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# IDENTIFICATION AND QUANTIFICATION OF THE INTERNAL BEHAVIOUR OF CEMENTITIOUS MATRIX COMPOSITES USING AN OPTICAL FIBRE SENSOR

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**Abstract**: Textile Reinforced Cementitious Matrix Composite (TRCMC) are considered one of the techniques for strengthening and repairing of civil engineering structures. The use of these composites was developed due to their high mechanical properties in terms of tensile strength. As a result, the mechanical behaviour of TRCMC has been the subject of several experimental and numerical studies and investigations to establish the parameters governing its behaviour. However, these studies are conducted using measurement techniques that evaluate the strain and stress state on the surface of the TRCMCs. Behaviour and internal interactions are deduced using continuum and failure mechanics approaches.
This work consists of integrating an optical fibre into the composite in order to measure the internal strain of the matrix and the textile. The results obtained are compared to the law of mixtures, which remains at this moment a hypothesis that has not been experimentally validated.

**Key words**: cementitious matrix composite, internal mechanical behaviour, optical fibre sensor, law of mixtures, internal strain, fibre-matrix interaction

# ODREĐIVANJE I KVANTIFICIRANJE UNUTARNJEG PONAŠANJA CEMENTNIH MATRIČNIH KOMPOZITA POMOĆU SENZORA S OPTIČKIM VLAKNIMA

**Sažetak**: Tekstilom ojačani cementni matrični kompoziti (TOCMK) smatraju se jednom od tehnika za ojačanje i popravak građevinskih objekata. Uporaba ovih kompozita je razvijena zbog njihovih visokih mehaničkih svojstava u pogledu vlačne čvrstoće. Zbog toga je mehaničko ponašanje TOCMK-a bilo predmet nekoliko eksperimentalnih i numeričkih studija i istraživanja kako bi se utvrdili parametri koji upravljaju njegovim ponašanjem. Međutim, ove studije se provode pomoću mjernih tehnika kojima se procjenjuje stanje naprezanja i deformacije na površini TOCMK-a. Ponašanje i unutarnje interakcije se izvode pristupima mehanike kontinuuma i loma.
Ovaj rad obuhvaća integriranje optičkog vlakna u kompozit kako bi se izmjerile unutarnje deformacije matrice i tekstila. Dobiveni rezultati se uspoređuju sa zakonom smjesa, koji u ovom trenutku ostaje hipoteza koja nije eksperimentalno potvrđena.

**Ključne riječi**: cementni matrični kompozit, unutarnje mehaničko ponašanje, senzor s optičkim vlaknima, zakon smjesa, unutarnja deformacija, interakcija između vlakna i matrice

# 1. Introduction

Textile Reinforced Cementitious Matrix Composite (TRCMC) materials are increasingly used for the repair and reinforcement of civil engineering structural component systems. The analysis of the mechanical behaviour of the TRCMC is madeby different measurement techniques that generally focus on the surface of the specimens, such as strain gauges, image correlation (DIC), LVDT, laser, etc [1–3]. From these measurements, the internal interactions of these composites are deduced by continuum and fracture mechanics approaches, which allowed to establish hypotheses and models describing the possible micro-mechanical parameters that govern the reinforcement/matrix interaction of the TRCMC.

Thanks to the geometric and extensometric advantages of distributed optical fibre sensing (DOFS) (small diameter, flexibility, lightness, precision, millimetric spatial resolution, sensitivity, etc.), this measurement technique has been used in several fields, including civil engineering. It is used as a mean of assessing the state of buildings [4,5], and has been the subject of several studies, including the monitoring of the behaviour at the core of concrete structures[6].

Concerning the study of the mechanical behaviour of composites, the use of optical fibre as a strain sensor has been the subject of several experimental investigations [7], in particular the Bragg grating. Composites with textile-reinforced polymer matrices, such as FRP [8] and thermoplastic matrix composites [9], were studied using optical fibres. However, so far, only a few experimental studies have been carried out with these optical fibre sensors on cement-matrix composites.

The objective of this study is to experimentally determine the internal behaviour of TRCMC composites, based on local measurements at the core of the tested material. For this purpose, DOFS based on the Rayleigh backscattering principle [10]is used as distributed strain sensors, embedded in the core of TRCMC composites, to obtain the local mechanical behaviour of the matrix and textile reinforcement, before and after cracking. The results obtained are compared with the assumptions of the law of mixtures in order to examine its validity.

