

A New Gasdynamical Coating Method using Detonation Tube Technology

Erweiterung der Detonationsrohrtechnik zu einem neuen gasdynamisch basierten Beschichtungsverfahren

Von der Fakultät für Maschinenwesen der
Rheinisch-Westfälischen Technischen Hochschule Aachen
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Ingenieurwissenschaften genehmigte Dissertation

vorgelegt von

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Christian Henkes

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Summary

A detonation driven spray technique in which particles are accelerated in a high enthalpy nozzle flow has been designed and successfully tested. Particle velocities in the average between 1500 m/s and 1800 m/s are achieved. In conventional thermal spray applications the maximum particle impact velocities are about 1000 m/s. Depending on the spray material and size, only spray material with a critical bonding velocity lower than 1000 m/s can be used in these applications. Furthermore, the coating quality increases when the impact velocity is close to the upper erosion velocity. Therefore, higher particle impact velocities extend the application range and lead to a better coating quality with very low porosity, high bonding strength and hardness. This method uses the detonation driven shock tunnel technology to operate a nozzle in an intermittent process with a frequency up to 5 Hz. High reservoir conditions are generated by the detonation of hydrogen (stoichiometric with oxygen). A specially designed particle feeder injects the particles into the nozzle flow with variable position along the nozzle axis in order to control the particle temperature and particle velocity. During the injection time, the nozzle flow is quasi-steady for about 10 ms with a reservoir pressure of 30 bar and a reservoir temperature of 3600 K. Maximum particle velocities over 2000 m/s in the free jet in front of the substrate have been observed. Theoretical particle temperatures are close to or exceed the melting point of the particular material. Due to the high particle exit velocities, measurements of particle temperature are not provided in this work. Several measuring techniques including PIV have been applied to characterize the flow features of the process as well as the particle behaviour. First coating samples with different material pairings and excellent properties concerning microhardness and porosity have been obtained so far. Due to the variability of process parameters, this method shows high potential for optimization of coatings produced so far and for testing further new material pairings.

Zusammenfassung

Ein gasdynamisches Beschichtungsverfahren, in welchem das Beschichtungsmaterial in Pulverform in eine hoch energetische Düsenströmung injiziert wird, ist entwickelt und erfolgreich getestet worden. Dabei werden Einschlaggeschwindigkeiten der Partikel auf dem Substrat zwischen 1500 m/s und 1800 m/s erreicht, während in den konventionellen Beschichtungsverfahren diese etwa 1000 m/s betragen. Je nach Größe und Material der Partikel können in diesen Beschichtungsverfahren nur Pulvermaterialien verwendet werden, für die eine kritische Haftgeschwindigkeit unterhalb von 1000 m/s nötig ist. Ausserdem nimmt die Beschichtungsqualität im Allgemeinen zu, je näher die Einschlaggeschwindigkeit an der oberen Erosionsgrenze liegt. Daher ermöglichen höhere Partikelgeschwindigkeiten einen größeren Anwendungsbereich und führen zu einer besseren Beschichtungsqualität mit sehr niedriger Porosität, hohen Bindungsenergien und hoher Festigkeit.

Das hier beschriebene Verfahren basiert auf einer detonationsgetriebenen Stoßrohrtechnik, mit welcher eine Düsenströmung in einem intermittierenden Betrieb mit einer Frequenz bis 5 Hz erzeugt wird. Durch die Detonation eines (stöchiometrischen) Wasserstoff/Sauerstoff-Gemisches werden sehr hohe Ruhebedingungen für die Düsenströmung erzeugt. Ein spezielles, in dieser Arbeit entwickeltes Partikelzufuhrsystem führt die Partikel der Düsenströmung mit veränderbaren Injektionsstellen entlang der Düsenachse zu, wodurch die Partikelgeschwindigkeiten und Partikeltemperaturen gesteuert werden können. Die Partikelinjektion geschieht in einer Zeitspanne von etwa 10 ms. Während dieser Zeit ist die Düsenströmung quasi-stationär bei einem Ruhedruck von 30 bar und einer Ruhetemperatur von 3600 K. Maximale Partikelgeschwindigkeiten oberhalb von 2000 m/s sind im Freistrahle und stromauf des Substrats beobachtet worden. Die Partikeltemperaturen liegen theoretisch nahe der Schmelztemperaturen der jeweiligen Materialien oder übersteigen diese, konnten jedoch aufgrund der sehr hohen Austrittsgeschwindigkeiten der Partikel aus der Düse nicht experimentell nachgewiesen werden. Verschiedene Messmethoden zur Charakterisierung der Gas/Partikel-Strömung sind eingesetzt worden, unter anderem PIV zur Messung der Partikelgeschwindigkeiten. Schließlich wurden Beschichtungsproben mit unterschiedlichen Materialpaarungen Substrat/Beschichtung erzeugt, die zum Teil schon sehr gute Qualitäten hinsichtlich Mikrohärtigkeit und Porosität aufweisen. Aufgrund der Variation der Prozessparameter, die starken Einfluss auf die Beschichtungsqualität haben, zeigt diese Methode ein hohes Potential zur Verbesserung der bisher erzeugten Beschichtungsqualitäten. Zudem können mit dieser Methode neue Materialpaarungen getestet werden.

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Nomenclature

Parameters

a	local speed of sound
A	area
C_D	drag coefficient
C_f	wall friction coefficient
c_p	specific heat
d	diameter, thickness
D	detonation wave velocity
E	internal energy
f	force
HV	Vickers hardness
I	current
J	energy (electr.)
L	inductivity
l	length
m	mass
$\dot{m}$	mass flow
Ma	Mach number
n	substance amount fraction
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Q	reaction heat
q	specific reaction heat
R	molar gas constant, resistance
Re	Reynolds number

T	temperature
t	time
U	voltage
u	velocity
V	volume
x	distance
γ	ratio of specific heats
β	flow deflection angle
η	loading ratio
Φ	molar equivalence ratio, mass fraction
λ	heat conductivity
μ	viscosity
ρ	density
ζ	volume fraction
σ	concentration, shock wave angle
θ	angle
τ	relaxation time

Subscript

0	reservoir; initial
a	ambient
c	compressibility, charge, cavity
cg	carrier gas
CJ	Chapman-Jouguet
con	conveying
d	dynamic
e	temperature equalization, exit
f	feeder

fc	flow cross section
g	gas
i	inert, species, inner
M	mixture
p	particle
r	rarefaction, response
S	shock wave
T	temperature, heat
t	tap
v	velocity

Superscript

*	critical
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