Welding of Fiber Reinforced 5-Harness Satin Woven Thermoplastic Composite Fabrics by Ultra-High Frequency Induction System

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Abstract

In this study, we report 6 plies of 5-harness satin woven fabrics were welded each other by ultra high frequency induction system between two tempered glass surfaces at 400°C under 640 kPa pressure for 120 seconds. The results of mechanical properties, Brinell hardness tests and SEM analysis proved an intimate contact between plies allowing the fusion in the bonding area for PEEK matrix.

1. Introduction

Advanced polymer-matrix composites are attracting increasing interest thanks to their unique features [1-4]. Applications of polymer-matrix composites took place efficiently in military and civil aviation, automotive, wind power generation and many other industries due to their lightness, light density and high performance in addition to high strength and rigidity in comparison with low weight ratio. In order to decrease the costs of aforementioned materials, new processing methods are required to shorten the manufacturing procedures. Induction heating becomes prominent among the researches within this context.

Besides induction heating is studied mostly in relation with metals [5.-11], it is also an effective fusion bonding method for polymer composites. On the interface of bonding area of composites with polymer matrix, there are three important forces: Mechanical, physical and chemical forces [12]. In the composite industry, these forces are referred as mechanical fastening, adhesive bonding and fusion bonding according to production processes [12]. There are many bonding technologies in these three categories. Choosing the proper technology to the industrial requirements, performance, weight, processing time and cost factors are taken into consideration.

Mechanical fastening [13], adhesive bonding [13], fusion bonding [14, 15], ultrasonic welding, microwave welding, resistance welding, hot plate welding, IR welding, laser welding and induction welding [16] methods are used in bonding process of thermoplastic composites.

Induction welding is based on, applying electric energy taken from a generator by a coil without a contact and causing transfer of the heat to the interface by the help of electrically conductive materials which are positioned in the bonding area or in the laminates. The laminates to be bonded are exposed to electromagnetic area. Eddy currents are induced when there are loops in laminates and heating occurs. Because of the advantages as being a clean, fast and contact-free process, suitable for automation and reprocessing or recycling, this method is counted the most promising technologies along with ultrasonic welding and resistance welding among the fusion bonding methods [16].

Regarding the mechanical performance of welding there are many studies in the literature [17]. As an example, Villegas et al. [17] recorded that the results of the single lap shear test of ultrasonic welding and induction welding were 27,3 MPa in average with a standard deviation of %1,5 ratio while resistance welding's results were 23,3 MPa in average with a standard deviation of %5 ratio. However, it was also stated that due to the variety of parameters used of the methods, samples and bonding ways, it is impossible to compare the mentioned methods within a range of exact standard values.

Many thermoplastic polymers used in the automotive, aircraft and space industries are welded with high frequency induction systems [18-21].

Induction welding is preferred in welding complex and big pieces because it does not require additional materials, does not cause dirt on the bonding area and it allows automation processes. In this study, 6 plies of 5-harness satin woven fabrics were welded each other by ultra-high frequency induction system between two tempered glass surfaces at 400°C under 640 kPa pressure for 120 seconds. In order to form mechanically high-performance thermoplastic composites, the parameters of induction heating, which is faster and more cost-effective compared with conventional methods, were examined. Mechanical properties, hardness and cross-sectional microstructure were examined to offer as a competing method to conventional production methods of thermoplastic composites in terms of the results.

2. Materials And Methods

In this study, 6 plies of 5-harness satin woven fabrics were welded each other by ultra-high frequency induction system between two tempered glass surfaces at 400°C under 640 kPa pressure for 120 seconds. The coupling distance was 3 mm because the thickness of the tempered glasses is 3 mm. The schematic view of the induction system is in Fig.1. For each test 5 samples were produced. The test results are given in average of these samples.

5-harness satin woven fabrics were received from MIR Innovation and Technology Center (MITEC). The reinforcement material is carbon fiber and the matrix is PEEK in the fabrics. The carbon fiber ratio is %72 in volume. The matrix thickness and the carbon fiber diameter are both 7 μm. The fabrics were cut by scissors into the dimensions of specimen of mechanical tests. The average thickness of the fabrics is 0,38 mm (± 0,02 mm).

