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ORIGINAL ARTICLE

A comparative machinability analysis of aged and freshly manufactured epoxy resins through orthogonal machining experiments

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Abstract

Applications of thermoset epoxy resins in load-bearing fibre-reinforced polymer (FRP) composites are decisive, mainly due to their excellent material properties, low viscosity before hardening and good adhesion with the reinforcing fibres. Although numerous experiences on the machinability of FRPs have been published, these experiences can be only indirectly adapted to pure epoxy resins. Reflecting on the lack of knowledge on the machinability of epoxy resins, the main aim of the present study is to compare the machinability of aged and freshly manufactured epoxy resins. Half of the epoxy specimens were naturally aged in a continental climate environment for a year, while the other half was manufactured prior to the orthogonal machining experiments. The experiments were conducted in a dry condition in a Kondia B640 machining centre. The cutting speed and the uncut chip thickness were varied systematically. The cutting force was measured by a KISTLER 9257B dynamometer, and the machined surfaces were characterised by a Mitutoyo SJ400 surface tester and a Keyence VR-5000 3D profilometer. The experimental results prove that the aged epoxy degraded significantly; thus, the specific cutting force is significantly smaller than that of freshly manufactured epoxy. However, the surface quality was not significantly influenced by the polymer degradation.

Keywords Epoxy · Machinability · Ageing · Orthogonal cutting · Cutting force · Surface roughness

1 Introduction

Properly implementing the principles and fundamentals of circular economy will possibly result in a significant improvement in the sustainability of our planet. Considering that repair, remanufacturing, and refurbishment are high-priority levels of circularity [1], more and more attention will be given to the machining of end-of-life thermosetting polymeric products in the future. Considering that the mechanical properties of end-of-life polymeric products are often degraded due to long-term natural impacts (e.g. thermal, UV, water absorption, etc.) [2], the analysis of the processability of aged polymeric products comes to the fore. Although there are some published experiences on the degraded material properties of aged thermosetting polymers [3], their mechanical machinability has not been analysed yet.

Thermosetting epoxy resins have high mechanical strength, excellent thermal and chemical stability, easy processing, low cost and high adhesiveness to many substrates [4, 5]. Therefore, epoxy resins are widely used in high-tech industries such as automobile, aerospace and electronics [6, 7]. Considering that the material properties of particular epoxy parts significantly depend on the type of epoxy resin, curing agent, and their mixing ratio [8], various fields require slightly different epoxy applications. For example, in the aerospace industry, thermosetting epoxies are used as matrices in carbon fibre-reinforced polymer (CFRP) composites that have to be lightweight and high-strength at the same time [9]. Therefore, the adhesion between the epoxy and the reinforcing fibres is a key issue [10]. Another example of a typical epoxy application is electrical equipment or electronic components, where thermal conductivity is the

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key property (not the load-bearing efficiency); therefore, thermally conductive fillers are often used [11].

Epoxies are easy to manipulate before curing due to their relatively low viscosity [12–14]; therefore, epoxy parts are usually manufactured by moulding techniques, where they get their final shape. However, post-manufacturing is often needed after curing to meet strict dimensional tolerances, mainly for assembly reasons [15]. Mechanical machining technologies such as drilling and edge trimming are the most frequently applied technologies for manufacturing difficult-to-mould geometric features (e.g. holes and pockets) in parts containing epoxies [16–21]. Therefore, there is a considerable need for an understanding of the machinability of epoxy resins. Although numerous studies have been published on the machinability analysis of fibrous composites having epoxy matrices, they focus on the reinforcing fibres rather than the matrices because the high-strength fibre reinforcements primarily affect the cutting resistance of FRPs. Nevertheless, the softer and lower-strength polymeric matrix also plays an important role in the chip formation mode, chip type and cutting temperature in the cutting zone [22–24]. Material removal in thermosetting epoxy resins is governed by brittle fracture mechanisms with little strain to fracture; thus, the machined surface is often rough [25]. Sheikh-Ahmad [22] summarised the key issues of machining thermosetting polymers and highlighted that (i) the larger the uncut chip thickness, the larger the possibility of transition from ductile to brittle behaviour, (ii) the larger the cutting speed, the higher the cutting temperature and dominance of ductile behaviour, (iii) the larger the cutting temperature in the cutting zone, the larger the polymer softening resulting in a change of material removal mechanisms.

Although the manufacturing technology can be appropriately planned based on the published experiences on the machinability of FRPs having epoxy matrices, these experiences cannot be directly adapted to the technology planning of aged epoxy parts. Parts containing epoxy resins degrade over time due to the ageing of polymers governed by thermal, UV and water absorption mechanisms [2]. Since polymer ageing significantly influences the mechanical properties of epoxy materials (i.e., decreases tensile, shear and impact strength [3], lowers the adhesiveness with fillers and reinforcements [26], increases the number and length of cracks [27], and forms delamination [26], etc.), the machinability is expected to be also significantly influenced by the ageing-induced polymer degradation. However, there is no published information on the machinability of aged epoxy resins in the open literature. In order to support the maintenance and renovation of old epoxy parts, a comparative machinability analysis of aged and freshly manufactured epoxy resins is required. Considering that the published experiences on the machinability of epoxy resins are moderate, the main aim of the present study is to analyse the machinability of pure epoxy resins experimentally. Freshly manufactured and naturally aged epoxy specimens were orthogonally machined to gain information on their cutting energetics and machined surface quality to provide helpful information for technology planning of fresh and aged epoxy materials.

