Sensors & Transducers, Vol. 22, Special Issue, June 2013, pp. 74-80

Sensors & Transducers

© 2013 by IFSA
http://www.sensorsportal.com

Experimental Study on the Corrosion of Buried Directly Heating Supply Pipeline Based on the BOTDA (R) Technique

LI Xiang-Li, ZHAO Xue-Feng, LU Xingjun
School of Civil Engineering, Dalian University of Technology,
No.2 Linggong Road Gaoxin Distric, Dalian, 116024, China
Tel.: +86-411-8470-7684, fax: +86-411-84674141
E-mail: lxl@dlut.edu.cn

Received: 15 April 2013 /Accepted: 20 June 2013 /Published: 28 June 2013

Abstract: A novel Brillouin Optical Time Domain Analysis sensors, BOTDA(R), has been developed, which can monitor steel corrosion in concrete structures and various insulation structures. The application of distributed BOTDA(R) technology in heating supply pipe corrosion detection is discussed in this paper. According to the characteristics of derictly buried heating supply pipe, we have designed the optical fiber corrosion sensors for the prefabricated pipe, and the sensors were arranged in the junction of pipe section. Accelerated corrosion tests were used to demo the acid soil environment. Quantitative evaluation was derived formula for steel pipe corrosion.

Keywords: Prefabricated derictly heating supply pipe, Brillouin optical time domain analysis, Brillouin optical fiber sensing technology, Online detection, Sensor, Corrosion.

---

1. Introduction

The corrosion of steel has become a worldwide problem. A long period of pipeline corrosion in harsh environments is particularly serious [1]. With the accelerated process of urbanization in China, China's heating supply pipe network scale has expanded year by year. According to the statistics of 2001, the length of district heating supply pipelines in China has reached 60 thousand kilometers with a growth rate of about 8 % per year [2]. Pre-insulated pipe direct-buried technique is widely used in heating supply pipe network in China. This installation method has advantages of short construction period, low cost etc. Almost all of the new heating supply pipelines have adopted this technique. But long-period buried pipelines with higher soil pH, especially in pipe joints would show relatively severe corrosion caused by the damage of protective layer during the Installation. At the present in china, 90 % accidents of directly-buried heat supply network system are caused by corrosion [3]. Fig. 1 is a picture of actual corrosion pre-insulated pipe and the pipe has run about 5 years underground. We don't know the situation of corrosion because the pipelines were buried under the soil and hidden by the protection layer and insulation layer.

We don't know the situation of corrosion because the pipelines were buried under the soil and hidden by the protection layer and insulation layer. With the effective corrosion monitoring to these sites, we can evaluate the change of the allowable stress so as to warn the corrosion of buried pipelines and avoid the blindness of pipe replacement.

Fig. 1. Corrosion pre-insulated pipe.

Based on above considerations, we need to select some appropriating corrosion sensors for monitoring the buried pipelines. But the performance and durability of the traditional corrosion sensors often cannot meet the actual needs of this condition [4, 5]. In recent years, BOTDA (R) technology is developing rapidly and this technology has been successfully used in many field, such as structure health monitoring, fire detection in a building, concrete temperature monitoring etc. [6-9]. Because of its good features such as durability, distributed measurement, frees from electromagnetic interference, corrosion resistance and low cost, it can be used for the corrosion of buried heat pipe monitoring [10]. This paper presents an actual application of BOTDA (R) technology for underground prefabricated heat-supply pipe-line monitoring methods. With this technique, we can build up an early warning mechanism to the underground pipeline and enhance the reliability of heating supply pipe network.

2. Experiment Design

2.1. Basic Principles of BOTDA(R)

Brillouin optical fiber sensing technology is combination of the Brillouin scattering and OTDR (Optical Time Domain Reflectometry) technology to achieve the distribution of fiber strain or temperature measurement. The shift that Brillouin frequencies of the scattered light related to the light frequency shift is named as Brillouin frequency shift. It can be expressed as [11]:

$$f_B = 2nv_a/\lambda, \tag{1}$$

where, f_B is the Brillouin frequency shift, n is the refractive index of fiber core, v_a is the sound velocity and λ is the wavelength of incident light.