Tensile, single lap shear and Brinell hardness tests were applied to the produced laminates and SEM views were examined. According to ISO 527-4 tensile test Type 2 specimen were produced. 5 samples were produced in the dimensions of 250 X 25 X 2 mm. Tensile test was carried out with Zwick 250 kN universal test machine with 2 mm/minute speed.

10 laminates with the dimensions of 100 X 25 X 2 mm were produced for ASTM D1002 single lap shear test. The laminates were welded each other from the ends by 12,7 X 25 mm area, under 640 MPa pressure and 400C for 120 seconds to produce 5 samples. The single lap shear test was carried out with Zwick 250 kN universal test machine with 1,3 mm/minute speed. In order to apply the pressure on the same axis, the grips of the machine were arranged.

For ISO 6506 hardness test specimen were produced in 25 X 60 mm dimensions. Hardness tests were carried out by BMS 200-RBOV Rockwell, Brinell and Vickers Hardness Test Machine. The test machine gives the results by calculating the dimensions of the imprint of a steel ball which is pressed to a chosen point. The diameter of the ball was 1,25 mm, the pressure was 100 kg and the pressure time was 10 seconds.

The scanning electron microscope (SEM) used for analyzing the samples works based on obtaining views by scanning the surface of samples via a focused electron beam. Zeiss Ultra Plus was used for SEM analysis under 10 kV high vacuum.

3. Results And Discussion

At the beginning of the study the uniformity of the heat generation was viewed by a thermal camera to assess the effectiveness of the pancake coil. Thermal image is shown on Fig.2. According to Fig.2, across the cross-section of bonding area where is circled with black line apparently has heat uniformity.

The thickness of the produced laminates is 2,3 mm (± 0,2 mm) in average. Reminding that each ply of the fabrics has the thickness of 0,38 mm (± 0,02 mm) and laminates are made of 6 plies, it was observed that the applied pressure of 640 kPa did not cause the matrix flow out. In this respect, the pressure was proper for the current induction system and the dimensions of the samples.

The results of the tensile test of specimen with the dimensions of 250X25X2 mm are given in Table 1.

Table 1 The results of tensile test

Sample No	Tensile Strength (MPa)
1	907,7 MPa
2	700,6 MPa
3	652,9 MPa
4	780,3 MPa
5	939,5 MPa
Average Result	796,2 MPa

The average tensile strength of the samples is 796,2 MPa. The standard deviation of the values is 125,4 MPa where the standard deviation ratio of the values is %15.75. The standard deviation is high, because the covering area of the coil is 12 times smaller than the sample surface that the coil had to be replaced 12 times to cover the whole area of the samples, so there were undesired bonding area failures. With a more powerful induction system and a pancake coil with the dimensions to cover the whole surface of samples, this challenge will be overcome.

In his study, McGrath [22] found the tensile strength of the 5-harness satin woven laminates, which have %68 fiber ratio in weight, as 669,9 MPa. The tensile strength of Toray Cetex® TC1200 PEEK 5-harness satin woven products, which have %50 fiber ratio in volume, of Toray firm is 776 MPa [23], where Tenax® -E TPCL PEEK-HTA40, which has %52 fiber ratio in volume, of Tenax firm is 963 MPa [24]. Within this range of results, we can say that 796,2 MPa value of this study is appropriate. Although the fiber ratio of the samples is %72 in volume leads an expectation to have higher values, with a more powerful induction system and a larger enough coil as mentioned above the expected values can be achieved.

The results of the single lap shear test of specimen with the dimensions of 100X25X2 mm are given in Table 2.

Table 2 The results of single lap shear test

Sample No	Shear Strength (MPa)
1	44,86 MPa
2	41,29 MPa
3	37,71 MPa
4	33,45 MPa
5	41,24 MPa
Average Result	39,71 MPa

The average shear strength of the samples is 39,71 MPa. The standard deviation of the values is 4,32 MPa where the standard deviation ratio of the values is %10,88. The standard deviation ratio is smaller compared to tensile test results, because the welding area dimensions are closer to the coils covering area. However, standard deviation ratio is still high. This situation can be explained as the result of the coil's covering area (17 X 20 mm) is larger than the welding area (12,7 X 25 mm) that edge effects occurred and the laminates which composed the samples were produced by aforementioned method which the coil was replaced several times to cover the whole area.