# 2. Materials and experimental set-up

## 2.1. Materials

### 2.1.1 Cementitious matrix

In order to facilitate preparation, minimise geometrical defects of the TRCMC specimens and avoid damaging the optical fibre, an ettringitic, liquid and self-placing cementitious matrix is used. It's mechanical characteristics are synthesised in Table 1.

### 2.1.2 Textile reinforcement

The textile reinforcement used in this study is an alkali-resistant glass grid (AR), with a surface weight of 525 g/m² and mesh size of 5×5 (mm²). Table 1 presents the main mechanical characteristics of this textile based on the characterisation tests carried out in the laboratory.

Table 1. Mechanical properties of the matrix and textile reinforcement used

| Material | $\sigma_{comp.max}$ (MPa) | $\sigma_{tension.max}$ (MPa) | $\varepsilon_{comp.max}$ (µm/m) | $\varepsilon_{tension.max}$ (µm/m) | Ec comp (MPa) | Et tension (MPa) |
|---|---|---|---|---|---|---|
| Matrix | 40 | 4.5 | 3000 | 400 | 13000 | 14000 |
| Textile | - | 520 | - | 1.5 | - | 35000 |

## 2.2. Experimental set-up

### 2.2.1. Tensile machine

The tensile test studied in this work is carried out using a Zwick universal testing machine shown in Figure 1, which has a maximum capacity of 65kN, equipped with load and displacement sensors. The whole is connected to a computer allowing the programming of the test and the acquisition of the results. The test is controlled in displacement, with a velocity of 0.1 mm/min.

### 2.2.2. Acquisition of optical fibre data

In this work, the ODiSI-B LUNA (Optical Distributed Sensor Interrogator) device is used as a device for acquiring data from the optical fibre. The latter is based on the OFDR-Rayleigh principle. It is possible to calibrate the optical fibre at the beginning of the test in order to eliminate residual strains, as well as to instantly visualise the results. For our study, the spatial resolution is 2.6 mm over the entire range of the optical fiber (2m), with a recording frequency of 2Hz.

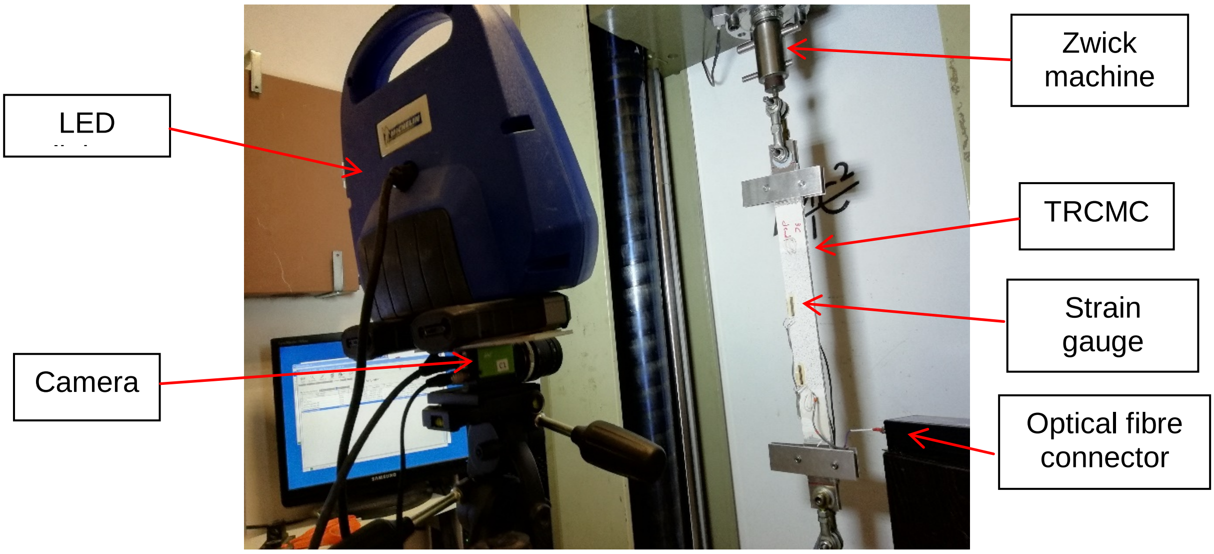
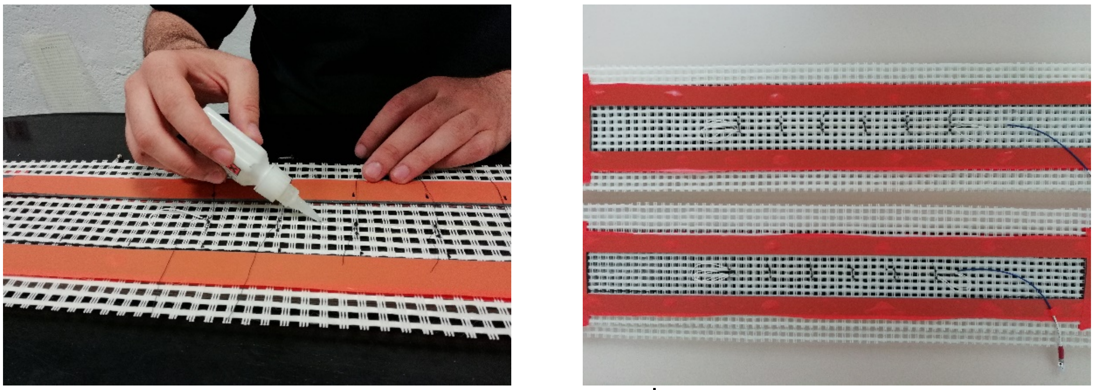



