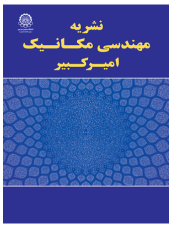

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Investigating the effect of thermal cycles on the recovery of tensile strength in self-healing composites under impact loading

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ABSTRACT: Here the healing process of glass/epoxy composites is studied experimentally. The healing agent is composed of ML506 epoxy resin and HA-11 hardener which is charged into microtubes. The microtubes are interleaved between the first and the second and the fifth and the sixth layers. The initial damage is introduced to the samples by drop weight impact tests and the recovery percentage of the tensile strength due to healing process is measured by tensile test. The effects of healing time (without thermal cycles), number of healing units and thermal cycles are investigated on the recovery of the tensile strength. Composite samples containing 8, 16 and 32 healing units are studied in the periods of 1, 6 and 12 days after the initial damage. Also, some damaged samples are set to 1, 3, 5 and 7 thermal cycles and after one day, tensile tests are carried out. The results show that without thermal cycles the healing process is almost completed after 6 days with an 83% recovery. In addition, the maximum amount of tensile strength recovery is equal to 86% which is related to the samples with 32 healing units after 12 days. This amount of healing efficiency can also be achieved by means of 5 thermal cycles. This is also true for thermal cycles where the effect of thermal cycles is tangible up to 5 cycles.

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1- Introduction

Composite structures demonstrate interesting mechanical properties to weight ratios. This has been the motivation of applying such materials in engineering structures. However, due to the mismatch between the matrix and the reinforcement phase of composite materials, different failure phenomena may occur in these structures during function, such as delamination, matrix cracking, fiber breakage and fiber pullout. These failures are basically due to crack initiation and propagation in the composite structure.

An important source of crack initiation and propagation in such structures is related to impact loading and/or thermal shocks. These kinds of loadings lead to initiation of microcracks in the material, where the propagation on these microcracks may cause catastrophic failures in the structure. Thus, online and offline health monitoring of composite materials by acoustic emission, thermography and X-ray is an essential procedure in industrial applications of such structures. However, consistent monitoring, replacing and/or repairing of the composite parts of the engineering structures are costly [1].

An alternative solution is to take advantage of composite materials with self-healing behavior. Self-healing composite materials are divided into two groups, intrinsic and extrinsic self-healing composites. The extrinsic behavior is achieved by taking advantage of an external agent which is stored at the fabrication procedure in hollow fibers, micro capsules or a vascular network. After a damage is introduced to the composite material, this external agent is delivered to the damaged area and causes some kind of repair mostly on a chemical reaction basis. A comprehensive review on the concept and applications of self-healing composites is presented by Zhang et al. (2021) [2]. In addition, several researches have been published on evaluating the effect of self-healing behavior on the restoration of mechanical behavior due to different failure mechanisms such as delamination, matrix cracking, fiber breakage and fiber pullout; for example, the researches of Dry et al. can be outlined [3-5].

As mentioned, composite materials are vulnerable to impact loading and the idea of taking advantage of self-healing behavior in repairing the damaged impacted area has been studied by researchers. The main stream of these researches has been the evaluation of the recovery of the mechanical properties of the composite material after being damaged by low velocity impact and being healed by the external agent [6-8].

In general, the healing process is a time dependent process. Furthermore, as described, the basis of the extrinsic healing behavior is a chemical reaction of the external agent. This external agent is mainly consisted of a low viscosity resin combined with a proper hardener, where the

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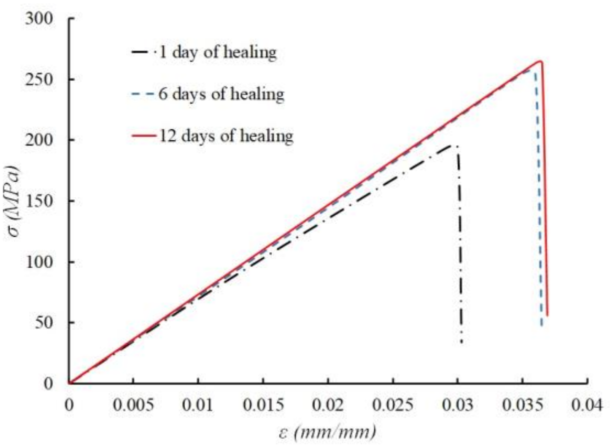

Fig. 1. The effect of time period on the healing process (samples with 32 healing units)