In literature, the results of single lap shear tests of satin woven carbon reinforced composites with PEEK matrix vary within the range of 27-55 MPa [25-29]. The main reason of this wide range in these studies is assessed as the varieties of the reinforcement rates, laminate thicknesses and production methods. The results of this study are within the range of the results in literature.

The failure surface of the second sample is given in Fig.3. It can be seen that the PEEK matrix was separated from the other laminate on the right picture while the carbon fibers on the other laminate were exposed on the left picture in Fig.3. So, there is a structural failure. With the results of single lap shear test and the structural failure of the samples, the welding process is considered successful in this study.

The Brinell hardness test results observed from 7 measuring points of 4 samples are given in Table 3. The average hardness value is 92,60 HB. The standard deviation is 2,43 and the standard deviation ratio is %2,62. Although the standard deviation seems low, there are differences up to %20 between the measuring points. This situation can be explained by the same reasons in tensile test. Meanwhile, in terms of thermoplastic composites the average hardness value is considered fair enough.

Table 3 Brinell hardness test results

Sample No.	Point a	Point b	Point c	Point d	Point e	Point f	Point g	Average Hardness Value (HB 1,25/100/10)
1	91,5	90	90,7	110,2	98,1	95,1	96	95,94
2	102,1	82	84,1	89,1	93,2	93,4	102,1	92,28
3	91,1	86,9	119	81,9	93	79,1	93,4	92,06
4	82,2	97	88,1	90,2	96,5	87,9	89	90,13
Average	91,72	88,97	95,47	92,85	95,20	88,87	95,12	92,60

The samples produced for the Brinell hardness test were cut to expose cross sectional area and the cross-sectional areas were analyzed by SEM to evaluate the weld. In order to compare the results, 250 times enlarged image of cross-sectional area of a 5-harness satin woven fabric layer which is not welded is given in Fig.4. The light-colored parts above and below the dashed lines is PEEK matrix and the black fibers are carbon fibers. The area in ellipse is void between woven fibers.

There are SEM images of two different laminates produced by welding 6 plies of 5-harness satin woven fabrics in Fig.5 and Fig.6. Although the microstructure of the fabrics is not homogeneous, it seems that the PEEK matrix with white color extending top-down in Fig.5 and left to right in Fig.6 welded successfully. It is considered the irregularities in the shape of PEEK matrix distribution is caused by diffusion of PEEK into carbon fibers during the manufacture process of the fabrics and also by the geometric structure of 5-harness satin weave.

In Fig.5. which has 82, 500 and 1000 times enlarged images, the PEEK matrix of plies bonded each other and there are no structural defects as void or cracks on the bonding areas which means there were no thermal stresses occurred during the heating process that the thermal expansion and contraction was avoided in the matrix.

Due to absence of cracks, matrix expansion or contraction and voids, the applied pressure is considered proper. Although the fabric plies don’t have a plain surface, there was intimate contact regarding the viscosity increase of matrix in high temperatures that there was no air balloon and delamination in bonding areas.

Considering the applied temperature, because there were no defects in the microstructure due to thermal dissociation 400°C is thought a good value for PEEK matrix.

When the secondary equipment of the heating system with high thermal conductivity which were used for applying pressure, setting the samples and other purposes contact the samples, it was observed that besides energy loss a uniform heat distribution couldn't be generated and the heating time had to longer than the optimal time. Hence, the secondary equipment in induction systems should have low electrical and thermal conductivity as much as possible to obtain more uniform internal structures in shorter times with less energy losses.

On the phase of determining the heat gradient of laminates produced by hot press and autoclave methods, deformation occurred on the corresponding area to coil's mirror image of laminates which don't have uniform internal structure during the induction heating process. Such structures should be reprocessed to solve this problem. On the other hand, there was no deformation in 5-harness satin woven which were produced by bonding the fabrics with induction system. Regarding this, induction heating is more successful in producing laminates with uniform internal structure than hot press and autoclave methods.

4. Conclusions

In this study, 6 plies of 5-harness satin woven fabrics were bonded each other with ultra-high frequency induction system successfully.

Considering the results of mechanical tests, 796,2 MPa tensile strength and 39,71 MPa shear strength are within the range of the values in literature. On the other hand, high standard deviations of the test results can be explained by coil size which covers a smaller area than the bonding area. Hence, it is concluded that the coil, the power of generator, the structure and the shape of the part to be processed should correspond to each other. The structural failure on the samples in single lap shear test shows the parameters in induction heating were determined properly.

