Theoretical Investigations of Ti and TC4 Depositions on TC4 Substrate

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***Abstract*—LS-DYNA software was used to investigate the deposition morphologies, collide depth, the highest collide temperature, and critical deposition velocities for Ti and TC4 particle on TC4 substrate. Theoretical results show that distortion, collide depth and the highest collide temperature for TC4 are larger than that of Ti powder under the same condition. Threshold deposition velocities of Ti powder are 750m/s, 489m/s, 409m/s, 383m/s, and TC4 powder are 730m/s, 465m/s, 392m/s, 361m/s under 25ºC, 400 ºC, 500 ºC, 600 ºC, respectively. It reveals that threshold deposition velocity of TC4 is lower than that of Ti powder and threshold deposition velocity of them also show the same laws: critical deposition velocities decreases when particle temperature increases. In a word, TC4 powder can be deposited easily onto TC4 substrate than that of Ti one when they are under the same deposition conditions.**

***Index Terms*—cold spray, Ti particle, TC4 particle, TC4 substrate, Collide**

I. INTRODUCTION

Titanium alloys are used widely in aeronautics, astronautics and nucleus industry.[1] But these titanium alloys components may be destroyed and its surface appears pit, groove and default because of machining, friction, collision and other reasons.[2,3] Therefore, these components have to be repaired and resume its prevenient functions. Among plenty of ways, thermal spray, welding, laser overlaying welding and so on were approbated in many factories and research institutes.[4] To our surprising, cold spray technique has some advantages, such as its coatings are dense, thick, residual stress is compressional. As a result, cold spray technique obtained mature application in thruster rocket, casing of aeroengine, vita, oil box (materials include Mg, Al, Zn light metals). [5-9]

Unfortunately, various studies showed that TC4 coatings on TC4 substrate can't be obtained wholly dense using cold spray method. The previous reports indicated that the best result is just 2% porosity according to Vidaller M V's monograph.[10] The porosities of TC4 coatings can achieve 45% and even more.[11] Therefore, the key target (porosity of TC4 coatings) is difficult to be adopted to repair surface damnification of TC4 alloy. The porosity of TC4 coatings is the key factor for applications of TC4 coatings. Except for these, the deposition morphologies, collide depth, the highest collide temperature, and critical deposition velocities for Ti and TC4 particle on TC4 substrate havenot been investigated systimically so far. In other words, the deposition process of Ti and TC4 on TC4 alloy arenot discussed deeply.

Based on the analysis above, the collide process and its properties should be considered for Ti and TC4 coatings prepared on TC4 substrate. The aim of this study is to give a deeper guide and reference in the future.

II. NUMERICAL MODELING AND CALCULATION PARAMETRES

A. NUMERICAL MODELING

3D models were developed to study the impacting behavior of a single particle on the TC4 substrate using the finite element code LS-DYNA. [12] Fig. 1 shows a typical finite element model for this study. A refined, uniform mesh was used in the impact region. The three dimensional 3D164 module, MAT_JOHNSON_COOK, and linearity EOS_GRUNEISEN state equation are considered and employed here. To reduce the computational cost, only half geometry was analyzed and the height of the substrate was taken to be nine times larger than particle radius (r=10μm, set as a fixed value). The symmetry planes were constrained not to move in the X-direction and a fixed boundary condition was applied to the bottom and the side surface. Particle and substrate experience large plastic strain during impact and were monitored to output the temporal evolutions of results. What we adopt has been proved reasonable and successful according to previous references. [13, 14]

In this study, 4 kinds of models (temperatures) are analyzed and one model corresponding to 4 velocities, as listed in Table 1.

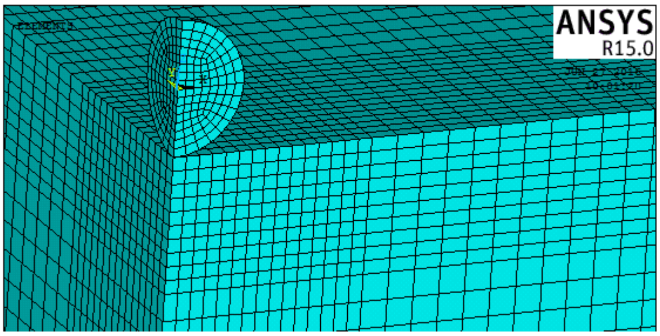

Figure 1. Model of Simulation

TABLE I.

