Comment on 'Adiabatic shear instability is not necessary for adhesion in cold spray'

H. Assadi [a,*] , F. Gärtner [b], T. Klassen [b, c], H. Kreye [b]

[a] Brunel University London, Brunel Centre for Advanced Solidification Technology (BCAST), Uxbridge, United Kingdom

[b] Helmut Schmidt University, Institute of Materials Technology, Hamburg, Germany

[c] Helmholtz-Zentrum Geesthacht, Center for Materials and Coastal Research, Geesthacht, Germany

Abstract

This paper concerns the statements of a recently published article on the mechanism of particle bonding (adhesion) in cold spraying of metallic materials, by Hassani-Gangaraj *et al.*, Acta Materialia 158 (2018). The core statements of the above article are that (1) jetting is the cause of particle bonding, as the title implies, (2) adiabatic shear instability is not necessary for jet formation, and (3) jetting and particle bonding are governed by the bulk speed of sound. In this paper we argue that the first statement is inaccurate, the second is correct but not new, and the third is incorrect.

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[*] Corresponding author. *Email address:* hamid.assadi@brunel.ac.uk (H. Assadi)

There is continual interest in cold spraying (CS) research because: (a) CS works, and (b) it is not entirely clear how. The *Article* by Hassani-Gangaraj *et al.* [1] focuses on the latter aspect of CS research. The authors postulate a new deposition mechanism highlighting the role of the bulk speed of sound, v_s, while refuting the previously suggested [2, 3] role of adiabatic shear instability (ASI) in particle bonding. Based on the new mechanism, the critical velocity for bonding is formulated as a unique function of v_s. The *Article* also reports on a set of measured critical velocities – which fit the proposed function – besides numerical simulations of particle impact – which provide a mechanistic description of jet formation. The authors' viewpoints on particle bonding are dramatically novel and likely to attract attention in the area of CS research. We note, nevertheless, that further work in this area can benefit from careful examination of the following questions on the newly proposed mechanism, and on the much-debated role of ASI in particle bonding.

What are the relevant questions and what are the suggested answers? The key questions regarding the bonding mechanism in CS deposition of metallic materials are whether ASI, jetting, jet fragmentation or any other dynamic phenomena can occur, whether they do occur, and whether they can lead to, hence be taken as an indication of bonding. A subsequent practical question is whether any of those phenomena can be quantified, hence be used as a basis for predictive modelling, e.g. to estimate the critical velocity as a function of process and materials parameters. Contrary to what the *Article* suggests, we argue that the answer to all the above questions regarding ASI is positive. We also demonstrate that the speed of sound, as suggested by the *Article*, can hardly play a role in bonding or jetting, and that the expression of the critical velocity for bonding as a function of the bulk speed of sound is misleading.

What is necessary for bonding? In principle, bonding occurs when clean surfaces of two components are brought into contact at the atomic level. One way to achieve this, for metals in the solid state, is to compress and stretch the interfacial region up to a certain level of strain, so that the surface oxide layers are broken up and clean metallic surfaces are in tight contact. An example is cold roll bonding [4], in which strong bonding can be achieved by 60-70% reduction, equivalent to an interfacial strain of around unity. This can be interpreted to mean that neither ASI nor jetting would be necessary for bonding, as they are both associated with significantly higher values of interfacial strain than 1, i.e. what is necessary for deformation-induced bonding under quasi-static conditions. On the other hand, bonding under dynamic conditions is often signified by prominent jetting, suggesting that particle bonding in CS is commonly associated with a higher interfacial strain. It is important to note, however, that the value of the threshold interfacial strain for CS deposition, $\varepsilon_{\text{bond}}$, is not known a priori. Moreover, jetting can cover a broad range of features, occur with or without ASI, and hence, be associated with a wide range of interfacial strains. Consequently, jetting alone cannot be used as an accurate criterion for particle bonding in CS, unless (1) it is represented by a unique interfacial strain, ε_{jet}, (2) the threshold interfacial strain to induce bonding, $\varepsilon_{\text{bond}}$, is known, and (3) there is evidence to support that even without ASI $\varepsilon_{\text{jet}} > \varepsilon_{\text{bond}}$. The *Article* does not substantiate any of these requirements.