The Brillouin frequency shift is proportional to the change of temperature and strain that can be show as:

$$\Delta f_B = k_t \Delta T + k_\varepsilon \Delta \varepsilon, \tag{2}$$

where Δf_B is the change of Brillouin frequency shift, ΔT is the temperature difference between the initial environment and the testing environment, $\Delta\varepsilon$ is the strain change, k_t is the temperature coefficient of Brillouin frequency shift and k_ε is the strain coefficient of Brillouin frequency shift.

The ΔT can be measured by additional thermometer. If ΔT is very small in the experimental environment, it can be ignored.

In our research, we are more concerned about the strain change and the temperature change which can be compensated. The temperature difference of hot water inside of pipeline and the installation environment are easy to measure.

2.2. Design of the Optical Fiber Sensor

There are three layers in the traditional prefabricated pipe, namely, protective layer of polyethylene, polyurethane insulation layer and the steel pipeline shown in Fig. 2.

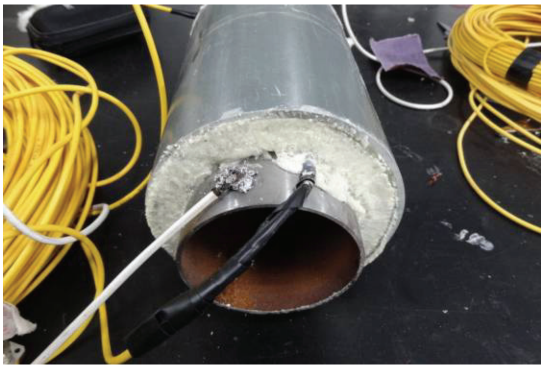


Fig. 2. Prefabricated pipe.

The black section is protective layer, the white section is insulation layer and the metal section is pipe (The general metal is Q235). The hot water flows in steel pipe.

The installation of Brillouin optical fiber corrosion sensor is shown in Fig. 3.

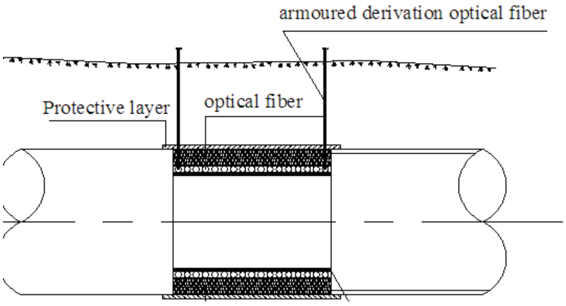


Fig. 3. The arrangement of BOTDA(R) optical fiber corrosion sensor.

For the actual engineering, we can select some key locations to arrange the BOTDA(R) sensors. There are many weld connection in the pipeline and these positions are easy to be corroded place. The connection position of steel pipe is the preferred position for the corrosion detection. The Brillouin optical fiber corrosion sensor can be winded to the joint of steel pipe before the foam- in-place is done. Then the derivation fiber can be drag to the ground and the derivation fiber should be armoured.

The BOTDA(R) optical fiber corrosion sensor is shown in Fig. 4 and it has been devoped by the intelligent research institution of Dalian University of Technology [12].

Fig. 4. BOTDA(R) optical fiber corrosion sensor.

The experiment of pre-insulated pipe corrosion is designed as follows:

1) A length of 1.2 m of DN76 ×5 pre-insulation pipe was used for experimental purposes. One end of the insulation layer and the protective layer was broken open and the steel pipe was exposed. The open section of steel pipe was polished for the experiment. The outside diameter was changed to 73.8 mm and the thickness was 3.5 mm.