MODELS OF SIMULATIONS AND SETTING OF PARTICLE PARAMETERS

	temperature	Velocities
Model 1	25ºC	500m/s、600m/s、700m/s、800m/s
Model 2	400ºC	500m/s、600m/s、700m/s、800m/s
Model 3	500ºC	500m/s、600m/s、700m/s、800m/s
Model 4	600ºC	500m/s、600m/s、700m/s、800m/s

B. PARAMETERS OF MATERIALS

Parameters of materials used in this study can be obtained from some references and database, [15] as shown in Table 2.

III. RESULTS AND DISCUSSION

A．MORPHOLOGY CHARACTERICS FOR Ti AND TC4 AFTER COLLIDING

1. Deformation for Ti and Tc4 particles under 25ºC

According to the model and calculation parameters above, a single powder colliding are calculated. Fig. 2(a), 2(b), 2(c), 2(d) show the morphologies of Ti particle of velocity 500m/s, 600m/s, 700m/s, 800m/s under 25ºC, respectively. It is seen clearly that particles of Fig. 2(a) and Fig. 2(b) happen to deform faintly. Contrary, Fig.2(c) and 2(d) produce violent deformation and a half of Ti (Fig. 2c) get into the inner of TC4 alloy substrate. Especially, a majority of particle cave in the interior of TC4 alloy substrate when the velocity of particle (Fig. 2d) increased to 800m/s. From Fig. 2(c) and Fig. 2(d), it is evaluated that the effective deposition velocity should exceed 700m/s, and the valve is about 730m/s.

Fig. 3 posts the morphologies of TC4 particle after colliding. What we obtain have the similar laws and morphologies with previous investigations. These results describe the similar phenomenon with WY Li's[12] and XL Zhou's[15] calculations, which indicate the model is reasonable and parameter is basically right. Comparing Fig. 2 and Fig. 3, we can find that the deforming of TC4 particle doesn’t have larger difference with Ti particle, but this exists the little difference: TC4 has larger deform characteristic than that of pure Ti particle, especially when velocity exceeds 700m/s.

2. Morphology characterics for Ti and Tc4 particles under 400 ºC

To distinguish further the morphology characteristics for Ti and TC4 particles after colliding, the prophase (10ns), metaphase (20ns) and telophase (40ns) of the 400ºC temperature are discussed systemically. The representational results were presented in Fig. 4, which describes that Ti and TC4 particle bring larger deformation and metal sputtering than 25 ºC. However, it still exists the obvious phenomenon, that is, contact area, deformation and jet of TC4 are more sufficient and obvious. The collide process of 500ºC and 600ºCstill display similar rule, that is, TC4 particle shows more appear deform than that of Ti one and deform is more evident when temperature become higher. But they aren’t listed here because less space for this journal.

TABLE II.

PARAMETERS OF MATERIALS USED IN THIS STUDY

material	Density ρ, kg/m^3	Yield strength σb, MPa	Poisson's ratio μ	Young's E, GPa	Shear modulus G, GPa	Hardening parameter β	Strain parameter	Specific heat, C_P, J/(kg.oC)	Thermal conductivity k,W/(m.ºC)	Melting, ºC	A	B	n

TC4	4650	930	0.36	100	59.6	0.50	100	100	60	1660	1923	807	482
Ti	4440	450	0.33	113	44.2	0.46	120	91	8.8	1600	1220	771	368

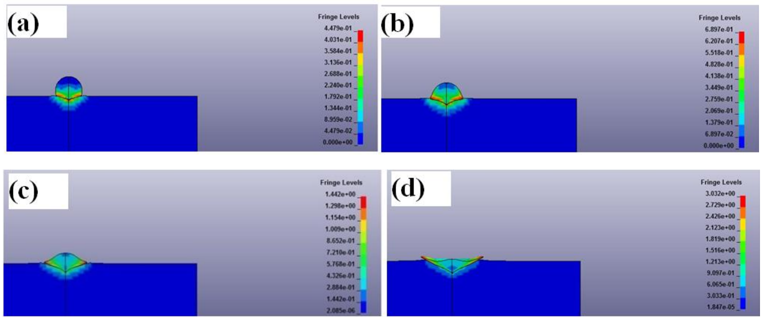

Figure 2. Morphologies of the Ti after colliding (a, b, c and d are 500, 600, 700 and 800m/s, respectively.)

