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BIMETAL BRAKE DISCS WITH A CAST GRAY IRON FRICTION CLADDING AND AN ALUMINUM ALLOY CORE: ECONOMIC BENEFITS AND OPPORTUNITIES FOR MASS PRODUCTION

BIMETALNI KOČIONI DISK SA FRIKCIONIM OMOTAČEM IZ LIVENOG GVOŽDJA I JEDROM IZ ALUMINIJEVE LEGURE: EKONOMIČNOST REŠENJA I MOGUĆNOSTI ZA MASOVNU PROIZVODNJU

VARUZAN KEVORKIJAN

Independent Researching p.l.c., Maribor, Slovenia

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ABSTRACT

In this article the economic benefits and opportunities for mass production of bimetal brake discs with a cast gray iron friction cladding and an aluminum alloy core were outlined in combination with economic analysis of various weight reduced brake discs.

Key words: bimetal brake disc, core/cladding structure, and economic analysis of weight reduction

IZVOD

U ovom radu su opisane ekonomske prednosti potencijalne proizvodnje bimetalnih kočionih diskova sa frikcionim omotačem od livenog gvoždja i jezgrom od aluminijumske legure kao i ekonomski učinci smanjivanja mase kočećeg diska.

Key words: bimetal brake disc, core/cladding structure, and economic analysis of weight reduction

INTRODUCTION

In the automotive industry there is a persistently growing interest in replacing the current generation of brake discs made in gray iron with 45-60% lighter aluminum [1-8]. A typical ventilated brake disc for passenger cars weighs 5.4 kg, while the aluminum-based equivalent weighs about 2.5 kg and is designed to have about a one third larger volume to achieve the equivalent mechanical properties. The expecting saving in weight would be about 10-12 kg. However, the main reason for introducing a lighter brake disc is not the weight reduction for improving fuel efficiency, but rather the reduction of inertial forces, increased acceleration and reduced braking distance. On the other hand, there is a target price the automotive industry is willing to pay for such a replacement and it is currently about 6 USD for a fully machined brake disc. For R&D teams dealing with replacing cast gray iron with lighter friction materials, this is one of the most important boundary condition they should respect. The main purpose of this paper is to identify some new material solutions brake disc designs suitable for achieving the target price.

BRIEF REVIEW OF THE CURRENT STATE OF ALUMINUM-BASED BRAKE DISCS

Because their inadequate wear resistance and low seizure loads prevent the direct use of aluminum alloys, reinforcement of the aluminum alloy matrix with ceramic particulates [3-7], local reinforcement of the aluminum alloy matrix on the friction surfaces [4, 8], and some state-of-the-art surface-coating techniques [9] have been explored to improve the wear resistance [2] of the aluminium-based brake disc surface. Many conceptually different Al MMC prototype brake discs were developed and fabricated in the last decade, including: (i) the monolithic type, made from aluminum-silicon alloy matrix reinforced with 10 vol.% SiC particulate and 5 vol.% nickel-coated graphite particulate [5, 6], (ii) the macro-composite disc with Al MMC cladding on the friction surface and an Al alloy core [8], as well as (iii) the aluminum-based brake disc having a friction surface covered by a ceramic layer [9]. However, due to various technical limitations and cost penalties, the mass production of these prototypes failed to appear in mass production.

BRAKE MATERIAL REQUIREMENTS

Because the amount of energy handled by the brakes can be the equivalent of many times the power developed by the engine and they are often called upon to decelerate the vehicle in a fraction of the time that the engine is normally expected to take to accelerate it, an advanced brake disc material should meet several requirements which cannot be provided by a single phase material. On the disc's friction surfaces, high wear resistance, self-lubrication and the correct friction level with minimal friction variations should be accompanied by reasonable wet behavior, low thermal conductivity, high thermal shock resistance, an adequate value of the coefficient of thermal expansion (CTE) and quietness of operation. Also, the disc's friction surfaces should be designed to be fully compatible with existing pad friction materials, otherwise a new pad friction material should be developed. The generally used material for commercial brake discs is cast gray iron, which is a composite material consisting of precipitated graphite particles in a solid metal matrix.

SOLUTIONS COMBINING CAST GRAY IRON AND ALUMINUM: THE DEVELOPMENT OF A BIMETAL BRAKE DISC

Actually, cast gray iron has only one serious disadvantage in that application-it is too heavy in comparison with aluminum-based materials [10]. So, an alternative might be to produce a bimetal brake disc with cast iron friction surfaces to provide standard wear properties and reduce the weight with an aluminum alloy core. Although the aluminum-based core and the friction cladding made in cast-iron can be welded, brazed or joined by other well practiced techniques of joining aluminum to ferrous alloys [11], the practical usage of these techniques in production of a bimetal brake disc is limited due to the formation of very brittle intermetallic compounds in a joint area, and by generation of stresses caused by differential thermal expansion and contraction as the cast-iron cladding and aluminum-based core heat or cool together during and after braking. Possible corrosion problems should also be considered. Two possible solutions for joining of cast gray iron cladding and the aluminum alloy core are presented in this work: (i) infiltration of a porous ceramic preform with cast gray iron from the top surface and with aluminum (or magnesium alloy) from the core; and (ii) mechanical joining using the dovetail technique.