Figure 1. Experimental protocol for the TRCMC tensile test with optical fibre

### 2.2.3. Preparation of specimens

The preparation of the specimens consists in forming a rectangular PVC mould measuring 60 cm long, 5 cm wide and 1 cm high. Particular care is taken to place the optical fibre in the middle of the matrix and on the textile, as shown in Figure 2-a. Once the mold has been prepared and the textile with the optical fibre placed (Figure 2-b), the cementitious matrix is cast. After demoulding, two aluminium plates are glued to both ends of the specimens for the tensile test (Figure 3). The preparation details (insertion and fixing of the optical fibre, casting of the matrix...) are presented in [11,12].



a b

Figure 2. Positioning of the optical fibre: (a) gluing on the textile reinforcement; (b) specimens ready for the matrix casting

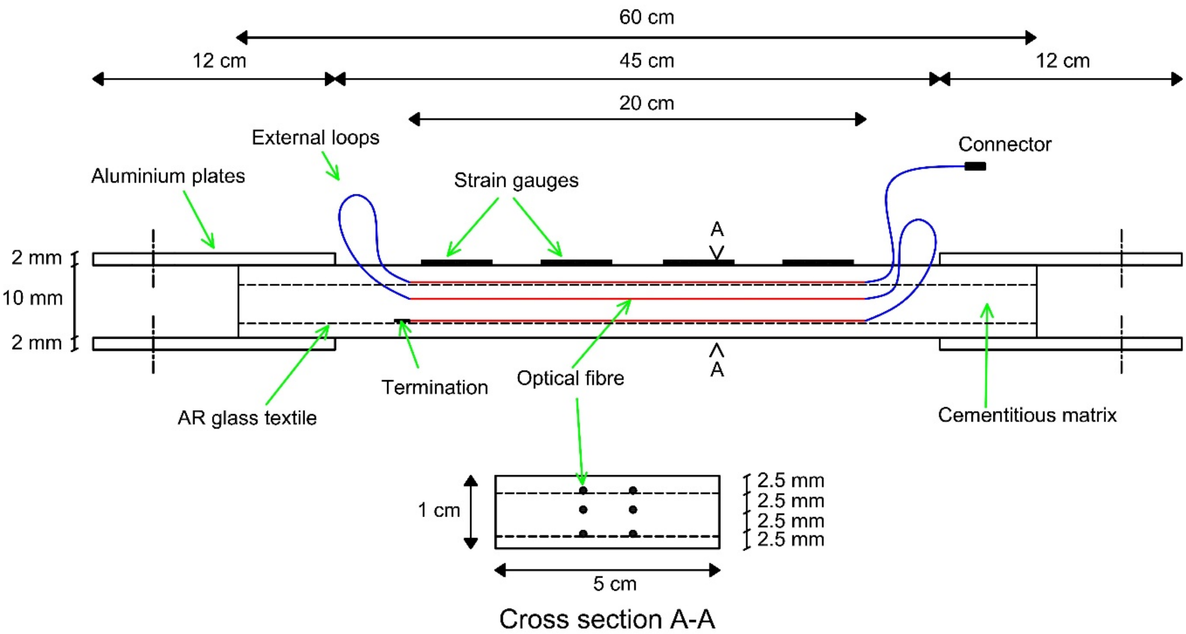



Figure 3. Outline diagram of the TRCMC with the location of the optical fibre

## 3. Results and discussion

The results from optical fibre are presented in Figure 4 and 5. The first shows the strain-stress curve for the textile and the matrix, while the second shows the evolution of the strain field along the specimen.

### 3.1. Pre-cracking zone

In accordance with the literature, the pre-cracking zone exhibits a quasi-linear behaviour in terms of stress and strain. The behaviour of the matrix and the textile in this zone is almost identical, and the values of the strains recorded for both components for a given stress are almost identical.

In order to compare the experimental results with the values obtained by applying the law of mixtures, the authors chose to work in terms of Young's modulus E1 of the pre-cracking zone. The results are summarised in Table 2. This table shows that there is a 4.68% difference between the experimental results and the law of mixtures. This difference

can be explained by the geometric imperfections of the specimen, which influence the value of the cross-sectional area, and therefore the composite stress and then the modulus E1.