2) The outside of steel pipe was wrapped by unbending optical fiber continuously with single layer. The length of optical fiber was about 15 m. It is needed to wind the optical fiber with a certain pre-stress to ensure close contact with the surface of the pipe and the optical fiber.

3) The optical fiber ends were fixed to the pipe with epoxy glue, and polyurethane were foamed on site. Some Polyethylene materials were adhered outside of the polyurethane. The common optical fibers with a protective cover (armored optical fiber) were drawn out to the soil along axial direction.

4) Experimental section of pipe was buried into the soil, and the soil should be kept moist by spraying a certain concentration of sulfuric acid to accelerate the corrosion of metal.

2.3. Evaluation of Steel Pipe Corrosion Formula

The formula derived in this paper is only suitable to Brillouin fiber corrosion sensors for monitoring corrosion evaluation of the results. Some basic assumptions are used for the formula derivation in this paper.

1) The actual thickness of the fiber layer is very small; it is approximately 2.3 ‰ of the pipe diameter. So the fiber layer has little effect on the measurement result. The fiber layer thickness is ignored in the derivation process.

2) The corrosion is uniform and the section of testing pipe is round in shape. All of the corrosion products at the testing part are supposed to remain within the fiber layer rather than spill outside the fiber layer.

3) The ambient temperature of laboratory is constant. The affection of the temperature change can be avoided in the experiment.

Steel corrosion rate of mass loss is expressed by δ and defined as:

$$\delta = \frac{\pi\left(D_o^2 - D_1^2\right)\rho}{\pi\left(D_o^2 - D_i^2\right)\rho} = \frac{\left(D_o^2 - D_1^2\right)}{\left(D_o^2 - D_i^2\right)}, \tag{3}$$

where D_o is the outside diameter of steel pipe (no corrosion), D_1 is the outside diameter of steel pipe rusted, to the exclusion of rusty scale, D_i is the inside diameter of steel pipe, ρ is the density of steel pipe.

The thickness of pipe is equal to half of outside diameter minus inside diameter of steel pipe.

$$e == \frac{\left(D_o - D_i\right)}{2}, \tag{4}$$

where e is the thickness of steel pipe.

The steel corrosion rate of mass loss δ can be written as:

$$\delta = \frac{\left(D_o^2 - D_1^2\right)}{2e\left(D_0 + D_i\right)} \tag{5}$$

The measured optical fiber strain is expressed by ε and defined as:

$$\varepsilon = \frac{\pi\left(D_2 - D_o\right)}{\pi D_o} = \frac{\left(D_2 - D_o\right)}{D_o}, \tag{6}$$

where D_2 is the total pipe outer diameter including rusty scales. The steel pipe diameter after rusting satisfies the following relationship:

$$\pi\left(D_o^2 - D_1^2\right)\cdot\eta = \pi\left(D_2^2 - D_1^2\right) \tag{7}$$

where η is the volume expansion ratio of rust scales.

Eq. (7) can be written as:

$$\eta = \frac{\left(D_2 + D_0\right)\left(D_2 - D_0\right)}{D_0^2 - D_1^2} + 1 \tag{8}$$

Combining the Eq. (5), Eq. (6) and Eq. (8), η can be expressed as follow:

$$\eta = \frac{\left(D_2 + D_0\right)\varepsilon D_0}{2e\delta\left(D_0 + D_i\right)} + 1 \tag{9}$$

The difference of D_2 and D_i is small when the corrosion is not too heavy. So it can be considered as:

$$\frac{D_2 + D_o}{D_o + D_i} \approx 1 \qquad (10)$$

The ratio of $\frac{D_o}{e}$ is a constant for a special series type of steel pipe and it is expressed by c. Then:

$$\delta = \frac{c\varepsilon}{2(\eta - 1)} \qquad (11)$$

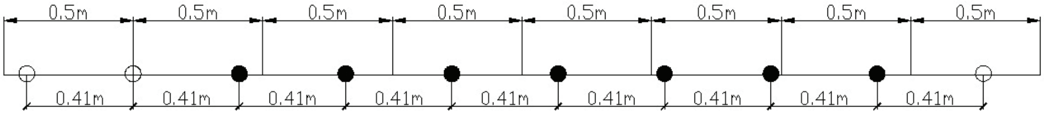
The Eq. (11) is the relationship expression of pipe corrosion detected by the BOTDA (R) sensor. When we get the thickness of corrosion we can evaluate the corrosion of buried steel heating supply pipe through comparing the exiting data [13].

