Fatigue Behavior of Two Acrylic Denture Base Resins

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Acrylic resins based on polymetyl metacrylate are used in dental prosthetics as base for dentures. One of the major failure causes of dentures is the fatigue damage of the acrylic resins. These materials, in addition to mechanical behavior, also present a high risk of structural defects (voids, micro-cracks, residual monomer) that can significantly affect the fatigue behavior. In this paper, two commercial acrylic resins have been experimentally analyzed in terms of mechanical and fatigue behavior. Tensile constant amplitude fatigue tests with stress ratio R = 0 and frequency of 2 Hz have been carried out on samples of the two acrylic resins, prepared according to the manufacturer's recommendations. The results revealed, besides the brittle fracture character, a similar fatigue behavior following a Weibull distribution. Also, through statistical processing of the results, the fatigue curve equations of the two analyzed materials were estimated for different levels of confidence.

Keywords. acrylic resin, dentures, mechanical properties, fatigue behavior, Weibull distribution.

Polymethyl methacrylate (PMMA) acrylic resins are widely used as denture base. These synthetically obtained materials can be modeled, packed or injected into molds during the plastic phase and become solid after chemical polymerization. The fracture of dentures is a common clinical occurence in prosthodontic service which is still a problem in consideration. Most fractures of the denture occur inside the mouth during function, primarily because of resin fatigue failure [1, 2]. Fatigue of acrylic resins originates from stress concentration areas or micro flaws, from which cracks are propagated resulting in complete failure, [3, 4]. Due to the brittle behavior, the presence of structural micro voids and defects these materials have a high susceptibility to fail by initiation and rapid propagation of a crack. In a review study about the biodegradation of the acrylic based resins, [5], the fatigue damage process caused by relatively low and repetitive chewing forces was described as one of the major degradation processes along with other factors as saliva or thermal and chemical dietary changes. In a comprehensive study on the fatigue behavior of pure PMMA acrylic resins and commercial dental base resins, Fujii [6] presents a series of observations including that: the increasing of the mean stress of the cyclic loading determines the decrease of the fatigue limit; during the fatigue damage process, the elastic modulus, toughness and tensile strength were reduced; the fatigue limit can be improved by the addition of a cross-linking agent; water absorption into heat cured resins caused the fatigue limit to decrease; the fatigue limit is influenced by the amount of the residual monomer. Ana Diaz-Arnold et all., [7], have shown in an experimental study that both static and fatigue flexure strength are higher for visible light-polymerized resins compared with PMMA heat-polymerized resins. Gurbuz et all., [8], reported that reinforcing the acrylic resins with glass fibers did not increase significantly the fatigue resistance. Instead, Salih et all., [9], found that reinforcing the PMMA acrylic resin with 5% Kevlar and glass fibers give a higher fatigue strength compared to pure PMMA. The fatigue strength at 10^6 cycles was 53 MPa for PMMA with Kevlar fibers, 38 MPa for PMMA with glass fibers and 15 MPa for pure PMMA resin.

Although there is a wide range of commercial acrylic resins used as base for dentures, there is a lack of studies and data on fatigue behavior. Thus, the paper presents an experimental study on the fatigue behavior of two commercial acrylic denture base resins commonly used in dental practice.

Experimental part

Materials and methods

Acrylic resins can be classified as chemical, heat or light activated depending on the factor that initiates the reaction [10, 11]. Chemical or auto-polymerized materials involves a chemical activator like, *N,N*-dimethyl-*p*-toluidine. For heat-polymerized materials, heat can be generated by hot water bath or microwave, while the light-activated use visible light as energy source, [12]. For this study, two types of acrylic resins were used. The first type was an auto-polymerized resin, Vertex (Vertex™ Dental, B.V., Yeist, Netherland) and the second was heat-polymerized resin named Superacryl (SpofaDental, Markova, Czech Republic). Both resins consisted of a polymer powder and a monomer liquid, being prepared as indicated by the manufacturers.

Tensile static and fatigue tests have been carried out on both materials using a tensile-compression testing machine Zwick/Roell of 5 kN, figure 1, respectively fatigue testing machine Walter-Bai, LFV-10-HM, of 10 kN, figure 2. Also, the tensile static tests have been performed according to BS EN ISO 527 standard, [13], being tested five specimens from each material. The fatigue tests have been carried aut according to ASTM D7791 standard, [14], using a frequency of 2 Hz and stress ratio, R = 0. The stress ratio applied in the fatigue tests is similar to cyclic loadings during mastication.

