Crack initiation and propagation on the polymeric material ABS (Acrylonitrile Butadiene Styrene), under ultrasonic fatigue testing

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ABSTRACT. Crack initiation and propagation have been investigated on the polymeric material ABS (Acrylonitrile Butadiene Styrene), under ultrasonic fatigue testing. Three controlled actions were implemented in order to carry out fatigue tests at very high frequency on this material of low thermal conductivity, they are: a) The applying load was low to limit heat dissipation at the specimen neck section, b) The dimensions of testing specimen were small (but fitting the resonance condition), in order to restraint the temperature gradient at the specimen narrow section, c) Temperature at the specimen neck section was restrained by immersion in water or oil during ultrasonic fatigue testing.

Experimental results are discussed on the basis of thermo-mechanical behaviour: the tail phenomenon at the initial stage of fatigue, initial shear yielding deformation, crazed development on the later stage, plastic strain on the fracture surface and the transition from low to high crack growth rate. In addition, a numerical analysis is developed to evaluate the J integral of energy dissipation and the stress intensity factor K, with the crack length

KEYWORDS. Crack initiation; Polymeric material; Ultrasonic fatigue; J integral; Stress intensity factor K.

INTRODUCTION

Polymeric materials used in modern industries present valuable combination of properties, such as: corrosion resistance, high elastic modulus and strength in regard their density, good thermal and electrical insulation, excellent shape design and formability [1]. The physical-chemical and mechanical properties of polymeric materials are modified in use for a wide variety of industrial applications [2, 3]. Often, mechanical loading determines the fatigue endurance properties of these materials; this is the case for thermoplastic polymers such as ABS (Acrylonitrile Butadiene Styrene), for which two fatigue failure modes can be observed: a) the low cycle regime, characterized for failure at low number of cycles and high stress loading, and b) the high cycle regime and low stress loading. The first mode is associated with high heat dissipation and hysteresis process during testing: high stress, high strain or high testing frequency and ductile failure; whereas the second mode presents low energy dissipation inside the hysteresis loops, revealing low influence of mechanical loading or frequency on the specimen temperature [4]. Furthermore, the fatigue testing frequency on glassy polymers is associated with the process of physical aging, since an increase on frequency promotes the heat dissipation and aging process on these materials [5]. In addition, polymers undergoing embrittlement degradation caused by three different physical-mechanical factors: cyclic stress, constant stress and thermo-physical aging; nevertheless, a complete understanding and differentiation of these factors inducing embrittlement degradation is not available [6].

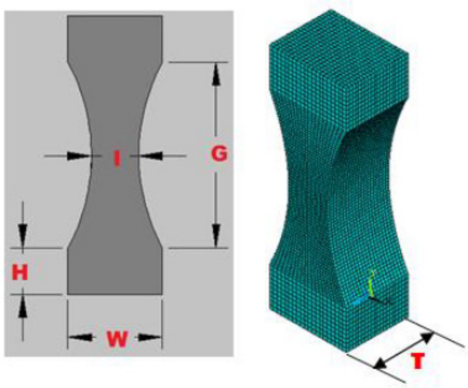
Concerning crack initiation and propagation on polymeric materials, the first stage may imply close to 95% of total fatigue life [7]; however, no clear division is defined for these two stages in most of polymeric materials. For PC (polycarbonate), PMMA (poly-methyl-methacrylate) and PP (polypropylene), fatigue tests under uniaxial extension have shown that first stage covers nearly 99% of total fatigue life and that crack initiation is anticipated by an important plastic deformation [8]. From thermo-mechanical point of view, two fatigue testing modalities are available on polymeric materials: isothermal fatigue testing and non-isothermal fatigue testing. The first modality is characterized by the true mechanical fatigue response, providing that heat dissipation is very low or eliminated. Under isothermal testing and cyclic stress loading or constant stress loading, an important increase on yield stress is observed as a consequence of physical aging [9, 10]; this behaviour is enhanced with the stress loading. For quenched polycarbonate at room temperature (23° C), under isothermal conditions and cyclic stress in tension, an appreciable increase on yield stress is observed after 100 sec of testing, when the applying load is 55 MPa [4], (yield stress of polycarbonate at 23° C and constant low strain rate is close to 73 MPa).