In conclusion, and according to these experimental results, the law of mixtures can be applied in the first zone of the behaviour of the TRCMC composite, on the condition that the geometric characteristics of the specimen are as well as possible controlled, and that the mechanical properties of the matrix and the textile are as precisely as possible known.

Table 2. Comparison between the experimental value of E1 and that calculated by the law of mixtures

| Reinforcement ratio $V_f$ (%) | $E_m$ matrix (MPa) | $E_f$ textile (MPa) | Experimental value $E_1$ (MPa) | Law of mixtures $E_1$ (MPa) | Difference (%) |
|---|---|---|---|---|---|
| 4.8 | 14000 | 35000 | 14336 | 15008 | 4.68 |

### 3.2. Post-cracking zone

Referring to the results presented in Figure 4, it can be seen that in the post-cracking area of the TRCMC, the textile takes up all the force applied during this loading phase, while the matrix remains tensed, but its strain no longer increases, or even a slight decrease is recorded. These findings are consistent with the assumptions of the law of mixtures regarding the behaviour of this zone. In addition, at the crack location (Figure 5), the textile reinforcement takes up the full load applied to the composite, and therefore the matrix no longer has a contribution at this point, which explains the large strain of the textile reinforcement recorded at the crack location.

In order to compare the tensile behaviour of the textile at the core of the TRCMC in the post-cracking zone with the tensile behaviour of the textile alone, a comparison of the values of Young's moduli is summarised in Table 3. Note that to have the Young's modulus of reinforcement at the core of the TRCMC ($E_{3f}$), the composite modulus $E_3$ is divided by the reinforcement ratio $V_f$.

From these results, it can be confirmed that in the third zone, the textile takes up the entire load applied during this zone. This force is added to that applied during the previous zones to constitute the total load taken up by the textile. On the other hand, the matrix generally retains the strain value after the occuring of the last crack. In addition, as mentioned in several studies [1,13], this behaviour explains the increase in crack opening observed during the post-cracking zone as shown in Figure 6.

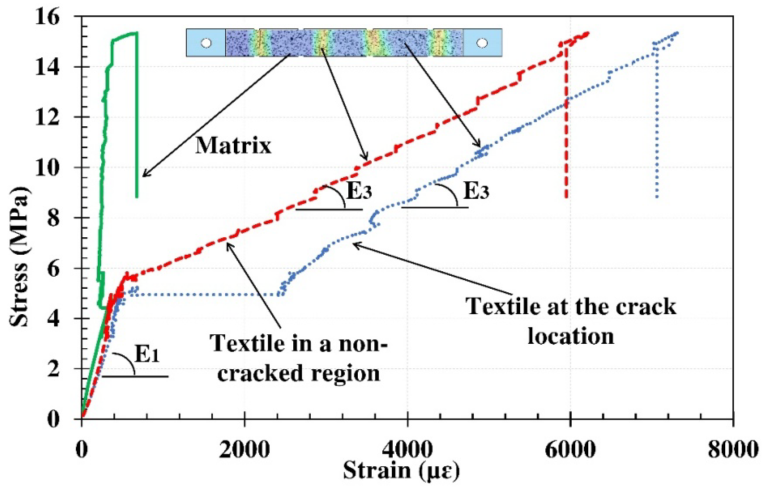



Figure 4. Experimental results of internal local behaviour of the matrix and textile