According the SEM analysis on cross sectional areas of bonded samples, it was understood that thermal stress didn't occur during the heating process, thus matrix expansion and contraction were avoided. Because there were no cracks, voids, matrix expansion or contraction in produced laminates, 640 kPa pressure is considered proper to provide an intimate contact between plies to allow fusion in bonding area. Due to absence of defects related to thermal dissociation in the internal structure of laminates, 400^{o}C is considered proper as processing temperature for PEEK matrix.

Declarations

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Conflicts of interest: The authors have no relevant financial or non-financial interests to disclose.

Data availability: All data generated during this study are included in this published article.

Code availability: Not applicable.

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Figures

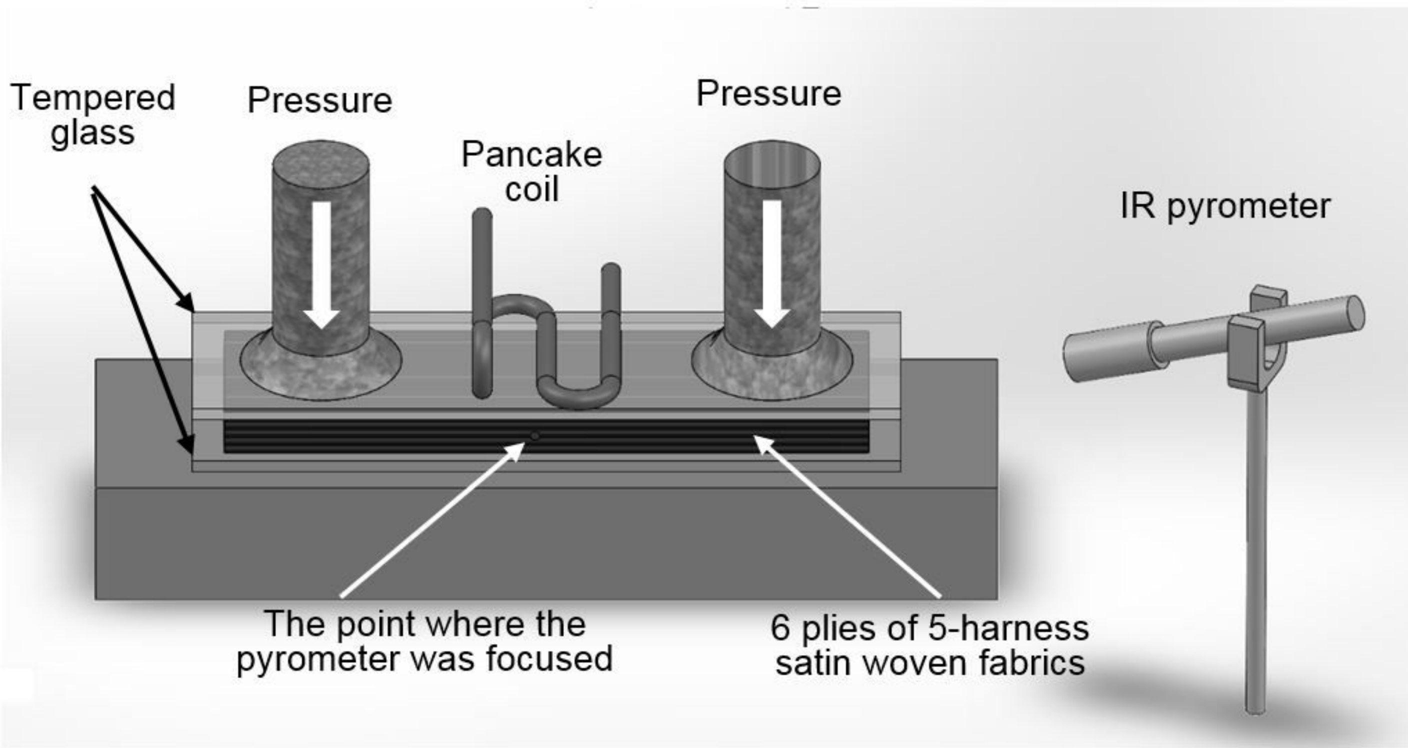

Figure 1

The schematic view of welding fiber reinforced 5-harness satin woven thermoplastic composite fabrics by ultra-high frequency induction system

