metals

MDPI

Review

Mechanical and Wear Properties of Additive Manufactured Metal Matrix Composites: A Review

Haris Farooq Kiani, Nan Xiao, Zan Li * and Shaofan Ge *

State Key Laboratory of Metal Matrix Composites, Shanghai Jiao Tong University, Shanghai 200240, China; harisfarooqkiani@sjtu.edu.cn (H.F.K.); xiaonan1321@sjtu.edu.cn (N.X.)
* Correspondence: njulizan@sjtu.edu.cn (Z.L.); geshaofan@sjtu.edu.cn (S.G.)

This Supplementary Information file (SI) contains two supplementary figures (Tables S1 and S2),

Table S1 Tensile properties of additive manufactured metal matrix composites

Composite	Temp(°C)	(UTS)MPa	(YS)MPa	References
2%TiCN/AlSi10Mg	100	344	245	[25]
	150	308	235	
	200	270	209	
5%SiC/AlSi10Mg	300	207	193	[31]
1%TiO2/2219Al	200	218	198	[26]
	300	120	104	
	315	101	93	
TiB2/Al2618	200	305.5	289	[29]
	300	130.6	126	
Ti/B-2618Al	150	344.8	330.7	[22]
	200	276.5	274.8	
	250	229.3	227	
	300	101.5	98	
35%TiC/Al	400	256	190	[42]
2%ZrB2/IN718	650	1162	1086	[34]
	800	603.1	552	
TiB2+In625	800	605	520	[33]
TiC+In625	800	387	362	
ZrB2+In625	800	495	435	
ZrC+In625	800	331	313	
Y2O3/ IN738LC	850	773	633	[43]
Y2O3/ IN718	650	942	690	[30]
1.75%Cr2O3/718	900	727	579	[44]
1%TiB2/ IN718	650	916.6	748	[39]
2%TiB2/ IN718	650	963.6	771	
2%TiB2/GH3230	850	470	311	[37]
1%TiB2/GH3230	850	390	254	[36]
	900	236	191	

TiC/GTD222	800	797	789	[38]
	850	636	620	
	900	432	426	
Ti3SiC2/IN625	650	668	377	[35]
15%TiC/316L	800	476	321	[23]
	950	170	110	
SiO2/316L	200	450	160	[40]
TiB/Ti6Al4V	400	1095	908	[41]
	500	926	761	
	550	723	645	
	600	522	466	
	700	341	-	
TiBw/TC4	500	621	590	[27]
	550	580	540	

Table S2 Coefficient of friction of additive manufactured metal matrix composites

No:	Metal Matrix Composites	Coefficient of Friction	References
1	15%TiC/Ti	0.2	[134]
2	2%TiB2/Ti6Al4V	0.24	[141]
3	3%TiC/Ti6Al4V	0.3	[143]
4	3%TiB/Ti6Al4V	0.35	[130]
5	0.2%B4C/Ti64	0.43	[133]
6	5%TiBw/Ti6Al4V	0.44	[147]
7	2%SiC/AlSi10Mg	0.12	[144]
8	Al4SiC4+SiC/Al	0.34	[131]
9	5%TiC/ AlSi10Mg	0.38	[135]
10	micro+nano/C22	0.19	[150]
11	TiC/IN718	0.29	[137]
12	12%BN/IN718	0.31	[138]
13	6%TiC/IN625	0.33	[132]
14	WC/IN718	0.35	[142]
15	Nano TiC/IN718	0.36	[136]
16	9%TiC/IN718	0.55	[139]
17	2%TiC/316L	0.12	[148]
18	TiB2/H13	0.2	[129]
19	1%CNT/316L	0.4	[146]
20	15%TiB2/316L	0.44	[127]
21	9%SiC/316L	0.52	[149]
22	TiC/H13	0.52	[128]
23	1.5%Graphene/M50 Steel	0.52	[140]