3. Corrosion Experiment

In order to shorten the experimental time, the electrochemical method was used to accelerate the steel pipe corrosion. The tip of experimental steel pipe was immersed in NaCl solution and the concentration of brine water was 5 %. A steel plate in the brine water was used as negative magnet and the experimental pipe was used as positive magnet. A voltage-stabilized source accelerated 16-22 V voltage constantly. The Fiber Optic Brillouin Analyzer, DiTest STA200 Series shown in Fig. 5, was use for data acquisition.

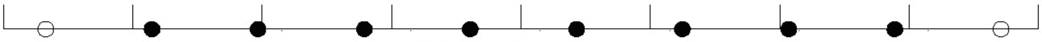
Fig. 5. DiTest STA200 Series.

The sampling interval time was set as 1.0 hour and the sample distance was 0.41 m, the space resolution ratio was 1.0 m. The effective length of measurement optical fiber is about 4.0 m, so the valid measurement point is 7 as shown in Fig. 6 we selected 5 measurement points as the continuous measurement points to analysis the data.



Case 1

Case 2



Case 3

● Valid measurement point ○ invalid measurement point.

Fig. 6. The distribution of valid measuring points on the optical fiber.

4. Results

We made two test specimens named No. 4 and No. 6 for the corrosion experiment separately and similar results were obtained. So we just talked over the results of specimen No. 4. The corrosion experiment of specimen No.4 was lasted about two days until the strain detected by Brillouin Analyzer basically did not change or it was in downward trend. The measure domain of optical fiber was about 4 m.

We got at least 7 valid effective measurement points in the testing. Take data in five strain peaks to analyze, which were 34.59 m, 35.0 m, 35.4 m, 35.81 m and 36.22 m from the starting point position of the fiber loop. The detection state of Brillouin optical fiber corrosion sensor after corrosion is shown in Fig. 8. As a comparative figure, Fig. 7 showed the initial state of pipe before corrosion.

The average strain value of each point was used to express the strain variation over time (1-25 hour) changes of the BOTDA(R) Fiber Optical Sensors, as shown in Fig. 9.

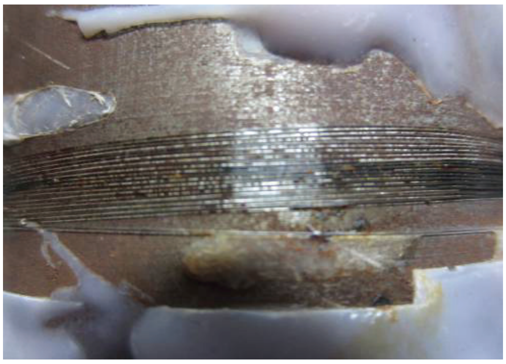


Fig. 7. Optical fiber sensor before corrosion.

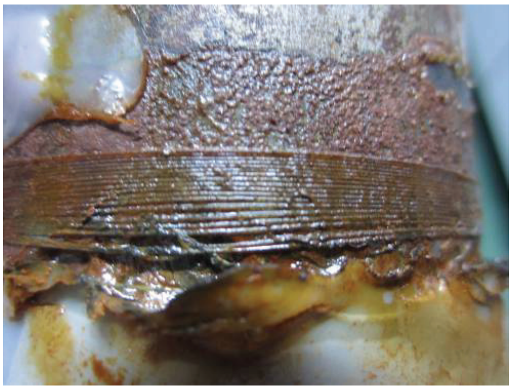


Fig. 8. Optical fiber sensor after corrosion.