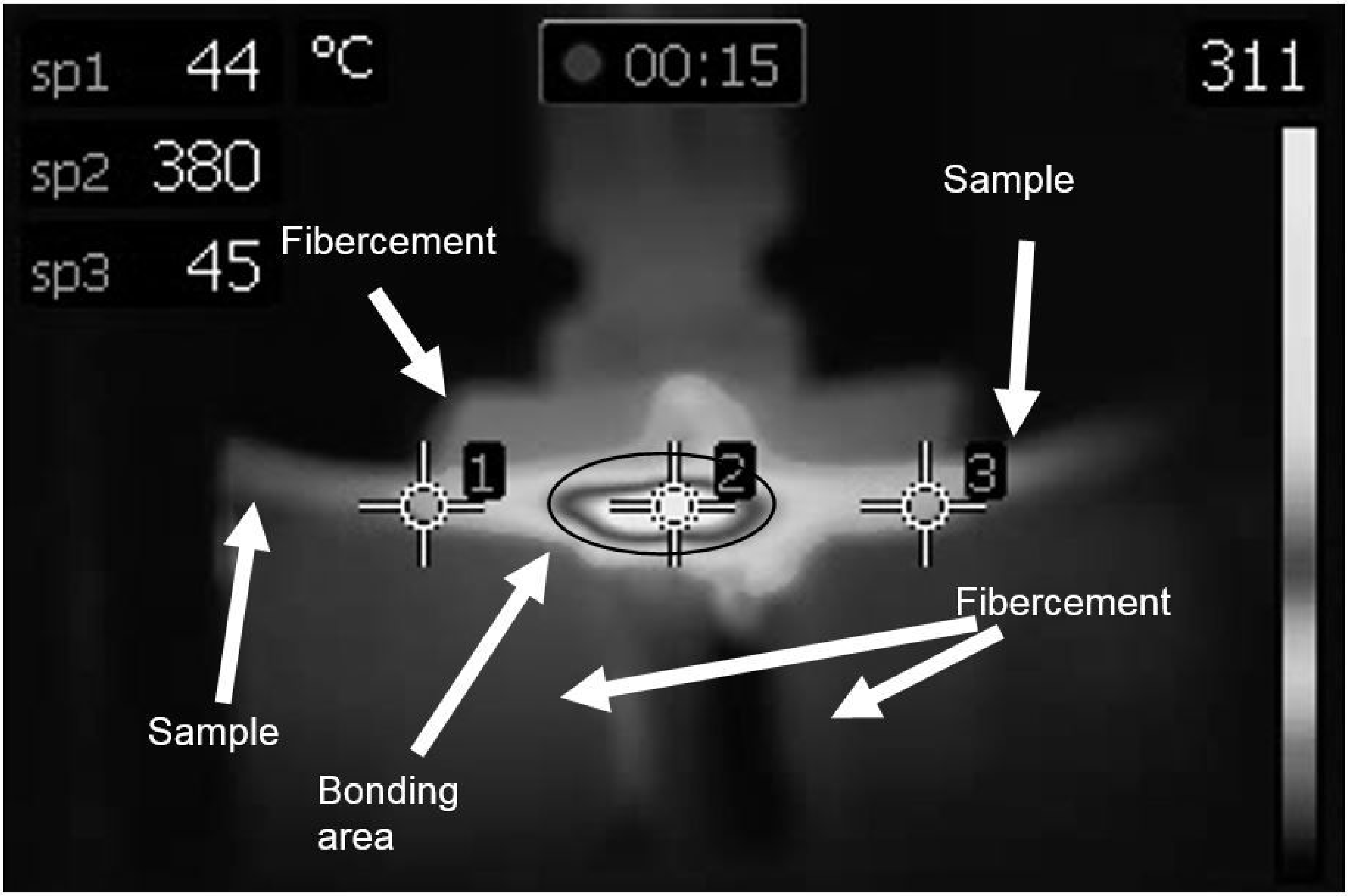

Figure 2

The thermal image of the cross-section of bonding area

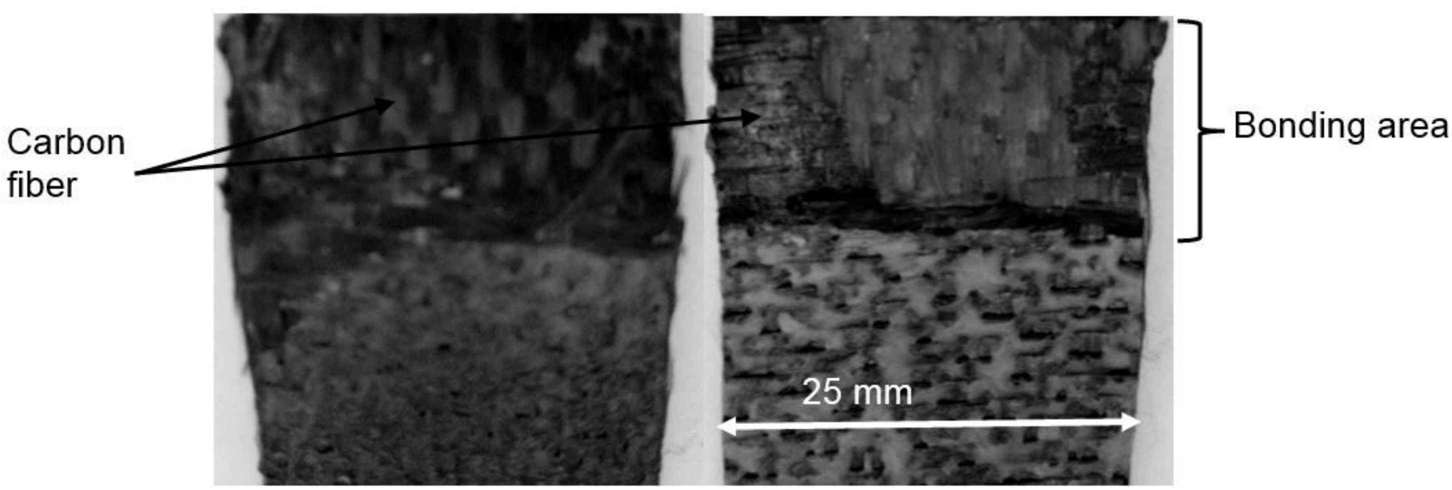

Figure 3