TESTING MATERIAL

Thermoplastic material ABS was used to carry out ultrasonic fatigue testing at low loading (5 to 15% in regard the yield stress of this material: 45 MPa), and at room temperature (23° C). Table I shows the principal mechanical and physical properties of this polymer at room temperature. ABS sheets of 210 x 270 mm and 8 mm of thickness were machined to obtain the specimen profile as shown in Fig. 1.

Property	Units	Value
Elastic modulus	GPa	2.3
Poisson modulus	-	0.4
Density	Kg/m^3	1040
Yield stress	MPa	45
Glass transition temperature	° C	105

Table I: Principal mechanical and physical properties of polymeric material ABS.



G = 20 mm

H = 5 mm (variable)

I = 5 mm

W = 10 mm

T = 8 mm

Figure 1: Ultrasonic fatigue specimen dimensions (mm) for polymer ABS.

Experimental testing

Ultrasonic fatigue testing on solid materials requires the resonance condition of vibrating system. This is attained when the natural frequency in longitudinal direction of testing specimen is close to vibration source frequency (20 KHz); under this condition, a stationary elastic wave along the specimen is obtained. If testing material is selected (polymer ABS), the mechanical and physical properties are fixed and the longitudinal natural frequency close to 20 KHz is accomplished with the modification of the specimen dimensions. Figure 1 shows the specimen dimensions fulfilling the resonance condition for this polymer. In Figure 2 is presented the modal analysis by Finite Element method in order to obtain the natural frequency of testing specimen; the corresponding value was 20039 Hz. Additionally, in Figure 3 is plotted the evolution along the specimen of stress and displacement under resonance conditions (generation of a stationary elastic wave).

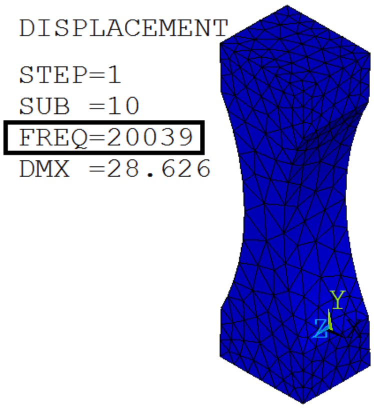
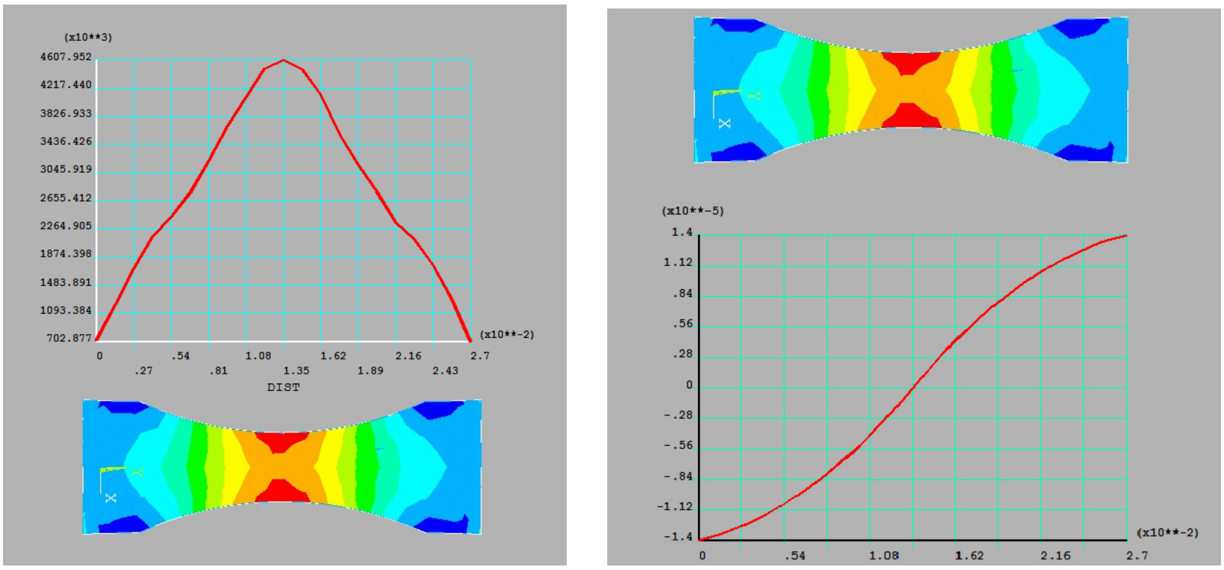