Results and discussions

Following the tensile tests, the mechanical behavior and properties were determined for both analyzed materials. The acrylic resins show a brittle fracture character, more pronounced in the case of Vertex resin. Table 1 gives the mechanical properties of the two analyzed materials. The

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Fig. 1. Tensile test on Zwick/Roell testing machine

Fig. 2. Tensile fatigue test on Walter-Bai testing machine

Table 1
MECHANICAL PROPERTIES OF THE TWO ANALYZED ACRYLIC RESINS

Material	Young's modulus [MPa]	Ultimate strength [MPa]
Vertex	1223	67.7
Superacryl	5333	64.7

results indicate a better elasticity of Superacryl resin compared to Vertex at comparable ultimate strength. In terms of mechanical behavior the Vertex resin presents a higher risk of failure in the presence of structural defects. Also, being an auto-polymerizable resin exhibits a higher risk of residual monomer content.

The results of the fatigue tests for the two acrylic resins are presented as log-log curves in σ_{max}-N coordinates (σ_{max} being the maximum stress of the loading cycle and N is the number of cycles until failure), (fig. 3).

The fatigue tests indicate a slightly lower slope for Vertex resin compared to Superacryl, which may indicate a slightly higher durability and a better fatigue behavior, respectively. However, the difference between the fatigue limits corresponding to the durability of 10^6 cycles and calculated based on the equations of the two curves, is too low to support a better fatigue behavior of one of the two analyzed resins, (table 2). The difference between the fatigue behavior of the two resins is more pronounced at durability under 1000 cycles, where a significance influence has the ultimate strength. Instead, over 1000 cycles the two fatigue curves intersect, indicating a similar fatigue behavior for the two acrylic resins.

Generally, the fatigue tests show great variability, even if they are carefully performed to minimize the experimental error. For this reason, the determination of the fatigue curve equation that fits the experimental points is based on statistical processing. According to BS ISO 12107, [15] standard, the estimation of the fatigue curve on the finite durability domain can be done using a linear model in semi-logarithmic coordinates:

$$x = b - a \cdot y \tag{1}$$

where $x = \log N$ and $y = \tau_{max}$, a and b are constants determined by statistical processing.

Once the coefficients *a* and *b* are determined, the equation (1) can be mathematically transformed into a power equation, as given in table 2. At the same time, starting from the basic equation, which is determined for a 50% probability of failure, equations of fatigue curves with different probability of failures can be established. Thus, in table 2 have been determined for the two acrylic resins the fatigue curve equations for a 10% probability of failure. Based on these equations, fatigue life predictions can be performed with 90% confidence.

Very often in processing the fatigue data and especially in the case of dental materials, Weibull distribution is used. The Weibull distribution describes an asymptotic function of the smallest extremes. This property is often referred to as the *weakest link*. According to this property, if a failure number of cycles of a component may be regarded as the shortest life associated with a large number of independent potential factors (e.g. defects or microcracks), then under fairly general conditions, the component failure distribution will tend toward the Weibull, [16]. There are two forms of the Weibull distribution in use, distinguished by the

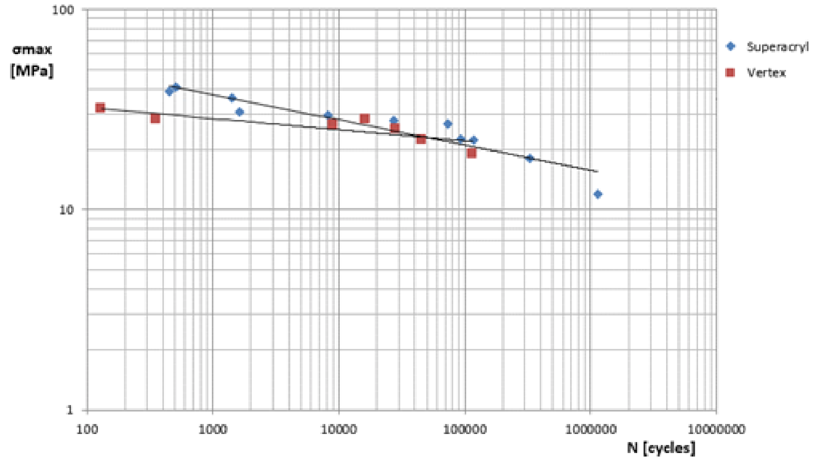


Fig. 3. The S-N curves of the analyzed acrylic resins

Table 2
THE FATIGUE LIMITS OF THE TWO ACRYLIC RESINS

Materials	Probability of failure/Confidence level [%]	Constants of equation (1)	S-N equations	Fatigue limits at 10^6 cycles [MPa]
Vertex	50/50	a = 0.222 b = 9.615	$\sigma_{max} = 57.248 \cdot N^{-0.091}$	16.28
	90/10	-	$\sigma_{max} = 37.126 \cdot N^{-0.08}$	12.29
Superacryl	50/50	a = 0.128 b = 7.802	$\sigma_{max} = 107.01 \cdot N^{-0.147}$	14.04
	90/10	-	$\sigma_{max} = 69.383 \cdot N^{-0.135}$	10.74