What do the simulations show? The simulations in the *Article* do not show that the experimentally observed jetting is not or cannot be associated with ASI. They show that even without ASI, the impact can still be associated with inhomogeneous deformation and some jetting, with the interfacial plastic strains reaching values of up to 4.5. This finding is not new. For instance, simulations in ref [2] already showed that the impact of copper particles with the velocities below 550 m/s did not exhibit ASI, yet they were associated with some jetting and interfacial strains of up to 4. They also showed that if ASI did occur, then it would lead to an abrupt increase of the interfacial strain from 4 to significantly larger values of around 10, and be manifested by more prominent jetting, as compared to the cases without ASI. The occurrence of ASI was later confirmed by other simulation studies [3], including those using an Eulerian approach [5]. As far as we understand, the main point of those earlier studies was to demonstrate that (1) there was a distinct transition from no-ASI to ASI, and that (2) the velocity marking the transition to ASI (550 m/s for copper) compared well with the experimentally evaluated critical velocity for bonding. It was not to show that ASI was necessary for jetting. On the contrary, ref [2] specifically pointed out that jetting was an ineffective criterion for bonding, hence investigating the role of ASI in jetting would be irrelevant. In this respect, the *Article* seems to refute a position that at least Assadi *et al.* [2] did not hold.

What do the experiments show? In the case of dynamic high-velocity impact, the experiments confirm that successful bonding is commonly associated with localised deformation, inelastic heat generation, prominent jetting and large interfacial strains of up to 10 [6]. Moreover, the experiments show that the critical velocity for bonding of copper particles is around 550 m/s [1, 2] and provide information on the location and the extent of bonding [6]. Contrary to what the *Article* suggests, there is no conclusive experimental evidence to support a bonding mechanism governed by the speed of sound, or to rule out the role of ASI in particle bonding.

Where are the shear bands in the cold-sprayed samples? Depending on the loading condition, ASI can occur during dynamic deformation and be a cause of (a) shear banding and rupture [7], and/or (b) solid-state bonding [6]. Shear banding occurs, for instance, when the bulk is under shear loading, so that the materials at the two sides of each band move in the opposite directions. Whether or under what conditions shear banding may occur during particle impact, or why shear banding is a rare feature in cold-sprayed samples are interesting questions. However, they are not relevant questions, as the absence of one effect (shear banding), does not rule out the possible cause (ASI) of another effect (bonding). In this respect, too, the *Article* seems to refute a position that is hardly relevant to the problem of interest.

What is the consequence of the ASI criterion? The comparison between the modelling and the experimental results suggests that (1) ASI can play a role in bonding of particles during CS deposition, and (2) it occurs at or beyond the critical velocity. This is the basis of the ASI criterion for bonding, which allows one to describe and predict the influence of process and materials parameters on the critical velocity. An important outcome of this criterion is that it relates the critical velocity to the thermal and plastic constitutive properties of the particles in the same way as observed experimentally. It predicts, for instance, that the critical velocity increases with increasing hardness and with decreasing the particle size. Moreover, the ASI criterion can be used to predict the extent of bonding, hence to explain the influence of various materials and process conditions on the properties of CS deposits.