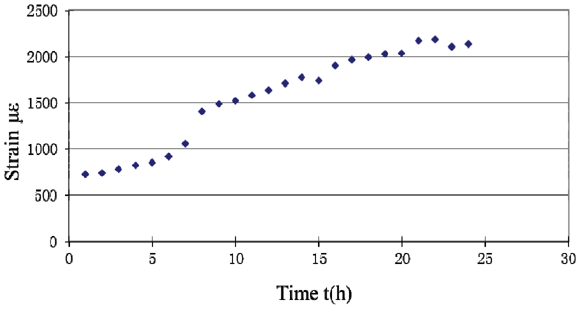


Fig. 9. The diagram of strain-time relationship.

At the same time, a 3D map for distance-time-strain relationship was drawn by the ORIGIN software as shown in Fig. 9. (take the valid data point position of 30.11 m, 30.52 m, 30.93 m, 31.34 m, 31.74 m, 32.15 m, 32.56 m, 32.96 m, 33.37 m, 33.78 m, 34.18 m, 34.59 m, 35.0 m, 35.4 m, 35.81 m, 36.22 m, 36.63 m, 37.03 m, 37.44 m, 37.85 m, 38.25 m, 38.66, 39.07 m, 39.47 m, 39.88 m, 40.29 m)

Strain with time change trend of the effective point fiber can be seen from Fig. 9 and Fig. 10. We can obtain the mass loss ratio δ by measuring the change of pipe diameter fore-and aft corrosion and solving the equation (3).

$$D_i = D_o - 2e = 73.6 - 2\times 3.5 = 67.6$$

The measurement value of D_1 is 72.8 mm. The volume expansion rust η can be obtained by making δ and ε into equation (11).

$$\eta = \frac{c\varepsilon}{2} + 1 = \frac{\frac{73.8}{3.5}\times 2181.2\times 10^{-6}}{2} + 1 = 1.15$$

In this experiment η is equal to 1.15 and it is thought a constant value during the experiment. So making the experiment data into equation (11), the biggest mass loss ratio is:

$$\delta = \frac{c\varepsilon}{2(\eta - 1)} = \frac{\frac{73.8}{3.5}\times 2181.2\times 10^{-6}}{2\times(1.15-1)} = 14.8\%$$

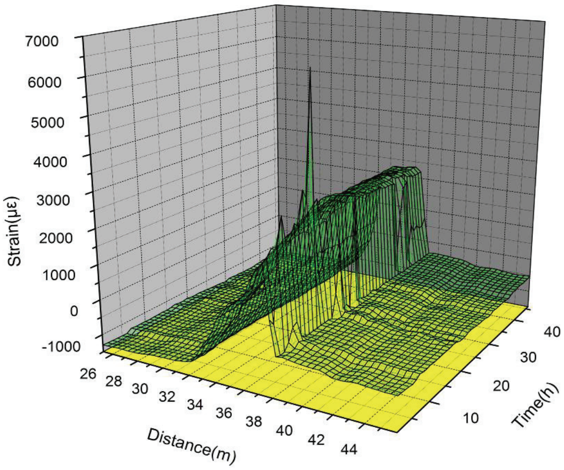


Fig. 10. The diagram of distance-time-strain relationship of points on the optical fiber.

The corrosion change of pipe is shown in Fig. 11. The strain resolution ratio is 6 $\mu\varepsilon$. Though we just do two specimens, the optical fiber corrosion sensor can detect the mass loss from 0 to 14.8 % for steel pipe and the experimental results can be obtained repeatedly.