appearance of either two or three constants in the mathematical expression. If a random variable X follows the two-parameter Weibull model, the probability that a random observed value will not exceed a specified value x is expressed as:

$$Prob[X < x] = F(x) = 1 - exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \quad (2)$$

where *F(x)* is the cumulative distribution function (CDF) or failure probability, η is the scale parameter or the characteristic value of the Weibull distribution having the same units as *X*, β is a dimensionless shape parameter.

One of the property of the Weibull distribution is the closure property, according to which the smallest of several identical Weibull variables is itself a Weibull variable, [16]. This property makes convenient to describe a size effect in structural materials. If the fracture strength of a structure of volume V_0 follows a Weibull distribution, then the fracture strength of a structure of greater volume *V* under similar loading will follow a Weibull distribution:

$$\left(\frac{V_0}{V}\right)^{\frac{1}{\beta}} \quad (3)$$

Similar scaling applies to the relative areas, the scale parameter for components having surface area *A* is reduced by the fraction $\left(\frac{A_0}{A}\right)^{\frac{1}{\beta}}$ from the scale parameter of components having area A_0.

To determine the Weibull parameters, β and η, must takes logarithms twice in equation (2) resulting:

$$\ln\ln\left(\frac{1}{1-F}\right) = \beta \cdot \ln x - \beta \cdot \ln \eta \quad (4)$$

The left-hand side of equation (4) is a linear variation in natural logarithms coordinates with a slope equal to the shape parameter β and the intercept equal to - β·ln η.

Applying the procedure given in Appendix, the Weibull parameters for the two acrylic resins were estimated as β = 0.3979 and η = 63998 cycles for Superacryl, respectively β= 0.4099 and η = 24914 cycles for Vertex.

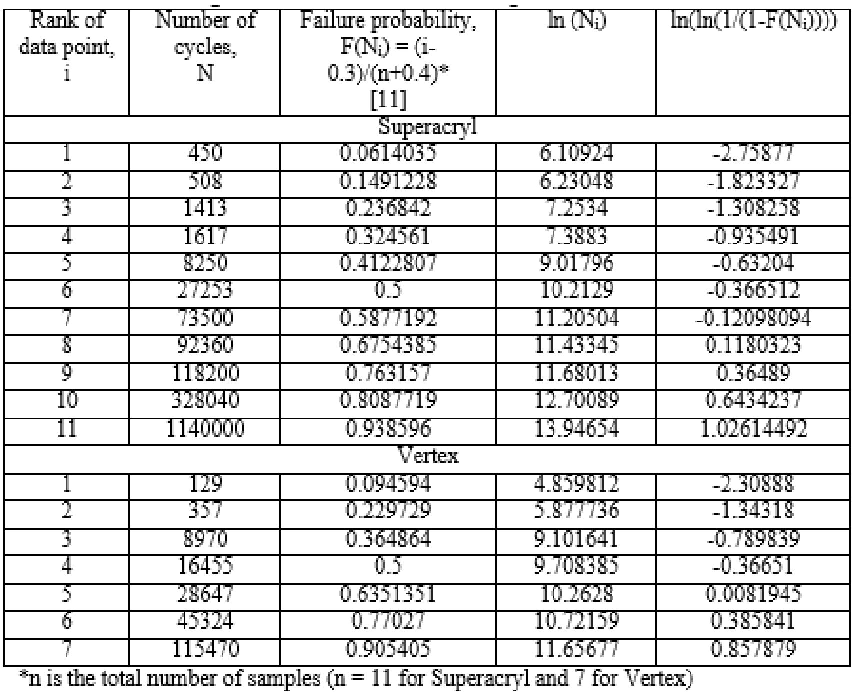
The shape parameter of the Weibull distribution, β, represents the failure rate behavior. If β < 1, then the failure rate decreases with number of cycles; if β > 1 the failure rate increases with time and if β = 1, the failure rate is constant. For the analyzed acrylic resins the shape parameter is less than 1, which means that the failure rate decrease with increasing number of cycles.