Figure 2: Modal analysis to obtain the logitudinal frequency of vibration for testing ABS specimen.



a) b)

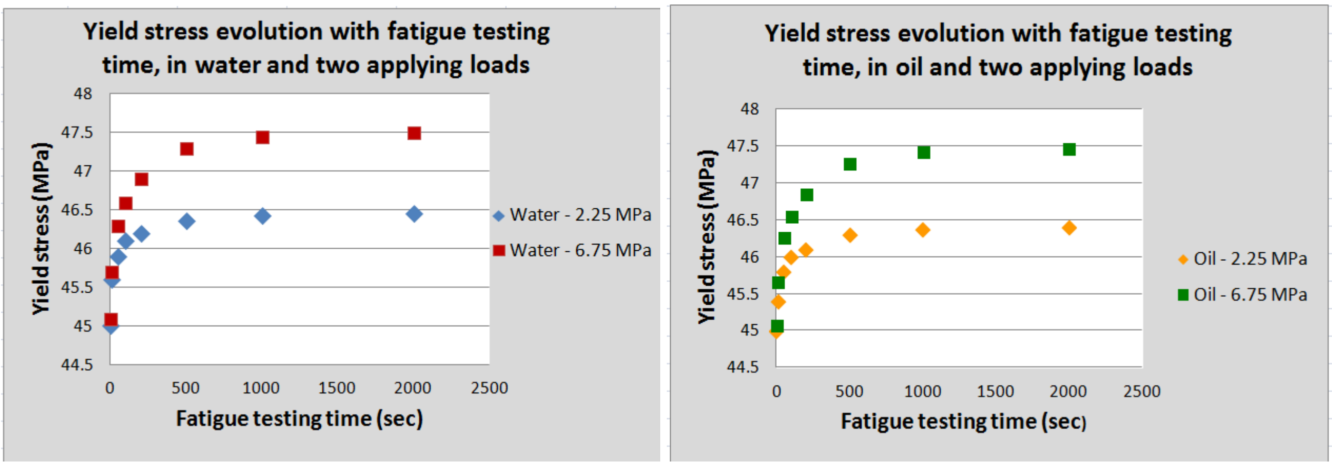
Figure 3: Evolution of stress (Pa) along testing specimen under a stationary elastic wave a), and evolution of displacement (m) along testing specimen under same conditions b).

The dimensions of testing specimen were as little as possible (fitting the resonance conditions), in order to increase the surface to volume ratio (reduction of thermal domain). Furthermore, testing specimens were immersed in water or oil for cooling purpose, Fig. 4, and the applying load was considerably low (5 to 15% the yield stress of this material), in order to approach the mechanical domain and reduce the thermal influence. A principal aspect to achieve ultrasonic fatigue testing on this polymer was the attachment of testing specimen to the ultrasonic fatigue machine; however, no details are provided in this paper.
Measures of yield stress (tensile tests at strain rate 10^{-3} s^{-1}), after ultrasonic fatigue testing were carried out in order to investigate the evolution of this property under the following conditions: a) previous ultrasonic fatigue testing, b) low loading (5 – 15% of yield stress), and c) cooling environment (water and oil). Figure 5 a) presents the yield stress evolution for testing specimens immersed in water and for two applying loads: 2.25 and 6.75 MPa, under fatigue stress ratio R= -1. In Fig. 5 b) are plotted the experimental points for the yield stress of this polymer immersed in oil and undergoing the same applying loads and fatigue stress ratio. The increase on yield stress for both cooling liquids is quite small;

furthermore, an increase on applying load (from 2.25 to 6.75 MPa), is accompanied by a low increase on the yield stress. These results are in accordance with the fact that, under the describing testing conditions, the thermal domain is negligible and mechanical domain becomes predominant.

a) b)

Figure 4: Ultrasonic fatigue testing of polymer ABS immeresed in water a) and in oil b). No cavitation effect was observed during ultrasonic fatigue tensting with specimens immersed in water or in oil.