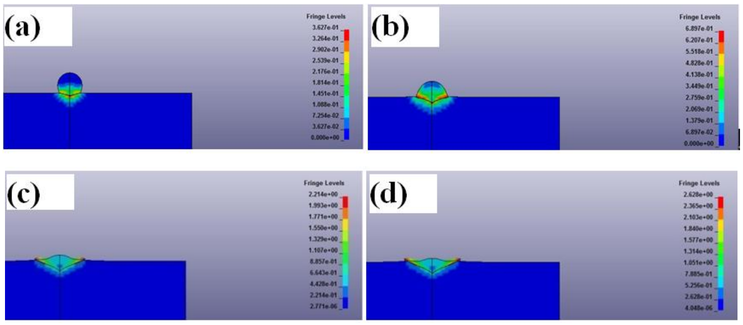

Figure 3. Morphologies of the TC4 after colliding (a, b, c and d are 500, 600, 700 and 800m/s, respectively.)

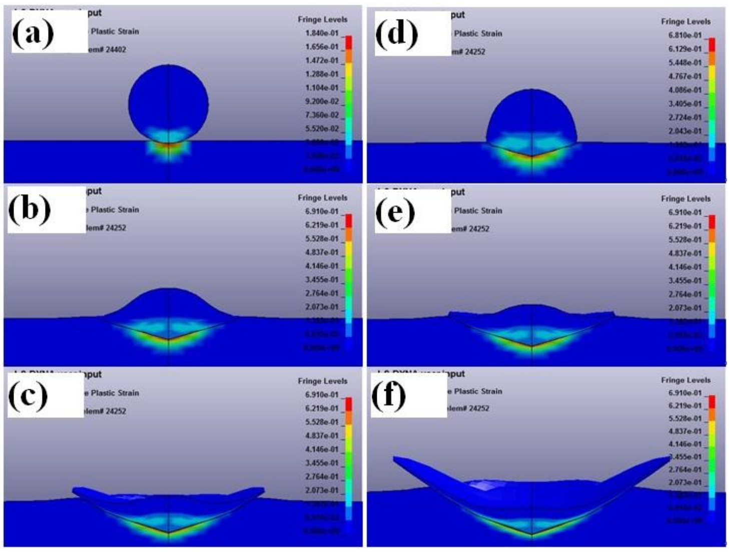

Figure 4. Evolvement process of particles during colliding (a, b, c are Ti powder; d, e, f are TC4 powder, respectively.)

3. Depth comparing for Ti and Tc4 particles under different colliding temperature

Fig. 5 shows that the process of depth verus time is exhibited when the temperatures of particles are 25^{o}C, 400^{o}C, 600^{o}C, respectively. It indicates that two kinds of particles of 25oC obtain the highest deepness (about 1.5μm) when colliding time is about 22ns. But the highest depth is just 1/7 of the diameter of original sphericity particle. The highest depth is too low and it is easily speculated that particle collide firstly and then rebound from the TC4 alloy substrate. The particle doesn't have effective deposition on substrate. Whereas, the pit deepness is nearly equal to the radius of TC4 particle and the near whole particle sink in the alloy substrate when the temperature is about 600^{o}C. The energy of TC4 depletes completely and doesn't resile at all. Ultimately, the particle deposes on the TC4 surface and integrates with the TC4 alloy. Please observe this aggradations' course combing Fig. 4 and readers can understand deeply.

B. THR HIGHEST COLLIDING TEMPERATURE AND CRITICAL DEPOSITION VELOCITIES FOR Ti(ORTC4)/TC4

1. The highest colliding temperature for Ti(ortc4)/Tc4

Fig. 6 describes the highest temperature when flight particles impinge against TC4 substrate under 25°C. It indicates that the highest temperature (900°C) is far lower than that of pure Ti material's melting point (1600°C) when the velocity of Ti is about 500m/s. The highest temperature reaches the melting point of Ti just when the velocity exceeds 755m/s. However, the velocity just need 730m/s, and the highest temperature of colliding TC4 can reach the melting point of (1640°C). The particle achieves its melting point and then it can react with substrate or mechanical occlude with protuberant surface of TC4. Reaching melt point for particles is the thermodynamics condition or it is the necessary condition of combing.

A comparison of Ti and TC4 results, it is found that the highest temperature of TC4 colliding is always higher than that of Ti when they are under the same colliding conditions. Therefore, TC4 has the strong distortion or combing ability than that of Ti particle. According to previous reports[16], particle/substrate has 4 kinds of types, i.e soft/hard, soft/soft, hard/hard, hard/soft. But, hard/hard and soft/soft types usually have stronger ability or feasibility for combing. As a result, what we obtain the phenomenon or conclusion is that hard/hard types can combine better. The hard/hard types are better than that of soft/hard types, and what we obtain the rules are consistent with the previous summing-up.