References

22. Belelli, F.; Casati, R.; Riccio, M.; Rizzi, A.; Kayacan, M.Y.; Vedani, M. Development of a novel high-temperature Al alloy for laser powder bed fusion. *Metals*. **2020**; *11,* 35.
23. Grzesiak, D.; AlMangour, B.; Krawczyk, M.; Baek, M.S.; Lee, K.A. Selective laser melting of TiC reinforced stainless steel nanocomposites: mechanical behaviour at elevated temperatures. *Mater Lett*. **2019**; *256,* 126633.
24. Guo, C.; Yu, Z.; Hu, X.; Li, G.; Zhou, F.; Xu, Z.; Han, S.; Zhou, Y.; Ward, R.M.; Zhu, Q. Y_2O_3 nanoparticles decorated IN738LC superalloy manufactured by laser powder bed fusion: Cracking inhibition, microstructures and mechanical properties. *Composites, Part B* **2022**; *230,* 109555.
25. He, P.; Kong, H.; Liu, Q.; Ferry, M.; Kruzic, J.J.; Li, X. Elevated temperature mechanical properties of TiCN reinforced AlSi10Mg fabricated by laser powder bed fusion additive manufacturing. *Mater Sci Eng A*. **2021**; *811,* 141025.
26. Li, G.; Huang, Y.; Li, X.; Guo, C.; Zhu, Q.; Lu, J. Laser powder bed fusion of nano-titania modified 2219 aluminium alloy with superior mechanical properties at both room and elevated temperatures: The significant impact of solute. *Addit Manuf*. **2022**; *60,* 103296.
27. Li, S.; Li, S.; Liu, H.; Liu, L.; Pan, D.; Li, G.; Wang, Z.; Hou, X.; Gao, J.; Zhang, X. Achieving back-stress strengthening at high temperature via heterogeneous distribution of nano TiBw in titanium alloy by electron beam powder bed fusion. *Mater Charact*. **2024**; *215,* 114132.
28. Lin, T.-C.; Cao, C.; Sokoluk, M.; Jiang, L.; Wang, X.; Schoenung, J.M.; Lavernia, E.J.; Li, X. Aluminum with dispersed nanoparticles by laser additive manufacturing. *Nature Communications*. **2019**; *10,* 4124.
29. Ma, S.; Dai, J.; Zhang, C.; Wang, M.; Liu, J.; Wang, L.; Wang, H.; Chen, Z. Enhanced high temperature mechanical properties and heat resistance of an Al–Cu–Mg–Fe–Ni matrix composite reinforced with in-situ TiB_2 particles. *J Mater Sci*. **2023**; *58,* 13019–39.
30. Song, Q.s.; Zhang, Y.; Wei, Y.f.; Zhou, X.y.; Shen, Y.f.; Zhou, Y.m.; Feng, X.m. Microstructure and mechanical performance of ODS superalloys manufactured by selective laser melting. *Opt Laser Technol*. **2021**; *144,* 107423.
31. Song, X.Y.; Shu, S.L.; Zhang, S.; Yang, H.Y.; Qiu, F.; Jiang, Q.C. Microstructure, solidification defects and mechanical properties of high-modulus and high-strength SiC/AlSi10Mg composites fabricated by selective laser melting. *Ceram Int*. **2024**; *50,* 26607–23.
32. Stegman, B.; Yang, B.; Shang, Z.; Ding, J.; Sun, T.; Lopez, J.; Jarosinski, W.; Wang, H.; Zhang, X. Reactive introduction of oxide nanoparticles in additively manufactured 718 Ni alloys with improved high temperature performance. *J Alloys Compd* **2022**; *920,* 165846.
33. Tekoglu, E.; Bae, J.-S.; Kim, H.-A.; Lim, K.-H.; Liu, J.; Doležal, T.D.; Kim, S.Y.; Alrizqi, M.A.; Penn, A.; Chen, W. Superior high-temperature mechanical properties and microstructural features of LPBF-printed In625-based metal matrix composites. *Mater Today*. **2024**; *80,* 297–307.
34. Tekoğlu, E.; O'Brien, A.D.; Bae, J.-S.; Lim, K.-H.; Liu, J.; Kavak, S.; Zhang, Y.; Kim, S.Y.; Ağaoğulları, D.; Chen, W. Metal matrix composite with superior ductility at 800 ℃: 3D printed In718+ ZrB_2 by laser powder bed fusion. *Composites, Part B*. **2024**; *268,* 111052.
35. Wang, C.; Xiao, Y.; Mi, G.; Zhang, M.; Hua, Z.; Hu, Y. Ti_3SiC_2 reinforced Inconel 625 composites prepared via laser directed energy deposition: new insights into microstructure evolution and mechanical properties. *J Alloys Compd*. **2024**; *970,* 172396.
36. Zhang, Z.; Han, Q.; Liu, Z.; Gao, J.; Wang, L.; Liu, H.; Wang, R.; Ma, T.; Gao, Z. Combined effects of heat treatment and TiB_2 content on the high-temperature tensile performance of TiB_2-modified Ni-based GH3230 alloy processed by laser powder bed fusion. *Mater Sci Eng A*. **2022**; *861,* 144379.
37. Zhang, Z.; Han, Q.; Liu, Z.; Wang, X.; Wang, L.; Yang, X.; Ma, T.; Gao, Z. Influence of the TiB_2 content on the processability, microstructure and high-temperature tensile performance of a Ni-based superalloy by laser powder bed fusion. *J Alloys Compd*. **2022**; *908,* 164656.
38. Zhang, Z.; Wang, R.; Lv, Y.; Liu, W.; Liu, Y. Microstructures and mechanical properties of heat treated TiC/GTD222 nickel-based composite prepared by selective laser melting. *Mater Sci Eng A*. **2022**; *851,* 143588.
39. Zhao, M.; Song, J.; Tang, Q.; Zhang, Z.; Feng, Q.; Han, Q.; Nie, Y.; Jin, P.; Jin, M.; Wu, H. Laser powder bed fusion of Inconel 718-based composites: effect of TiB_2 content on microstructure and mechanical performance. *Opt Laser Technol*. **2023**; *167,* 109596.
40. Zhong, Y.; Liu, L.; Wikman, S.; Cui, D.; Shen, Z. Intragranular cellular segregation network structure strengthening 316L stainless steel prepared by selective laser melting. *J Nucl Mater*. **2016**; *470,* 170–8.