What is the role of the bulk speed of sound? The *Article* posits that jetting and particle bonding are governed by the bulk speed of sound, v_s, based on the observed linear correlation between v_s and the critical velocity for four metals [1]. This is in contrast with an earlier presumption that the elastic properties (from which v_s is derived) are amongst the material parameters with the weakest influence on the critical velocity. For example, simulations in ref [2] showed that the threshold velocity for the occurrence of ASI in copper particles would increase by only 1 m/s, if the Young's modulus was doubled. To clarify this argument and to explore further the role of the bulk speed of sound [1], we have performed a series of simulations using the same methods and parameters as described in ref [2]. In the first set of simulations, all the materials and calculation parameters, except the Young's modulus, are fixed and set to that of a spherical copper particle impinging a copper substrate with an impact velocity of 400 m/s. In this case, the simulations were performed for three values of the Young's modulus, corresponding to three velocity ratios of v/v_s = 0.07, 0.1, and 0.14. In the second set of simulations, for each value of Young's modulus, the impact velocity was readjusted with respect to v_s, to give a fixed velocity ratio of v/v_s = 0.1. Fig. 1 shows the results of these simulations. The cases shown in (a), (b) & (c) are almost identical, showing little influence of the bulk speed of sound on the jet morphology and on the equivalent plastic strain field. This clearly contradicts the newly proposed bonding mechanism, which takes the velocity ratio v/v_s as a most determining factor in jetting and bonding. The cases shown in (a), (d) & (e) reconfirm that v/v_s is an incorrect measure of jetting. Although the respective velocity ratios are fixed at 0.1, there is a drastically large difference between (d) which shows prominent jetting, and (e) which shows no jetting at all. It is disconcerting that the authors of the *Article* did not perform this simple test of their own hypothesis, despite their extensive simulation work using a similar concept of scientific control and isolation of parameters to assess the relevance of ASI.

What is the consequence of the new criterion? Regardless of the theoretical validity of the new criterion, it does not lead to a generally correct prediction of the critical velocity as a function of materials and process parameters. A reason is that the critical velocity is taken as a unique function of the bulk speed of sound, a property which does not capture the effects of thermal and plastic properties of the particles. The predictions of the new criterion are thus strictly against the existing CS experience. This can be shown with respect to the available experimental data, where the elastic properties (hence v_s) are fixed and the plastic properties are manipulated by heat treatment. An example is provided by Krebs *et al.* [8], where the softer powder is shown to result in better bonding as compared to the harder powder of the same material (i.e. of the same v_s). This clearly confirms that the bulk speed of sound cannot be a dominant factor in particle bonding during CS deposition. The observed correlation between the critical velocity and v_s should therefore be taken as one that does not imply causation. The new criterion is also not useful in interpreting the effect of particle size, or in predicting the extent of bonded area in cold-sprayed deposits.

In summary, the *Article* provides a new perspective on jet formation and jet fragmentation. Extensive simulations are performed to reconfirm an old finding that jet formation does not require ASI. The authors of the *Article* posit that jetting is the cause of bonding, and that it can occur without ASI, hence conclude that ASI is not necessary for bonding. Although the latter two statements may be true, neither the experiments nor the simulations support the premise of this conclusion. Moreover, finite element simulations of a sufficiently high mesh resolution confirm the existence of ASI and the associated large interfacial strains at impact velocities beyond the critical velocity for bonding. These predictions are consistent with the experimental observations, suggesting that ASI can and does happen during particle impact, and that it is likely to play a role in bonding. We acknowledge that ASI is not a universal mechanism for bonding and can be falsified. However, the *Article* does not seem to succeed to show this for the examined group of materials. Theoretical arguments aside, the ASI criterion seems to be useful, as it leads to a realistic prediction of the critical velocity as a function of materials and process parameters for cold spraying of metals. Moreover, the role of the bulk speed of sound in jetting and particle bonding can be easily ruled out by isolation of parameters in a simulation study. Therefore, formulation of the critical velocity as a unique function of the speed of sound is incorrect and misleading.