2. Critical deposition velocities for Ti(ortc4)/Tc4

This investigation still obtains the critical deposition velocities for two kinds of particles under different temperature (shown in Fig. 7). Fig. 7 implys that the critical deposition velocities decrease following the temperature increase. And the critical deposition velocities of TC4 is always lower than that of Ti particle. Therefore, the conclusion can be given that TC4 can reach more strong distortion ability than that of Ti, and TC4 is more easy to combine with TC4 substrate.

To analyze further our theoretical results, our data and others are summarized as following. The critical deposition velocities of ours, Yang's[16], Assadi's[17], Schimdt's[18] and Manap's[19] are about 730m/s, 657m/s, 730m/s, 700~1300m/s and 750~1000m/s, respectively. Because different researchers use different theoretical models, size of particles and mathematic means, the results calculated are different among them. For experimental studies, chemical components, particle size, size distribute, oxidation content, spray equipment and methods of velocity measurement are different among experimental scientists, thereby the values obtained aren't the same and have some decentralization. However, what we obtained are in error about 10% comparing with previous reports, so the results are nearly satisfying. The important significance is that what we have done give some guide for cold spray and decide the condition of deposition.

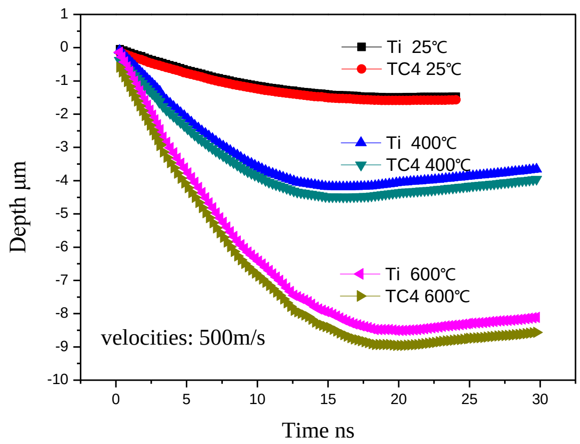

Figure 5. Relation between depth and time for Ti and TC4 under different temperatures.

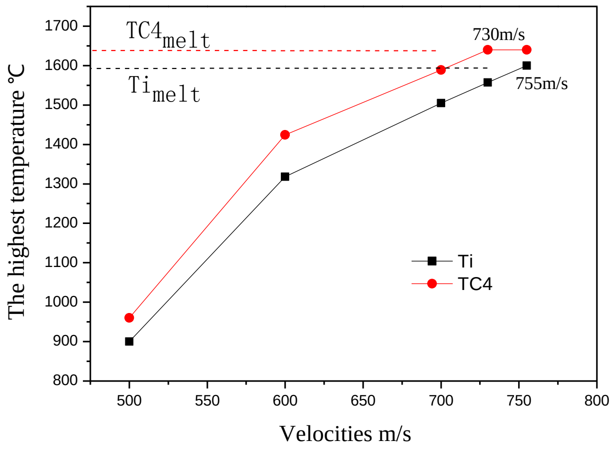

Figure 6. The highest temperature of colliding under different fly velocities.

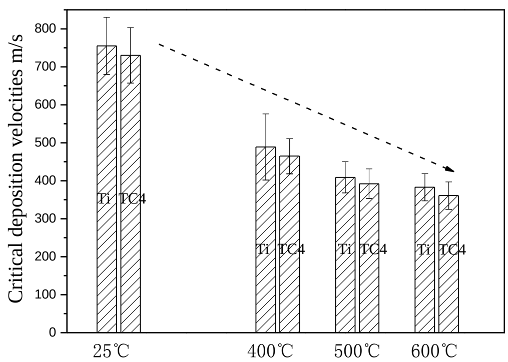

Figure 7. The critical deposition velocities verus colliding temperature.

Table III.