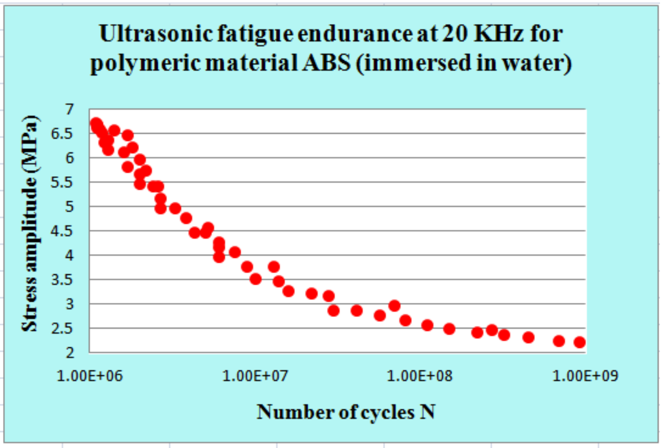
a) b)

Figure 5: Yield stress measured by tensile tests after ultrasonic fatigue testing in water and two applying loads a), yield stress measured by tensile test after ultrasonic fatigue testing in oil and two applying loads b).

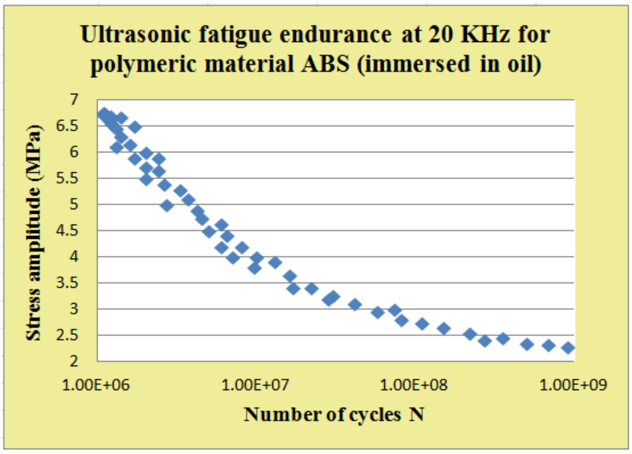
No appreciable difference is observed for the yield stress evolution under ultrasonic fatigue testing when testing specimen is immersed in water or oil; however, in both cases a low increase on yield stress is registered in increasing the applying load. Another aspect of these results is the fact that the experimental tendencies grow up rapidly in the first 100 seconds of ultrasonic fatigue testing, and they tend to an asymptotical value afterwards. This behavior should be attributed to very high fatigue testing frequency, to very low applying loading and the control of temperature by the cooling environments (water and oil). The measured temperature at the specimen neck section during fatigue testing was close to 33° C.
Assuming mechanical domain under the described conditions, it is expected that the low increase on yield stress of testing material during ultrasonic fatigue testing is a combination of aging and rejuvenation processes [11, 12]; even though, the last process is not fully recognized [13].

ULTRASONIC FATIGUE RESULTS ON POLYMER ABS

Experimental ultrasonic fatigue results for this polymer are shown in Fig. 6 a) and b), immersed in water and oil respectively. The range of applying load in both cases was low: between the 5 and 15% the yield stress of this material (45 MPa at 23°C and at strain rate reference of 10^{-3} s^{-1}).