41. Zhou, Z.; Liu, Y.; Liu, X.; Wu, L. High-temperature tensile and creep properties of TiB-reinforced Ti6Al4V composite fabricated by laser powder bed fusion. *Mater Charact*. **2023**; *200,* 112859.
127. AlMangour, B.; Grzesiak, D.; Yang, J.-M. Rapid fabrication of bulk-form TiB_2/316L stainless steel nanocomposites with novel reinforcement architecture and improved performance by selective laser melting. *Journal of Alloys and Compounds*. **2016**; *680,* 480–93.
128. AlMangour, B.; Grzesiak, D.; Yang, J.-M. Nanocrystalline TiC-reinforced H13 steel matrix nanocomposites fabricated by selective laser melting. *Mater Des*. **2016**; *96,* 150–61.
129. AlMangour, B.; Grzesiak, D.; Yang, J.-M. Selective laser melting of TiB_2/H13 steel nanocomposites: Influence of hot isostatic pressing post-treatment. *J Mater Process Technol*. **2017**; *244,* 344 – 53.
130. Cai, C.; Radoslaw, C.; Zhang, J.; Yan, Q.; Wen, S.; Song, B.; Shi, Y. In-situ preparation and formation of TiB/Ti-6Al-4V nanocomposite via laser additive manufacturing: Microstructure evolution and tribological behavior. *Powder Technol*. **2019**; *342,* 73 – 84.
131. Chang, F.; Gu, D.; Dai, D.; Yuan, P. Selective laser melting of in-situ Al4SiC4+ SiC hybrid reinforced Al matrix composites: Influence of starting SiC particle size. *Surface and Coatings Technology*. **2015**; *272,* 15–24.
132. Chen, L.; Sun, Y.; Li, L.; Ren, Y.; Ren, X. In situ TiC/Inconel 625 nanocomposites fabricated by selective laser melting: Densification behavior, microstructure evolution, and wear properties. *Applied Surface Science*. **2020**; *518,* 145981.
133. Fereiduni, E.; Ghasemi, A.; Elbestawi, M. Microstructural characterization and mechanical properties of nano-scale/sub-micron TiB-reinforced titanium matrix composites fabricated by laser powder bed fusion. *Journal of Alloys and Compounds*. **2022**; *896,* 163054.
134. Gu, D.; Hagedorn, Y.C.; Meiners, W.; Wissenbach, K.; Poprawe, R. Nanocrystalline TiC reinforced Ti matrix bulk-form nanocomposites by Selective Laser Melting (SLM): Densification, growth mechanism and wear behavior. *Compos Sci Technol*. **2011**; *71,* 1612–20.
135. Gu, D.; Wang, H.; Dai, D.; Chang, F.; Meiners, W.; Hagedorn, Y.-C.; Wissenbach, K.; Kelbassa, I.; Poprawe, R. Densification behavior, microstructure evolution, and wear property of TiC nanoparticle reinforced AlSi10Mg bulk-form nanocomposites prepared by selective laser melting. *J Laser Appl*. **2015**; *27*.
136. Gu, D.; Zhang, H.; Dai, D.; Xia, M.; Hong, C.; Poprawe, R. Laser additive manufacturing of nano-TiC reinforced Ni-based nanocomposites with tailored microstructure and performance. *Composites Part B: Engineering*. **2019**; *163,* 585–97.
137. Jia, Q.; Gu, D. Selective laser melting additive manufacturing of TiC/Inconel 718 bulk-form nanocomposites: Densification, microstructure, and performance. *J Mater Res Technol*. **2014**; *29,* 1960–9.