Parameters of materials used in this study

coatings/substrate	SPH		FEM	
	Vcrit	vmax	Vcrit	vopt
Ti/Ti	750[16]	1000[16]	700[18]	1300[18]
Ti/TC4	750[This study]			
TC4/TC4	730[This study]			

IV. CONCLUSION

LS-DYNA software was adopted to study the deposition morphologies, collide depth, the highest collide temperature, and critical deposition velocities for Ti and TC4 powder on TC4 substrate. Theoretical results show that distortion, collide depth and the highest collide temperature for TC4 are larger than that of Ti powder. Threshold deposition velocities of Ti powder are 750m/s, 489m/s, 409m/s, 383m/s, and TC4 powder are 730m/s, 465m/s, 392m/s, 361m/s under 25ºC, 400 ºC, 500 ºC, 600 ºC, respectively. It reveals that critical deposition velocities decreases when powder temperature increases and threshold deposition velocity of TC4 is lower than that of Ti powder. In a word, TC4 powder can be deposited easily onto TC4 substrate than that of Ti one when they are under the same condition conditions.

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REFERENCES

[1] R. R. Bayer, "An overview on the use of titanium in the aerospace industry", *Mater. Sci. Eng. A*, 1996, A213: 103-114.
[2] S. Q. Zhang, C. H. Tao, and M. G. Yan, "The effect of various microstructures on low cycle fatigue behavior in TC6 titanium alloy", *ASTMST*, 1988, 942: 838-845.
[3] Lee, J. Komotori, and M. Shimizu, "Corrosion fatigue behavior of Ti-6Al-4V alloy in a simulated physiological", *Prog. Mech. Behav. Mater*, 1999, 1: 393-399.
[4] A. Astarita, S. Genna, and C. Leone, "Study of the laser remelting of a cold sprayed titanium layer", *Procedia CIRP*, 2015, 33: 452-457.
[5] Navair corrosion resistant alloy workshop. Cold spray technology for repair of magnesium rotorcraft components, 2006, America.
[6] S. B. Pitchuka, B. Boesl, C. Zhang, "Dry sliding wear behavior of cold sprayed aluminum amorphous/nanocrystalline alloy coatings", *Surf. Coat. Technol*, 2014, 238: 118-125.
[7] V. K. Champagne "The repair of magnesium rotorcraft components by cold spray", *J. Fail. Anal. Prev*, 2008, 8(2): 164-175.
[8] R. Jones, N. Matthews, "On the use of supersonic particle deposition to restore the structural integrity of damaged aircraft structures", *Int. J. Fatigue*, 2011, 33: 1257-1267.
[9] T, Marrocco, D. Harvey, "The potential of the cold spray process for the repair and manufacture of aluminum alloy parts", *13th Int. Conf. Alum. Alloy*, 2012, 257-266.
[10] M. V. Vidaller, "Metallic coatings deposited by cold gas spray onto light alloys". Barcelona univestity, 2013.
[11] W. Y. Li, M. Yu, H. L. Liao, "Effect of vacuum heat treatment on microstructure and tensile property of cold sprayed porous Ti bulk", *Chin. J. Nonferrous Met*, 2010, 20: 902-905.
[12] W. Y. Li, H. L. Liao, and C. J. Li, "On high velocity impact of micro-sized metallic particles in cold spraying", *Appl. Surf. Sci.*, 2006, 253(5): 2852-2862.
[13] M. Grujicic, J. R. Saylor, and D. E. Beasley, "Computational analysis of the interfacial bonding between Feed powder particles and the substrate in the cold-gas dynamic-spray process", *Appl. Surf. Sci*, 2003, 219(3-4): 211-227.
[14] M. Grujicic, C. L. Zhao, W. S. and DeRosset, "Adiabatic shear instability based mechanism for particles/substrate bonding in the cold-gas dynamic-spray process", *Mater. Des*, 2004, 25(8): 681-688.
[15] X. L. Zhou, X. Y. Su, and H. Cui, "Simulation effect of cold-sprayed particles properties on their impacting behaviors", *Chin. J. Nonferrous Met*, 2008, 44(11): 1286-1291.
[16] Y. Yang, Y. Hao, and L. Y. Kong, "Research on critical velocity of particle during cold spray process", *J. Therm. Spray Technol*, 2015, 7(4): 1-16.
[17] H. Assadi, F. Gärtner, and T. Stoltenhoff, "Bonding mechanism in cold gas spraying", *Acta Mater*, 2003, 51(15): 4379-94.
[18] T. Schmidt, H. Assadi, and F. Gärtner, "From particle acceleration to impact and bonding in cold spraying", *J. Therm. Spray Technol*, 2009, 18(5-6): 794-808.
[19] A. Manap, O. Nooririnah, and H. Misran, "Experimental and SPH study of cold spray impact between similar and dissimilar metals", *Surf. Eng*, 2014, 30(5): 335-341.