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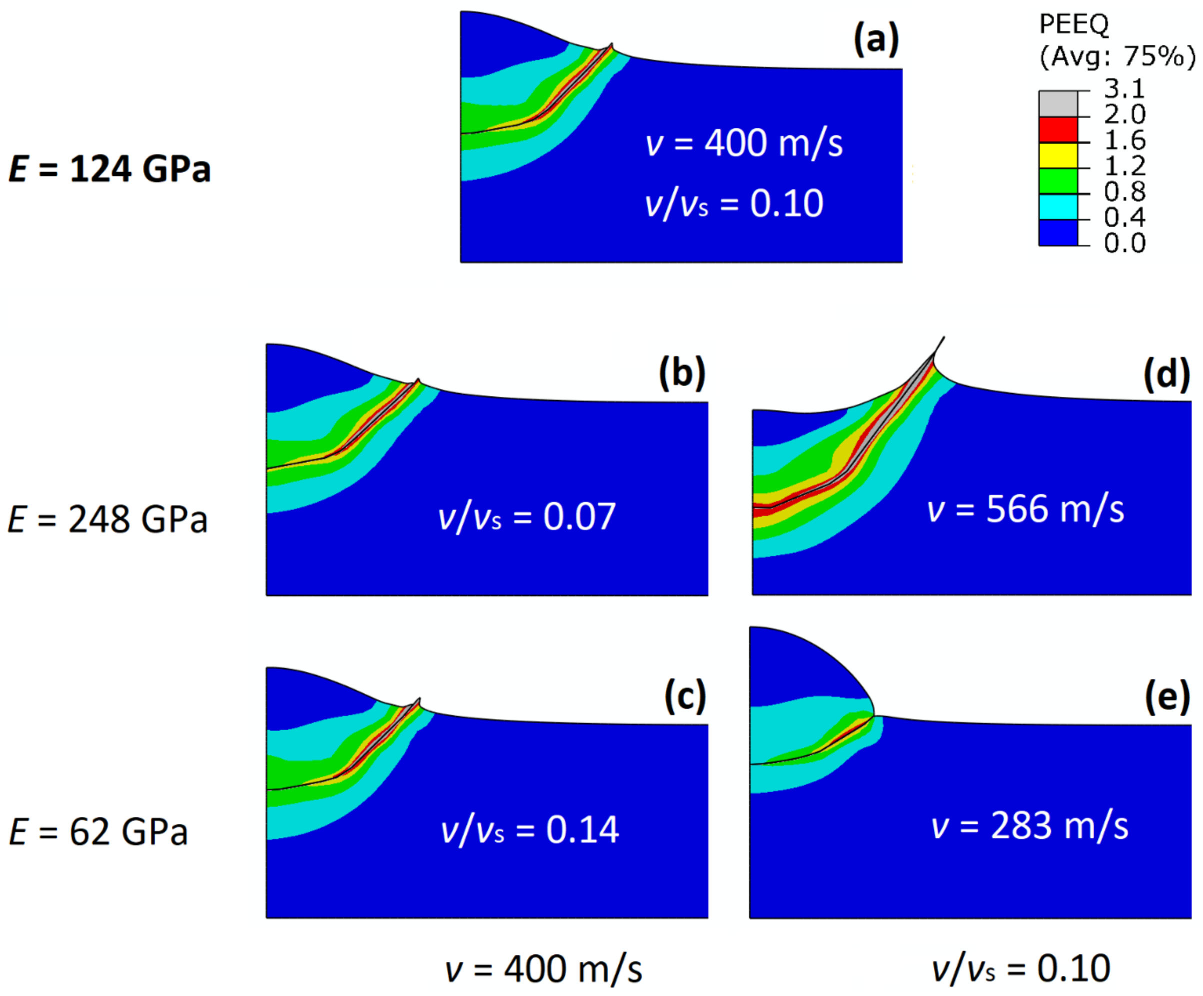

Fig. 1. Finite element simulation of particle impact (a), (b) & (c) for the same impact velocity, v, but different speeds of sound, v_s, and (a), (d) & (e) for the same v_s but different impact velocities. The contours correspond to the equivalent plastic strain field. The material data used for the case shown in (a) corresponds to copper. The Young's modulus has been changed in (b), (c), (d) & (e) to obtain the illustrated ratio of v/v_s for the corresponding impact velocity, while keeping all other material data constant. The results show that the ratio v/v_s is not an appropriate measure of deformation and jet formation.