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Microstructurally inhomogeneous composites: Is a homogeneous reinforcement distribution optimal?

L.J. Huang [a,*], L. Geng [a], H-X. Peng [b,*]

[a] State Key Laboratory of Advanced Welding and Joining, Harbin Institute of Technology, P.O. Box 433, Harbin 150001, PR China
[b] Institute for Composites Science Innovation (InCSI), School of Materials Science and Engineering, Zhejiang University, Hangzhou 310027, PR China

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ABSTRACT

Since the 1960s, it has been a common practice worldwide to pursue a homogeneous distribution of reinforcements within a matrix material, discontinuous metal matrix composites (DMMCs) in particular. Taking an overview of the worldwide activities in DMMC research, despite many favourable attributes such as improved specific strength, stiffness and superior wear resistance, DMMCs with a homogeneous microstructure tend to exhibit a very low room temperature damage tolerance even with a highly ductile matrix material such as aluminium. In this review, a range of uniquely multi-scale hierarchical structures have been successfully designed and fabricated by tailoring reinforcement distribution for DMMCs in order to obtain superior performance. A variety of specific microstructures that were developed in Al, Mg, Cu, Fe, Co and TiAl matrices indicate that there must be adequate plastic regions among the reinforcements to blunt or deflect cracks if one wants to toughen DMMCs. Following this path, aided by theoretical analyses, the most recent success is the design and fabrication of a network distribution of in situ reinforcing TiB whiskers (TiBw) in titanium matrix composites (TMCs), where a tailored three-dimensional (3D) quasi-continuous network microstructure displays significant improvements in mechanical properties. This resolves the brittleness surrounding TMCs fabricated by powder metallurgy. It is the large reinforcement-lean regions that remarkably improve the composite's ductility by bearing strain, blunting the crack and decreasing the crack-propagation rate. The fracture,

* Corresponding authors.
E-mail addresses: huanglujun@hit.edu.cn (L.J. Huang), hxpengwork@zju.edu.cn (H-X. Peng).

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strengthening and toughening mechanisms are comprehensively elucidated in order to further understand the advantages of such an inhomogeneous microstructure, and to justify the development of novel techniques to produce such inhomogeneous microstructures. This approach opens up a new horizon of research and applications of DMMCs and can be easily extended to general multi-phase composites with enhanced physical and mechanical properties.

Nomenclature

MMCs	metal matrix composites
DMMCs	discontinuous metal matrix composites
TMCs	titanium matrix composites
DRA	discontinuously reinforced aluminium matrix composites
DRTMCs	discontinuously reinforced titanium matrix composites
TiBw	TiB whiskers
TiCp	TiC particles
CNTs	carbon nanotubes
TEM	transmission electron microscopy
SEM	scanning electron microscopy
EBSD	Electron Backscattered Diffraction
EDS	Energy Dispersive Spectrometer
XRD	X-ray Diffraction
PM	powder metallurgy
CAPAS	current-activated pressure assisted sintering
3D	three-dimensional
phase α	reinforcement-rich region
phase β	reinforcement-lean region
H–S	Hashin–Shtrikman
H–T	Halpin and Tsai
V_L	local volume fraction of reinforcement
RoM	rule of mixtures
$E_{\text{HS-Upper}}$	the elastic property of the upper H–S bounds
$E_{\text{HS-Lower}}$	the elastic property of the lower H–S bounds
FEM	finite element model
MFP	the mean free path
COD	crack opening displacement
YS	yield strength
UTS	ultimate tensile strength
RPS	relative particle size
GEM	general effective media
HAP	hydroxyapatite
IT	ice-template
ESE	elastic strain energy