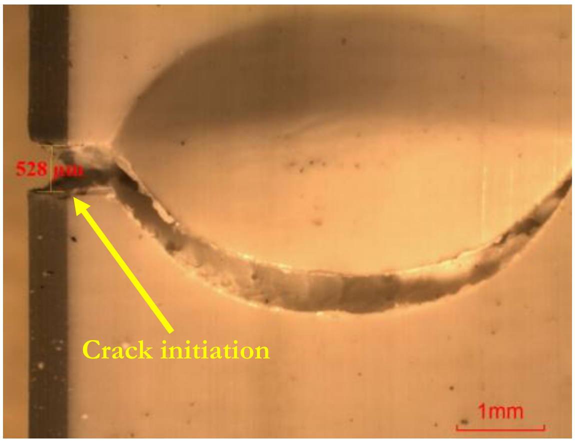
a)



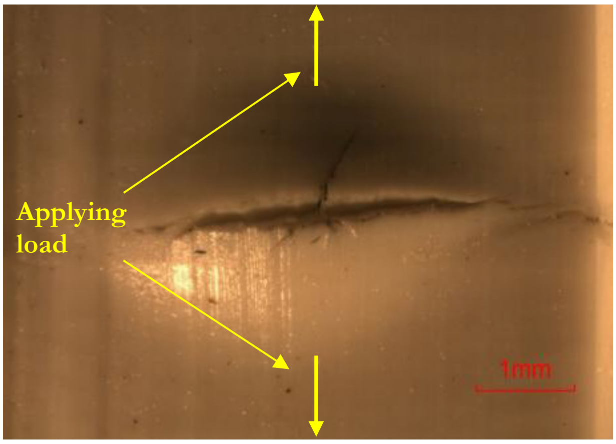
b)

Figure 6: Ultrasonic fatigue endurance of polymeric material ABC immersed in water a), and in oil b).

Ultrasonic fatigue endurance on thermoplastic ABS is close to one millions of cycles when the applying load is about 15%regarding the yield stress of this polymer, independently of cooling liquid used. Furthermore, dispersion of experimental points is higher for high applying load (from 4 to 6.75 MPa); it decreases for low loading or long fatigue life. Concerning crack initiation and propagation under ultrasonic fatigue testing associated with the described testing conditions, Fig. 7 a) and 7 b) show the corresponding images for the specimens immersed in water and in oil, respectively.



a)



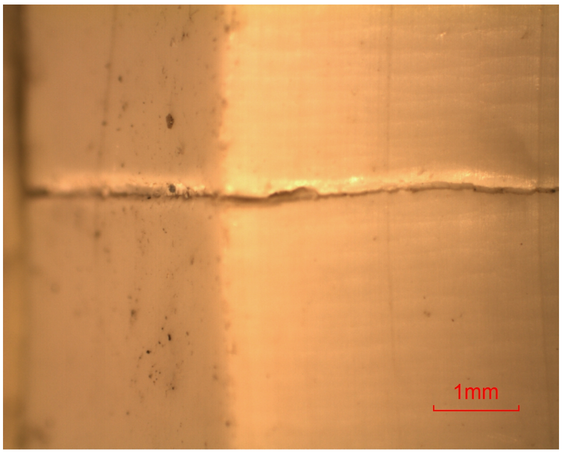
b)

Figure 7: Crack initiation and propagation under ultrasonic fatigue testing of polymer ABS immersed in water a), and in oil b).

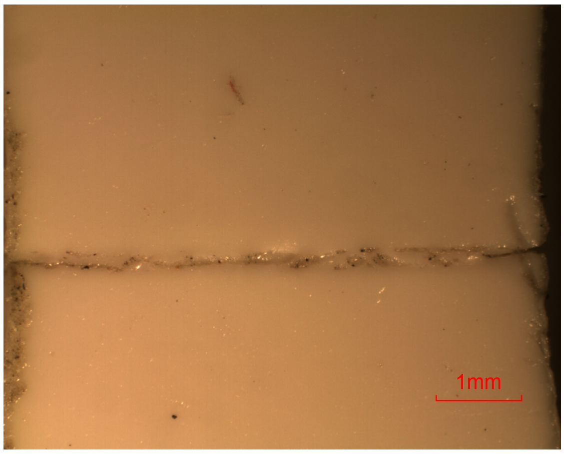
Physical-chemical reactions are expected to take place on the interface of polymer surface and the cooling liquid during ultrasonic fatigue testing, such as the swelling phenomenon [14-16]. Swelling is the absorption process of the solvent (water or oil) penetrating the polymer and this process should be enhanced by the very high frequency loading. The tail phenomenon [17, 18], or the transition process of damage accumulation and the corresponding plastic deformation is observed at the first stage of crack, particularly for specimens immersed in water, Fig. 7 a).
In most of testing specimens it was observed a bubble or protuberance at the neck section that is caused by the expansion of micro-porosities inside the specimen when loading at very high frequency, Fig. 8. The swelling contribution for this protuberance should be negligible.

