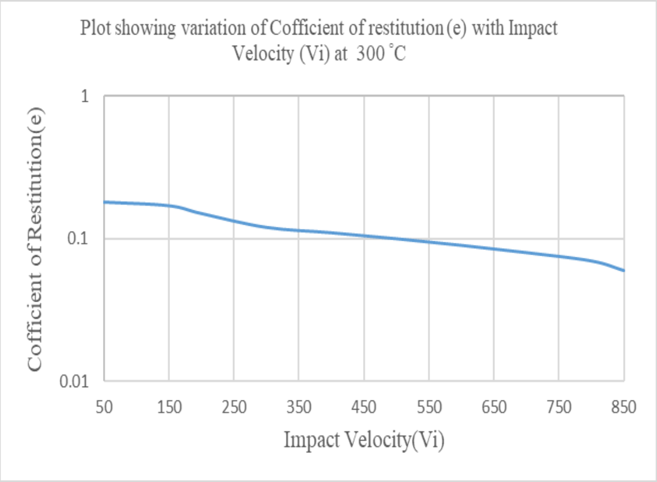

Figure 11 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 300 ˚C

Table 8 Variation of Impact velocity (V_i) and Coefficient of restitution (e) at 300^{0}C

Impact Velocity (V_i)	Coefficient of restitution (e)
50	0.18
150	0.17
200	0.15
300	0.12
400	0.11
500	0.1
600	0.09
700	0.08
800	0.07
850	0.06

From data obtained in the form of tables and graphs, following inferences can be made:

- At low impact velocities, the rebound speed increases linearly, which would be expected if there was proportional energy absorption by the particle with increasing impact energy.
- Increasing the temperature to 200 °C has little effect on the rebound of AA6061 particles. However, at 300 °C there is a distinct change in the rebound velocity of these particles. This is supported by the nominal decrease in mechanical strength of AA6061 from 23-200 °C and the distinct decrease from 200-300 °C.
- Thermal softening and the change in mechanical properties of the micro particles is responsible for the change in rebound energies above 200 °C.
- Furthermore, it can be concluded that the temperature has little effect on the HSR deformation of these micro particles below 200 °C.
- The rebound velocity begins to settle for all temperatures around 20 m/s except 300 °C, at which it settles at lower rebound velocity of 18 m/s. This change from a linear growth trend marks the ability of the particle to deform plastically absorbing a large fraction of the impact energy.
- The impact energy is absorbed by the particle and dissipated effectively at all temperatures in this impact speed region except 300 °C, where the rebound energy is even lower. This implies that the thermal softening caused by the heating at 300 °C has a greater effect on the deformation process.

4 Conclusion

Cold Spray is a field that has been growing for many years, with numerous industries and disciplines involved with the advancement of this promising method of addictive manufacturing. Due to the extreme nature of the plastic deformation, it has proven to be challenging to observe and understand. It is discovered, through observation of the collisions of AA6061 micro particles to a polished AA6061 substrate, that the critical velocity is lowered at elevated temperatures, which was predicted. However, the critical velocity did not lower until the temperature exceeded 100 °C. Furthermore, the rebound velocity actually increased rather than decreasing for temperatures less than 300 °C, which remained higher than room temperature experiments as well.

Compliance with ethical standards

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Disclosure of conflict of interest

It is declared that there is no relevant or material financial interests of both authors pertaining to the research work. The data used in this research is proprietary in nature.

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