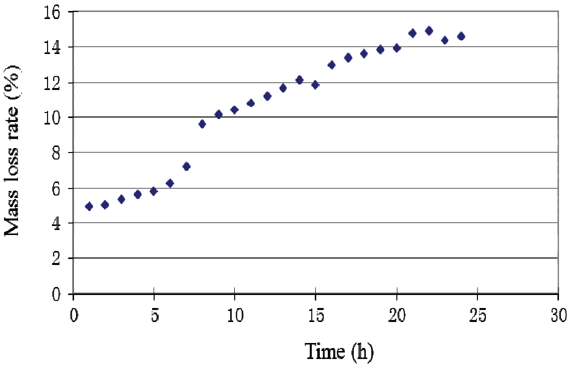


Fig. 11. The relation between the mass lost rate of steel pipe and time of the specimen No. 4.

5. Discussion

Comprehensive analysis shows that the Brillouin optical fiber corrosion sensor has the following good features:

(1) The sensor has a good sensitive characteristic in the trial beginning one hour. It indicates that the sensor has a good sensitivity characteristics effective monitoring for the early corrosion phase.

(2) The sensor can detect the mass loss up to 14.8 % and this measurement range is sufficient to meet the actual needs of the heating supply pipe network project.

(3) The sensor has good linearity, it can be used in the real-time corrosion monitoring of underground buried pipe.

The cost of Brillouin optical fiber corrosion sensor and the whole monitoring loop is very low. The main component of the fiber is SiO_2, chemically stable. Brillouin optical fiber corrosion sensor has durability for corrosion monitoring in prefabricated insulating steel pipe under long-term rusting and harsh environment.

Furthermore, we need to measure the internal corrosion and pressure of the heap-supply pipe when estimate the healthy situation of pipeline, but it is not convenient for the optical fiber to do that. So, it is necessary turning to some other sensors or methods to accomplish the whole health monitoring. There are many available methods can be used to detect the internal corrosion of steel pipe. A simple method is gravity drop method [14]. The heating supply system is stable relatively, so we can select one or two experiment pipe sections and assign some gravity drop slice into the pipe. The corrosion velocity and status can be measure by the gravity drop.

6. Conclusions

In this paper, we design a Brillouin optical fiber corrosion sensor which can be used in the corrosion detection of underground heating supply pipelines. The experiment is ongoing now and the preliminary results are very satisfactory. It is suitable for the out wall corrosion of steel pipe. In addition to this use, Brillouin optical fiber corrosion sensor can be used in the detection of water supply pipe, drain water pipe and gas supply pipe too.

Acknowledgements

The authors appreciate the assistance provided by the National Natural Science Foundation of China (50808031) and National Science & Technology Pillar Program during the 12th Five-year Plan Period, No. 2012BAJ04B03-02.

References

[1]. Qiao Guo-Fu, Hong Yi, Ou Jin-Ping, Corrosion Monitoring of Reinforcing Steel in RC Beam by an Intelligent Corrosion Sensor, *Proceedings of the SPIE*, 2009, 74930C, pp. 1-7.

[2]. Liu He-Ming, Development and reformation situation of China urban district heating, *District Heating*, 2003, No. 3, pp. 4-8.

[3]. Song Huina, Tan Zhongqi, Discussion of anti-corrosion of directly-burid heating pipe network, *Chinese Technology Read Extensively,* 2012, Issue 5, pp. 141-142.

[4]. S. Srikanth, T. S. N. Sankaranarayanan, K. Gopalakrishna et al. corrosion in a buried pressurised water pipeline, *Engineering Failure Analysis*, 12, 2005, pp. 634-651.

[5]. Marton Balasko, Erzsebet Svab, Attila Kuba et al., Pipe corrosion and deposit study using neutron- and gamma- radiation sources, *Nuclear instruments and Methods in Physics Research*, *A,* Vol. 542, 2005, pp. 302-308.

[6]. Mao, J. H., Jin, W. L., He, Y. Cleland, D. J., Bai, Y., A novel method of embedding distributed optical fiber sensors for structural health monitoring, *Smart Materials and Structures,* Vol. 20, Issue 12, pp. 1-9.