138. Kim, S.H.; Shin, G.H.; Kim, B.K.; Kim, K.T.; Yang, D.Y.; Aranas, C.; Choi, J.P.; Yu, J.H. Thermo-mechanical improvement of Inconel 718 using ex situ boron nitride-reinforced composites processed by laser powder bed fusion. *Sci Rep-Uk*. **2017**; *7*.
139. Kong, D.; Dong, C.; Ni, X.; Zhang, L.; Man, C.; Zhu, G.; Yao, J.; Wang, L.; Cheng, X.; Li, X. Effect of TiC content on the mechanical and corrosion properties of Inconel 718 alloy fabricated by a high-throughput dual-feed laser metal deposition system. *Journal of alloys and compounds*. **2019**; *803,* 637–48.
140. Liu, X.; Shi, X.; Huang, Y.; Deng, X.; Lu, G.; Yan, Z.; Zhou, H.; Xue, B. The sliding wear and friction behavior of M50-graphene self-lubricating composites prepared by laser additive manufacturing at elevated temperature. *Journal of Materials Engineering and Performance*. **2018**; *27,* 985–96.
141. Patil, A.S.; Hiwarkar, V.D.; Verma, P.K.; Khatirkar, R.K. Effect of TiB_2 addition on the microstructure and wear resistance of Ti-6Al-4V alloy fabricated through direct metal laser sintering (DMLS). *J Alloys Compd*. **2019**; *777,* 165–73.
142. Rong, T.; Gu, D.; Shi, Q.; Cao, S.; Xia, M. Effects of tailored gradient interface on wear properties of WC/Inconel 718 composites using selective laser melting. *Surface and Coatings Technology*. **2016**; *307,* 418–27.
143. Tang, M.; Zhang, L.; Zhang, N. Microstructural evolution, mechanical and tribological properties of TiC/Ti6Al4V composites with unique microstructure prepared by SLM. *Mater Sci Eng A*. **2021**; *814,* 141187.
144. Xi, X.; Chen, B.; Tan, C.; Song, X.; Feng, J. Microstructure and mechanical properties of SiC reinforced AlSi10Mg composites fabricated by laser metal deposition. *J Manuf Process*. **2020**; *58,* 763 – 74.
145. Yang, Y.; Ma, S.; Liu, G.; Wang, T.; Lei, J. Nano and micron WC particles reinforced Hastelloy C_{22} coatings manufactured by directed energy deposition. *Journal of Alloys and Compounds*. **2024**; *970,* 172540.
146. Yin, H.; Yang, J.; Zhang, Y.; Crilly, L.; Jackson, R.L.; Lou, X. Carbon nanotube (CNT) reinforced 316L stainless steel composites made by laser powder bed fusion: Microstructure and wear response. *Wear*. **2022**; *496,* 204281.

147. Zhao, X.；Lu, X.；Zuo, H.；Ma, S.；Wang, C.；Li, M.V. TiBw reinforced titanium matrix composites fabricated by selective laser melting: influence of energy density on microstructure and tribological performance. *Ceram Int*. **2023**; *49,* 28920–33.
148. Zhao, Z.；Li, J.；Bai, P.；Qu, H.；Liang, M.；Liao, H.；Wu, L.；Huo, P.；Liu, H.；Zhang, J. Microstructure and mechanical properties of TiC-reinforced 316L stainless steel composites fabricated using selective laser melting. *Metals*. **2019**; *9,* 267.
149. Zou, Y.；Tan, C.；Qiu, Z.；Ma, W.；Kuang, M.；Zeng, D. Additively manufactured SiC-reinforced stainless steel with excellent strength and wear resistance. *Addit Manuf*. **2021**; *41,* 101971.