The failure surface of the second sample

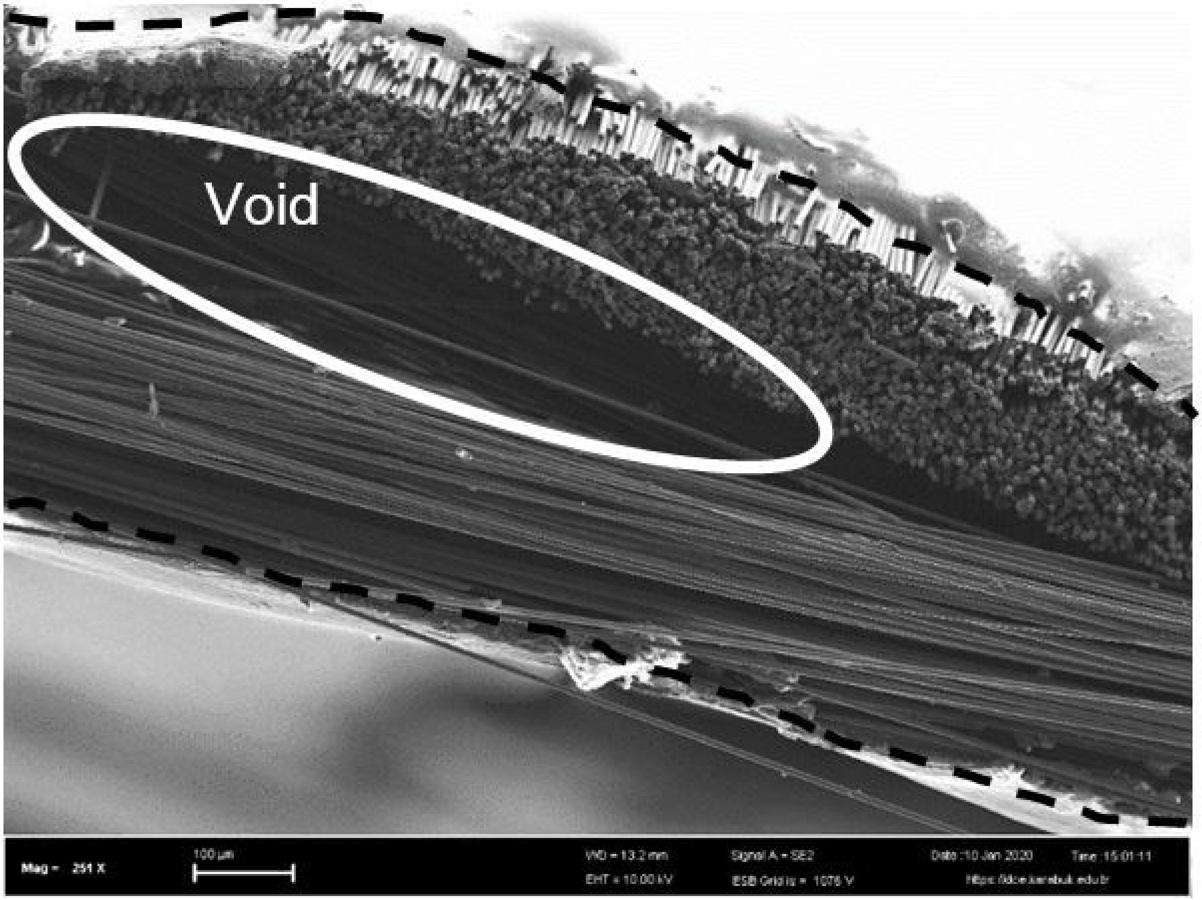

Figure 4

The image (x250) of cross-sectional area of a 5-harness satin woven fabric layer