[7]. Glisic, Branko, Chen, Jeremy, Hubbell, David, Streicker Bridge: A comparison between Bragg-grating long-gauge strain and temperature sensors and Brillouin scattering-based distributed strain and temperature sensors, *Proceedings of the SPIE* - The International Society for Optical Engineering, Vol. 7981, 2011, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, Sandiya, USA, March, 2011.

[8]. Kwon, Il-Bum, Kim Chi-Yeop, Seo, Dae Cheol, Application of fiber optic BOTDA sensor for fire detection in a building, *Key Engineering Materials*, Vol. 321-323, 2006, pp. 212-216.

[9]. Xiong Juhua, Wang Lujie, He Wenyong, Xing Haofeng, Application of BOTDA in mass concrete temperature monitoring, *Applied Mechanics and Materials,* Vol. 238, 2012, pp. 346-349.

[10]. Zhou Zhi, Huang Ming-Hua, He Jian-Ping, et al., Ice structure monitoring with an optical fiber sensing system, *Cold Regions Science and Technology*, Vol. 61, 2010, pp. 1-5.

[11]. Zhao Xue-Feng, Lu Jie, Ou Jin-Ping, Research on BOTDR Sensing Technique in Structural Health Monitoring, in *Proceedings of the Earth and Space: Engineering, Science, Construction and Operations in Challenging Environments,* 2010, pp. 2487-2493.

[12]. Zhao Xue-Feng, Gong Peng, Lu Jie et al., Experimental study based on the Distributed Brillouin optical time domain reflectometer fiber corrosion sensors, *Journal of Optoelectronics Laser,* 2011, Vol. 23 Issue 3, pp. 333-337.

[13]. Zhao Ting-Ting, Xu Shan-Hua, Kong Zheng-Yi et al., *Journal of Water Resources and Architectural Engineering*, Vol. 8, No. 2, 2010, pp. 13-15.

[14] Zhou Hongbing, Huang Yunfei, Qiu Zuolin, Chen Xiaohong, Jiao Jianfeng, Sha Congliang, Jiang Yi, Corrosion rate measurement and anticorrosion measures of carbon steel pipeline in central heating systems, *HV&AC*, 2004, Vol. 34, Issue 9, pp. 107-111.

Conference Announcement

Topic E2: Transportation & Mobility

The Euromat conference series, organised by the Federation of European Materials Societies (FEMS), is one of the largest events of its kind in Europe, covering the full width of materials science and technology. We would like to direct your attention to the following Symposia which are focussing specifically on transport applications:

E2.I: **Modeling, simulation, optimization of materials and structures in transportation**
Prof. Kambiz Kayvantash, Société CADLM, Massy (F)

E2.II: **Intelligent and adaptive materials and structures**
Dr.-Ing. Dirk Lehmhus, ISIS Sensorial Materials Scientific Centre, Bremen (D)

E2.III: **Energy absorbing and protective materials and structures**
Prof. Massimiliano Avalle, Politecnico di Torino, Torino (I)

E2.IV: **Production, properties and applications of hybrid materials and structures**
Dr.-Ing. Kai Schimanski, Foundation Institut für Werkstofftechnik (IWT), Bremen (D)

DEADLINE CALL FOR PAPERS END OF JANUARY – WATCH OUT FOR DETAILS AT www.euromat2013.fems.eu OR CONTACT

ISIS Sensorial Materials Scientific Centre, University of Bremen

Board of Directors
Prof. Dr.-Ing M. Busse
Prof. Dr. W. Lang
Prof. Dr.-Ing. H.-W. Zoch

Managing Director
Dr.-Ing. Dirk Lehmhus

Wiener Straße 12
28357 Bremen

Fon +49 (0)421 5665 408
Fax +49 (0)421 5665 499

dirk.lehmhus@uni-bremen.de
www.isis.uni-bremen.de