Infiltration enables processing in stages, first pressurelessly infiltrating the upper part of the porous silicon carbide preform with molten cast iron. After that, the friction surface of the insert is machined and the bottom, non-infiltrated part of the insert is pressurelessly infiltrated with aluminum alloy via the insertion casting procedure.

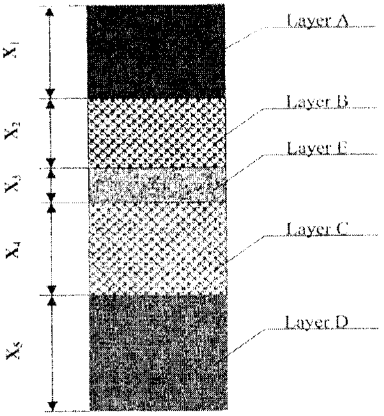

Fig. 1 - Shematic presentation of the multi-layered structure obtainable by the reactive infiltration/penetration of a ceremic preform with two different infiltrans
Sl.1 - Šematski prikaz višeslojne strukture dobijene iniftracijom/penetracijom keramičke predforme sa dva različita infiltranta

Apart from silicon carbide, other ceramic preforms (e.g. various borides, nitrides and carbides) wettable both with molten iron and aluminum alloys or with molten iron and magnesium alloys can also be applied. The structure of the functionally graded metal-ceramic laminate obtained is schematically represented in Fig. 1. The dense or porous (sintered, pressed or in the form of powder bed) ceramic preform is pressurelessly infiltrated (or penetrated, if it is dense) from one side by the first infiltrant (molten metallic alloy or pure metal). Infiltration proceeds to the desired cross section of the preform, producing the top layer (layer A) made up of the solidified infiltrant and the underlayer (layer B) consisting of the reactive (or non-reactive) infiltrated preform. The partly infiltrated preform is then completely infiltrated starting from the other side by the second metallic infiltrant, in this way fabricating two additional layers: the internal layer (layer C), consisting of the ceramic preform infiltrated with the second infiltrant, and the bottom layer (layer D) formed by the solidified second infiltrant. In some cases, when the infiltrants react producing intermetallic compounds, an intermediate layer (layer E) is formed between layers B and C. By controlling the depth of infiltration and the chemical reaction between the applied infiltrants, the thickness of layers B, C and E can be easily regulated. The thickness of the top (layer A) and bottom layer (layer D) depends on the excess of individual infiltrants applied for infiltration.

The volume fraction of ceramic reinforcement in layers B and C depends on the porosity of the applied preform and the product yield of any chemical reactions proceeding between the ceramic skeleton and the infiltrants. The volume fraction of the intermetallic phase in the layer E is controllable by the kinetics of chemical reaction between the two infiltrants. The suggested fabrication method is characterized by a significant inherent simplicity and cost-effectiveness in the scale-up manufacturing of functionally graded metal-ceramic laminates. It also allows great flexibility in selection of the ceramic preform and metallic infiltrants. The only limitation in the case of pressureless reactive infiltration is that the selected ceramic preform should be wettable and should also react with both metallic infiltrants. In the case of reactive penetration of a dense ceramic preform, the requirements remain the same.

Systems already investigated include carbide, nitride and boride ceramic performs infiltrated with aluminum and magnesium alloys. The combination of ferrous and non-ferrous infiltrants (aluminum alloys and cast gray iron) was also experimentally studied.

Another technique used in this work is joining by dovetailing (the details will be given elsewhere). This joining technique is cost effective and also stress free if an appropriate design of the dovetail is used. The aluminum alloy core and cast gray iron friction plates are machined separately and then simply mechanically joined into a bimetal brake disc.

ECONOMIC ANALYSIS OF VARIOUS WEIGHT REDUCED BRAKE DISCS

The cost of a fully machined brake disc comprises the cost of material, manufacturing cost (including capital) and cost of recycling.

The structure of the raw materials consumed in production of various brake discs is listed in Table 1.