Figure 8: Bubble or protuberance at the especimen neck section, under ultrasonic fatigue testing (before crack propagation).

Very often, fatigue ctack initiation and propagation were associated with the bubble or protuberance generated during the high frequency loading. Figs. 7 a) and b) show the principal crack patterns of this material under ultrasonic fatigue testing: for specimens immersed in water a noticeable plastic deformation [19, 20] is observed at the specimen corner where stress concentration is higher; then, crack propagates following the protuberance contour. For specimens immersed in oil, crack initiation is localized at the top of the bubble and propagates along the principal elliptical axis of the protuberance, perpendicular to applied loading, Fig. 7 b). A study is in cours in order to formulate a comprehensive understanding of these behaviors, taking into account the involved physical-chemical and mechanical parameters [21, 22].
Crack propagation along the specimen lateral side is shown on Figs. 9 a) and b), for specimens immersed in water and in oil, respectively. In both cases, low plastic deformation is observed and low thermal effect can be assumed.



a)



b)

Figure 9: Crack propagation along the specimen lateral side immersed in water a) and in oil b).

Numerical evaluation of J integral and stress intensity factor K, with crack propagation on polymer ABS

A numerical analysis was carried out to evaluate the two parameters controlling the energy relaxation and stress state of material during crack propagation. A bi-dimensional numerical model using PLANE183 element (Ansys software), was developed to obtain J and K under plane strain condition, Fig. 10. Crack length was imposed from 0.5 mm to 4 mm with increments of 0.5 mm; the symmetrical condition of specimen allows developing a half of specimen surface, as shown in Fig. 10.
Three applying loads were imposed corresponding to: 1.67, 2.5 and 3.34 MPa, and these loads were maintained constant during crack propagation. The numerical model uses 6 close trajectories in order to evaluate the J integral. The numerical results are plotted on Fig. 11 a) and b) for the J integral and the stress intensity factor K, respectively.
Values for these two parameters present an exponential evolution with crack length, as shown in Fig. 11; these results are of same order in regard previous results obtained on the polymeric blend PC/ABS [23].