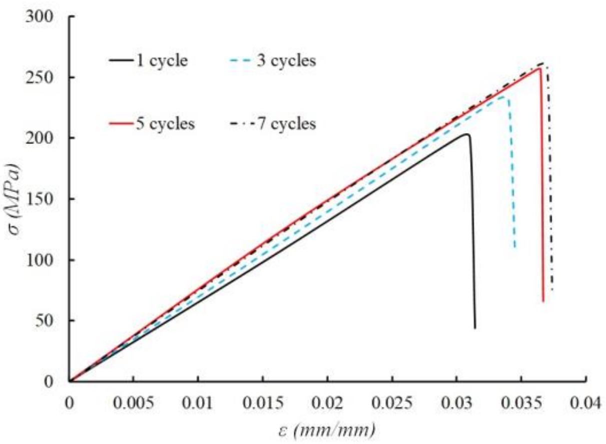

Fig. 2. The effect of thermal cycles on the healing process (samples with 32 healing units)

combination reacts with the composite elements and leads to the restoration of the microstructure of the composite. This chemical reaction may be affected by introducing thermal cycles into the healing procedure, especially the required healing time. However, reviewing the present literature in this field shows that the effect of thermal cycles on the healing behavior is not studied thoroughly. In addition, the damage is caused by Charpy impact and three-point bending tests to the composite, while in real applications the impact loading is mostly occurred in a form nearly like a drop hammer test.

Based on the above explanation, in this research the effects of healing time and thermal cycles on the healing process of glass/epoxy composites are studied. The investigation is carried out experimentally and the initial damage is introduced to the composite by drop hammer test. The aim is to determine the effect of healing process on the recovery percentage of the

2- Experimental Procedure

Materials: Epoxy resin EPIKOTE828 manufactured by Shell Chemicals combined with an Amine hardener plus E-glass fiber mat with a density of 400 g/m^2 (manufactured by Lintex Ins.) are utilized in fabricating the test samples. ML506 epoxy resin (that has a low viscosity) and HA-11 which is a polyamine hardener are used as the healing agent. In addition, hollow glass microtubes with an outer diameter of 200 micrometers are applied for storing the healing agent.

Fabrication of test samples: 6-layer composite beams are fabricated by hand layup. The resin and hardener of the healing agent are stored in separated microtubes which are joined beside each other. Each set of resin and hardener microtubes are called one healing unit hereafter. Control samples are produced without any healing units. Other samples are produced by 8, 16 and 32 healing units, where this amount of healing units are equal to 0.67%, 1.34% and 2.68% of volume fraction, respectively. Half of the healing units are placed between the first and the second layers and the remaining half are interleaved between the fifth and the sixth layers.

Inserting damage: The damage is introduced to the samples by a 3.1 Kg drop hammer which is released from a height equal to 45 cm. This means that the velocity of the hammer is equal to 2.97 m/s at the impact the impact energy is also equal to 13.68 J.

Thermal cycles: Although healing process is a time dependent procedure and is carried out automatically, applying thermal cycles to the damaged samples can accelerate this process. In order to investigate this fact, some damaged samples are placed under thermal cycles directly after impact. The time of each thermal cycle is 120 minutes which includes 60 minutes of heating to 150°C proceeded with 60 minutes slow cooling at room temperature.

Tensile Tests: Tensile tests are carried out on the samples before damage, directly after damage and in periods of 1, 6 and 12 days after damage. In addition, tensile tests are done on the samples which have met thermal cycles 1 day after damage.

3- Results and discussion

The results for recovery of tensile strength before and after damage as functions of time and thermal cycles are demonstrated in Figures 1 and 2.

The results are also listed in Table 1. As can be seen, applying thermal cycles efficiently accelerates the healing process and increases the recovery percentage as well.

Table 1. The result of healing efficiency as functions of time and thermal cycles (samples with 32 healing units)

	Healing Efficiency (percentage)						
	1 day	6 days	12 days	1 TC**	3 TC	5 TC	7 TC
8 HU*	8	64	63	15	49	62	61
16 HU	10	75	77	18	57	72	74
32 HU	11	83	86	19	67	85	87

* HU: Healing units
** TC: Thermal cycles

4- Conclusions

In this paper the effect of thermal cycles on the recovery of tensile strength of self-healing composite samples which were damaged by low velocity impact is investigated. The results show that although interleaving the healing units decreases the strength of undamaged samples up to 10%, the healing process leads to a recovery percentage more than 85%. In addition, introducing thermal cycles to the damaged samples accelerates the healing process, as the recovery percentage of damaged samples after 12 days is almost equal to recovery of the samples which have met 7 thermal cycles after 1 day.

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