Table 3. Comparison between the experimental value of E3 and that calculated by the law of mixtures

| Reinforcement ratio $V_f$ (%) | $E_m$ matrix (MPa) | $E_f$ textile (MPa) | Experimental value $E_3$ (MPa) | $E_f = E_3 / V_f$ (MPa) | Difference (%) |
|---|---|---|---|---|---|
| 4.8 | 14000 | 35000 | 1700 | 35417 | 1.17 |

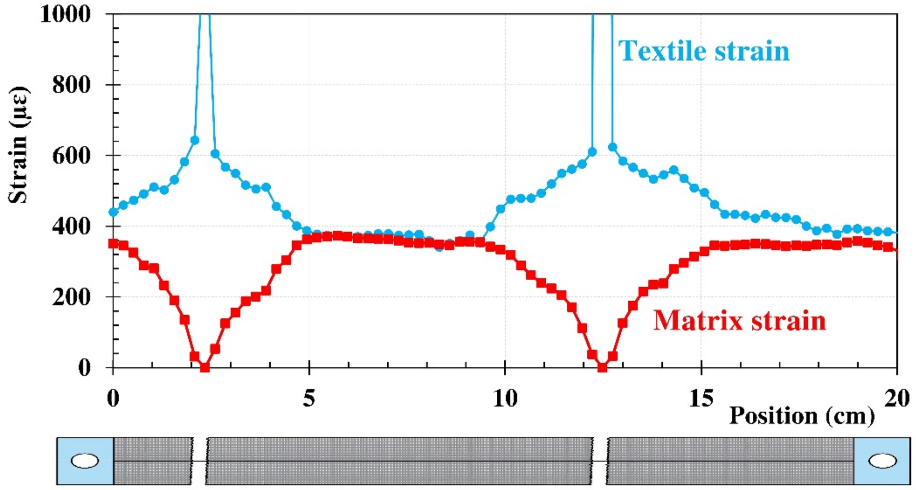



Figure 5. Distribution of the matrix and textile reinforcement strains along the TRCMC during crack propagation