Conclusions

In this paper fatigue behavior of two commercial acrylic resins, often used as denture base, has been experimentally evaluated. Besides the brittle fracture of the two acrylic resins, the fatigue behavior is also similar, the difference being made only by the content and density of micro-structural defects. The fatigue behavior of the two acrylic resins follows a normal log-log variation, for which the equations of the curves were determined. Also, the fatigue data follows a Weibull distribution for which the corresponding parameters were determined.

Appendix

Table A1
THE PROCEDURE FOR WEIBULL PARAMETERS DETERMINATION



Rank of data point, i	Number of cycles, N	Failure probability, $F(N_i) = (i-0.3)/(n+0.4)$* [11]	$\ln(N_i)$	$\ln(\ln(1/(1-F(N_i))))$
		Superacryl		
1	450	0.0614035	6.10924	-2.75877
2	508	0.1491228	6.23048	-1.823327
3	1413	0.236842	7.2534	-1.308258
4	1617	0.324561	7.3883	-0.935491
5	8250	0.4122807	9.01796	-0.63204
6	27253	0.5	10.2129	-0.366512
7	73500	0.5877192	11.20504	-0.12098094
8	92360	0.6754385	11.43345	0.1180323
9	118200	0.763157	11.68013	0.36489
10	328040	0.8087719	12.70089	0.6434237
11	1140000	0.938596	13.94654	1.02614492
		Vertex		
1	129	0.094594	4.859812	-2.30888
2	357	0.229729	5.877736	-1.34318
3	8970	0.364864	9.101641	-0.789839
4	16455	0.5	9.708385	-0.36651
5	28647	0.6351351	10.2628	0.0081945
6	45324	0.77027	10.72159	0.385841
7	115470	0.905405	11.65677	0.857879

*n is the total number of samples (n = 11 for Superacryl and 7 for Vertex)

By plotting the last two columns of the Table A1, results in the equation of the linear variation that gives the parameters of the Weibull distribution, fig. A1 and A2.

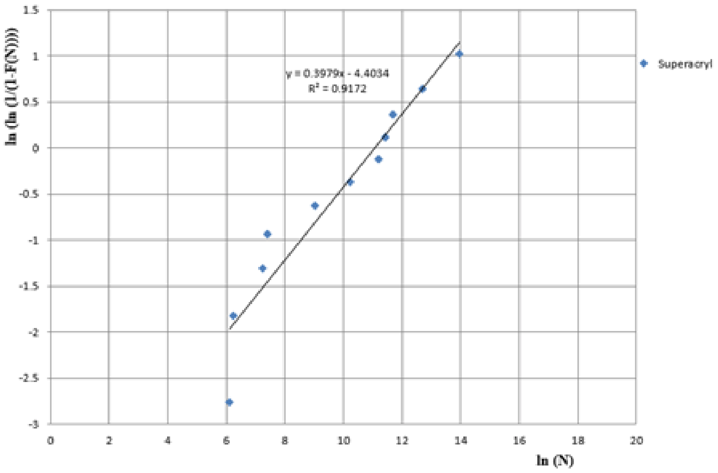


Fig. A1. The graphic representation for Weibull parameters of Superacryl

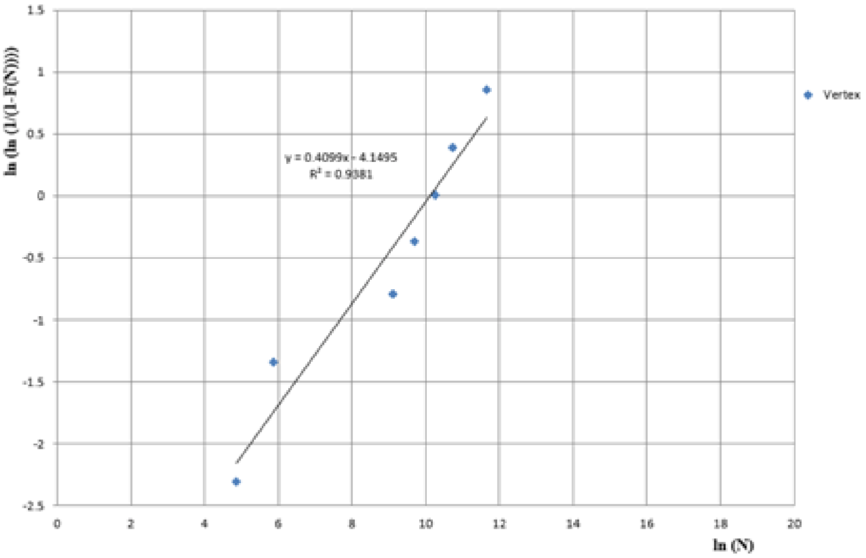


Fig. A2. The graphic representation for Weibull parameters of Vertex

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