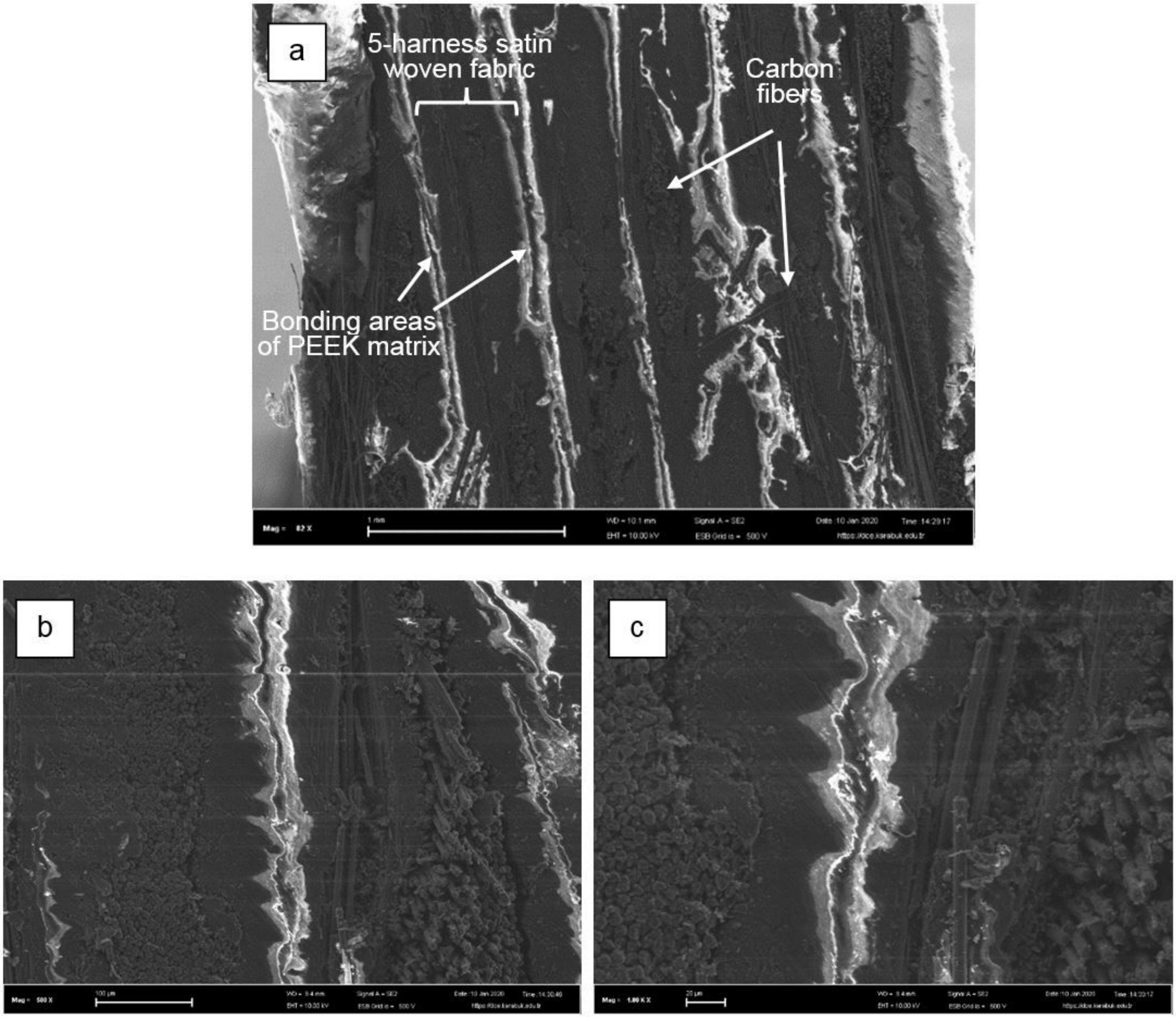

Figure 5

The SEM images of a laminate produced by welding 6 plies of 5-harness satin woven fabrics a) x82 b) x500 c) x1000