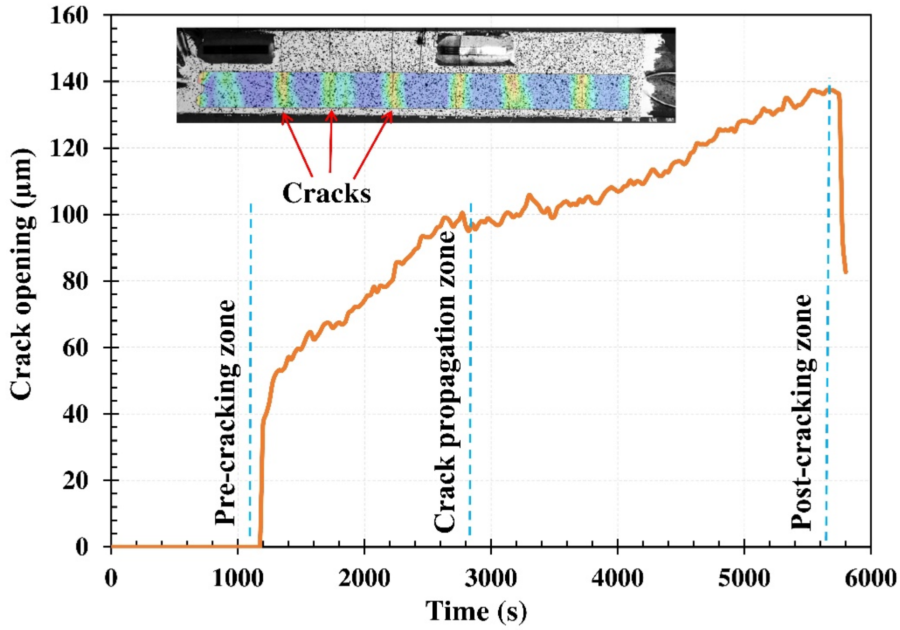



Figure 6. Evolution of the crack opening during the TRCMC tensile test

## 4. Conclusion

Experimentally, the local tensile behaviour of TRCMC composites is discussed in this work, using distributed optical fibres as strain sensors embedded in the core of these composites. Thanks to the advantages of strain measurement by this new technique, the behaviour of the matrix and textile during the TRCMC tensile test was measured, identified and compared with the assumptions of composite mechanics. The main results are listed below :

- In the pre-cracking zone of the TRCMC, the mechanical behaviour of the matrix and the textile reinforcement are approximately identical, characterised by an almost linear stiffness. The validity of the law of mixtures in this zone is demonstrated and the hypothesis of a perfect bond between matrix and textile is validated.
- In the post-cracking zone, the textile takes up almost all the applied load, and the matrix remains tensed while retaining its strain undergone during the previous stages. These results confirm the validity of the assumptions of the law of mixtures. In addition, they help to understand the increase in crack opening in this zone.
- As an outlook, it would be wise to use optical fibre measurement to identify and quantify micromechanical parameters describing load transfer mechanisms such as load transfer length, shear stress distribution, residual stress, etc.

## 5. References

1. Caggegi, C., Lanoye, E., Djama, K., Bassil, A. & Gabor, A.: *Tensile behaviour of a basalt TRM strengthening system: Influence of mortar and reinforcing textile ratios.*Compos. Part B Eng, 2017, 130, 90–102.
2. Contamine, R.: *Contribution à l'étude du comportement mécanique de composites textile-mortier: application à la réparation et/ou renforcement de poutres en béton armé vis-à-vis de l'effort tranchant*, Université Claude Bernard - Lyon I-France, 2011.
3. Promis, G., Gabor, A. & Hamelin, P.: *Analytical modeling of the bending behavior of textile reinforced mineral matrix composite beams*,Compos. Struct.,2011, 93, 792–801.
4. Henault, J.-M.: *Approche méthodologique pour l'évluation des performances et de la durabilité des systèmes de mesure réparties de déformation : application à un câble à fibre optique noyé dans le béton*, Université Paris-Est-France, 2013.
5. Rao, Y.: *Recent progress in applications of in-fibre Bragg grating sensors*,Opt. Lasers Eng, 1999, 31, 297–324.
6. Tixier, A., Rospars, C., Dufour, F., Khadour, A. & Masson, B.: *Analyse des déformations par fibres optiques le long de l'interface acier-béton dans un essai push-in*, in 31èmes Rencontres de l'AUGC, 2013.
7. Bruno, L.: *Mechanical characterization of composite materials by optical techniques: A review,*Opt. Lasers Eng., 2018,104, 192–203.
8. Kim, S.-W.: *Characteristics of strain transfer and the reflected spectrum of a metal-coated fiber Bragg grating sensor,*Opt. Lasers Eng., 2017, 96, 83–93.
9. De Baere, I., Luyckx, G., Voet, E., Van Paepegem, W. & Degrieck, J.: *On the feasibility of optical fibre sensors for strain monitoring in thermoplastic composites under fatigue loading conditions,*Opt. Lasers Eng., 2009, 47, 403–411.
10. Soller, B. J., Gifford, D. K., Wolfe, M. S. & Froggatt, M. E.: *High resolution optical frequency domain reflectometry for characterization of components and assemblies*, Opt. Express, 2005, 13, 666.
11. Saidi, M. & Gabor, A.: *Use of distributed optical fibre as a strain sensor in textile reinforced cementitious matrix composites*,Measurement, 2019, 140, 323–333.
12. Saidi, M. & Gabor, A.: *Experimental analysis of the tensile behaviour of textile reinforced cementitious matrix composites using distributed fibre optic sensing (DFOS) technology,*Constr. Build. Mater., 2019, 230, 117027.

13. Contamine, R., Si Larbi, A. & Hamelin, P.: *Contribution to direct tensile testing of textile reinforced concrete (TRC) composites*,Mater. Sci. Eng. A, 2011, 528, 8589–8598.