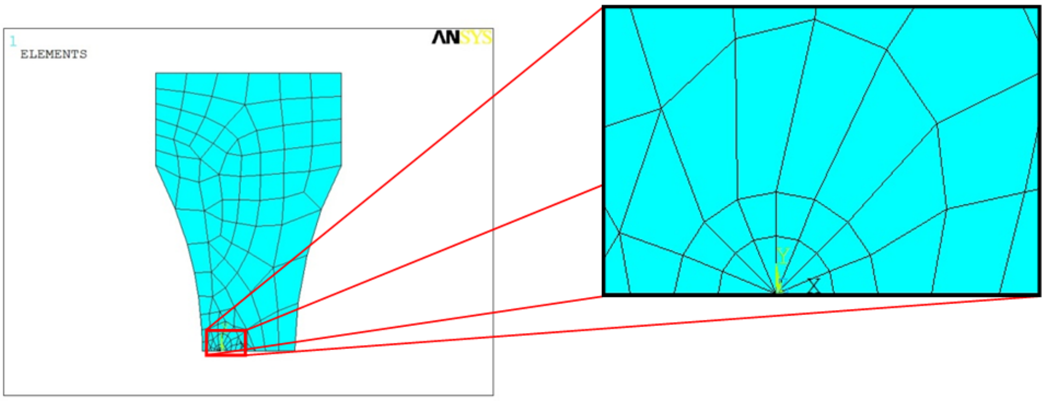
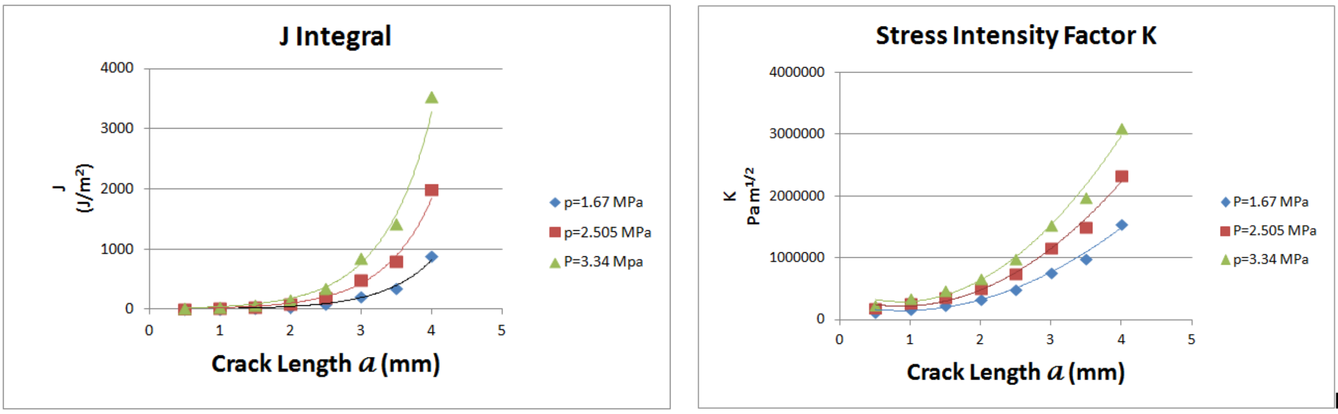


Figure 10: Bi-dimensional numerical model to evaluate J and K under plane strain, different crack lengths and applying loads.



a) b)

Figure 11: Numerical results for the J integral and the stress intensity factor K, for three applying loads and different crack lengths.

CONCLUSIONS

The following conclusions can be drawn from this research work:

- Ultrasonic fatigue endurance on polymeric material ABS was obtained under controlled temperature.
- Experimental tests were carried out under mechanical domain, since thermal domain was minimized by three factors: low loading, low dimensions of testing specimen and immersion in a cooling liquid.
- Ultrasonic fatigue life of ABS polymer is close to one millions of cycles when the applied load is close to 7 MPa; it increases to one thousand millions of cycles when the applied load decreases to 2.25 MPa, no matter the cooling liquid used (water or oil).
- Under ultrasonic fatigue testing with low applying load and predominant mechanical domain, the yield stress increase (aging) is low and it is developed during the first 100 seconds of ultrasonic testing; for the long testing time, an asymptotical tendency is observed. This behavior is not modified using water or oil as cooling liquid.
- The patters of crack initiation and propagation of this polymer were quite different for specimens immersed in water and in oil: for the first ones, crack initiates at one corner of prismatic specimen associated with appreciable plastic deformation; then, crack propagates contouring the protuberance and extending to lateral sides with low plastic deformation. For specimens immersed in oil, crack initiates at the top of the protuberance with apparently less plastic deformation; then, it propagates along the principal axis of the elliptical bubble, extending to lateral sides where plastic deformation is very low.

- Numerical simulation were carried out using a bi-dimensional model and plane strain condition, in order to obtain the J integral and the stress intensity factor K with the crack length. The results are in good agreement with previous ones obtained for PC/ABC polymeric blends.
- Further investigation are needed to improve the understanding of ultrasonic fatigue endurance on ABC polymer, the role of the mechanical and physical-chemical parameters affecting the crack initiation and propagation and the non linear interaction of these parameter, on the fatigue life and the crack initiation and propagation of this polymer.

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