Table 1 - The structure of raw materials consumed in production of various brake discs considered in this work

Tabela 1 - Pregled materijala koriščenih za izradu kočionih diskova

Type of brake disc	Composition (wt.%)		
	Al	Fe	SiC
Monolithic in cast gray iron	-	100	-
Monolithic in Al MMC*	72	-	28
Core (Al alloy)-cladding (Al MMC*)	93	-	7
Bimetal produced by infiltration	61	27	12
Bimetal produced by mechanical joining	44	56	-

*Al MMC is with 30 vol.% SiC particle

The material cost of mass produced brake discs is presented in Table 2, while the cost of each grade of fully machined discs is reported in Table 3. As evident, the cost of Al MMC for a monolithic brake disc overcomes cast gray iron by more than three times and results in a production cost of the fully machined brake disc two and half times higher than the target price. Although, the combination of an aluminum alloy core and Al MMC cladding significantly reduces both material cost and the cost of the fully machined component, it is still almost double the target price.

Table 2 - Material cost for mass production of brake discs*

Tabela 2 - Cena pojedinih materijala pri masovnoj proizvodnji kočionih diskova

Type of brake disc	Weight of fully machined disc; (kg)	Material cost** (USD/disc)
Monolithic in cast gray iron	5.571	2.90
Monolithic in Al MMC*	2.710	9.23
Core (Al alloy)-cladding(Al MMC)	2.601	6.14
Bimetal produced by infiltration	3.178	4.88
Bimetal produced by mechanical joining	3.585	3.96

**Mass production of 3 million brake discs per year is estimated*

***Material efficiency and recycling benefits are included in the material cost calculation*

Table 3 - Production cost of fully machined brake disc

Tabela 3 - Troškovi proizvodnje mašinski obradjenog kočionog diska

Type of brake disc	Cost of fully machined brake disc (USD/disc)
Monolithic in cast gray iron	5.80
Monolithic in Al MMC	14.20
Core (Al alloy)-cladding(Al MMC)	10.23
Bimetal produced by infiltration	8.13
Bimetal produced by mechanical joining	7.93

In contrast, the production cost of both grades of bimetal brake discs (infiltrated and mechanically joined) is just one third higher than the target price. With further optimization of the design of the bimetal braking zone (e.g. by decreasing the thickness of the ferrous cladding and volume of the disc) and improvements in production technology (by developing mechanical joining, which is more cost effective), the production cost could be brought closer to the target price.

The economic analysis performed demonstrates that the layered composite structure consisting of cast gray iron friction cladding and an aluminum alloy core could provide many more economic benefits than the monolithic or locally reinforced Al MMC. The economic benefits are summarized in Table 4, where the cost of weight reduction resulting from replacing cast gray iron with several composite materials is calculated for each brake disc considered in this study.

Table 4 - Weight reduction and cost of weight reduction on replacing cast gray iron in the brake disc with various composite materials

Tabela 4 - Smanjivanje mase i troškovi smanjivanja mase kočionog diska usled zamene livenog gvoždja različitim kompozitnim materijalima

Type of brake disc	Weight (kg/disc)	Weight reduction (kg/disc)	Cost of weight reduction (USD/kg)
Monolithic in cast gray iron	5.571		-
Monolithic in Al MMC*	2.710	-2.86	2.94
Core (Al alloy)-cladding(Al MMC)	2.601	-2.969	1.49
Bimetal produced by infiltration	3.178	-2.393	0.97
Bimetal produced by mechanical joining	3.585	-1.986	1.07

CONCLUSION

The economic analysis performed in this work answered the question why the mass production of Al MMC-based brake discs failed to appear and remains uncertain. This is because both prototype grades of brake discs made either from monolithic Al MMC or the macro composite brake disc consisting of Al MMC cladding and an Al alloy core significantly exceed the actual target price of about 6 USD/disc, required by representatives of the automotive industry. Based on the calculation made in this study, the cost of mass production of monolithic Al MMC brake discs is about 8 USD/disc higher than the target price; in the case of the macro composite brake disc consisting of Al MMC cladding and an Al alloy core, the target price is exceeded by about 4 USD/disc.

More promising results are obtained with two types of bimetal brake discs consisting of cast gray iron friction cladding and an aluminum alloy core. For the bimetal brake disc obtained by infiltration of a porous ceramic preform, the calculated cost of mass production is about 8.13 USD/disc; in the case of dovetail joining of the core and cladding, the production cost is calculated to be even slightly lower (7.93 USD/disc). The calculated cost of brake disc weight reduction in comparison with the cast gray iron equivalent is about 3 USD/kg for a monolithic Al MMC, about 1,5 USD/kg for a macro composite consisting of Al MMC cladding and an Al alloy core, and about 1 USD/kg for bimetals.

Further optimization of the bimetal brake disc, particularly toward decreasing the thickness of ferrous cladding and brake disc volume, is necessary for narrowing the gap to the target price.

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