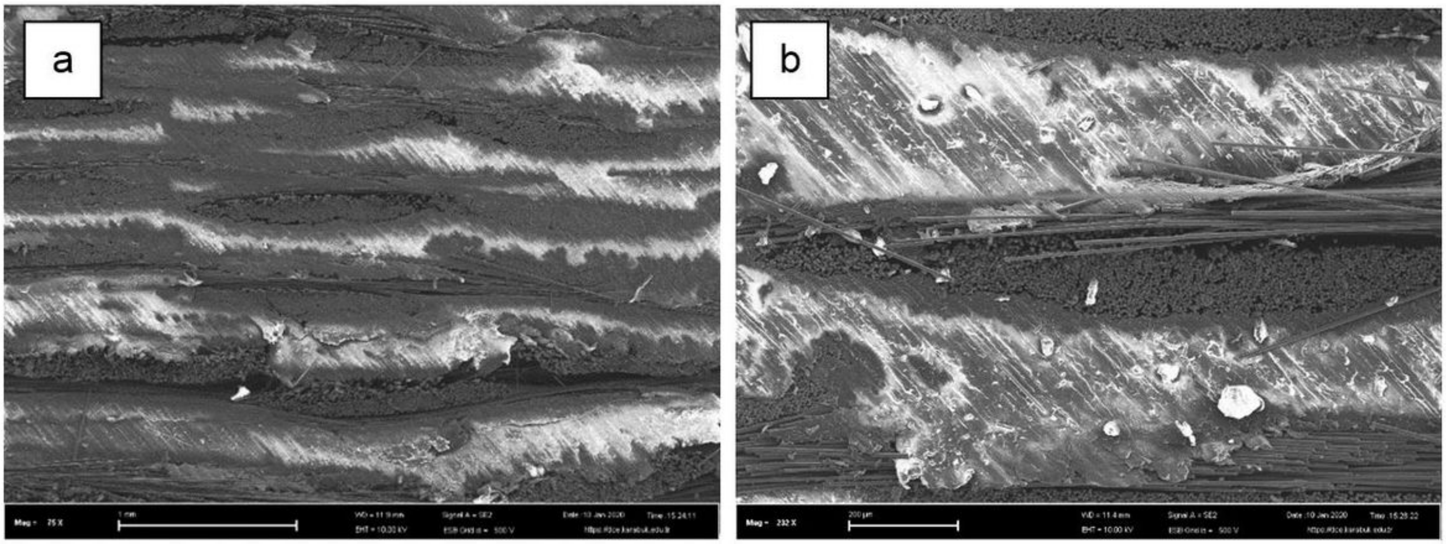

Figure 6

The SEM images of a laminate produced by welding 6 plies of 5-harness satin woven fabrics a) x75 b) x232