2 Experimental setups

Orthogonal machining experiments were conducted in a three-axis (X, Y and Z) Kondia B640 vertical machining centre. A turning tool was inserted into the spindle of the machine tool by using own-developed adapters aiming to fix the spindle orientation in a position where the main cutting edge of the cutting insert is perpendicular to the machined surface, as is illustrated in Fig. 1.

The interpolated linear movement of the cutting tool along the X-axis provided the cutting motion, i.e. the cutting speed. Considering that the maximal applicable feed rate of the machine tool is 20,000 mm/min, the maximum of the applicable cutting speed was limited to 20 m/min. A SECO CCGT09T304F-AL, KX cutting insert conducted the chip removal, which was inserted into a SECO SCLCR1616H09 tool shank. The machining experiments were conducted in dry conditions. The experimental setup is illustrated in Fig. 1.

The cutting force along the cutting motion was measured by a KISTLER 9257B dynamometer using a sampling frequency of $f = 10{,}000$ Hz. The instrument signal was amplified by a KISTLER 5070A11100 multichannel laboratory charge amplifier and collected by an NI USB-4431 five-channel dynamic signal acquisition module. The noise (i.e., high-frequency vibrations) was decreased by the moving average method expressed by Eq. (1).

$$Y_i = \frac{1}{2n+1}\sum_{j=-30}^{n=30} y_j = \frac{y_{j-30} + \cdots + y_{j-1} + y_j + y_{j+1} + \cdots + y_{j+30}}{2n+1} \tag{1}$$

where Y_i is the filtered response value, y_j denotes the original signal, and $2n+1 = 61$ are the neighbouring signal values affecting the actual response value corresponding to $v_c\,(2n+1)\,f^{-1} \approx 1$ mm of tool movement at 10 m/min cutting speed. The surface roughness parameters of the machined features were measured by a Mitutoyo SJ400 surface tester using the ISO 4287:1997 standard, and the surface quality was analysed by a Keyence VR-5000 3D profilometer. The machined surfaces were treated by a Helling 3D laser scanning spray to improve measuring accuracy by decreasing the transparency of the polymer specimens.

Epoxy resin specimens were manufactured by casting into silicone moulds with a two-component MR3010/MH3124

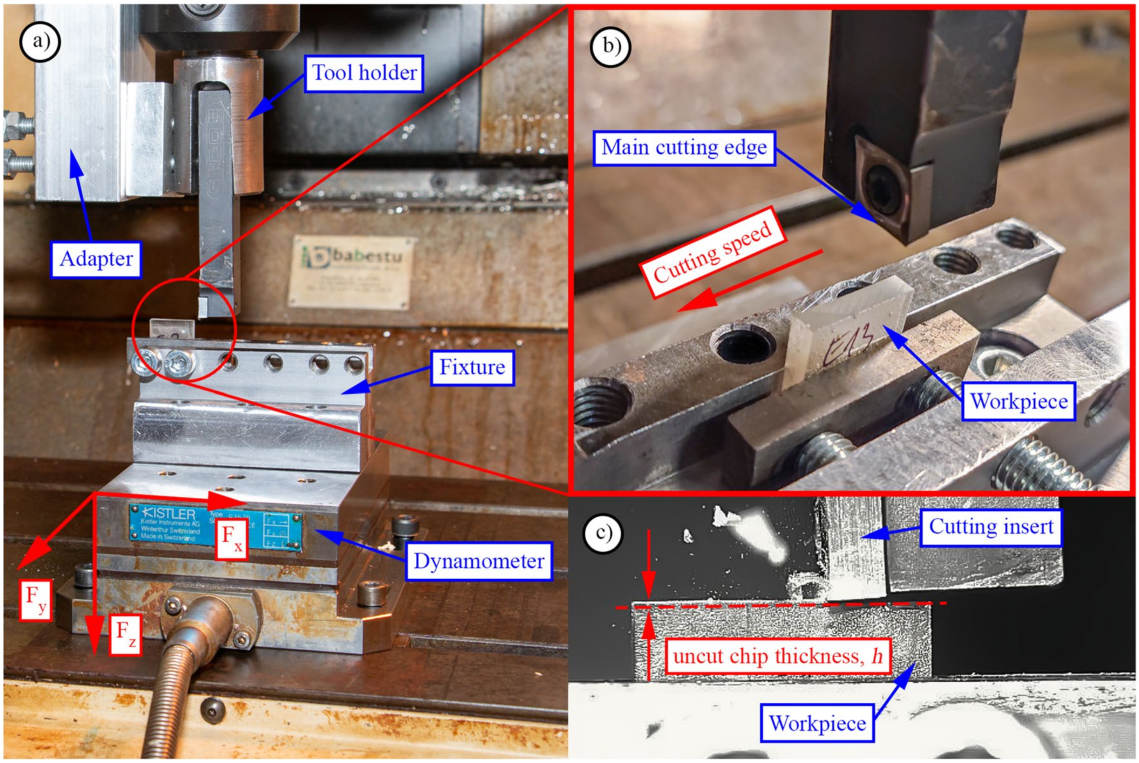


Fig. 1 Orthogonal machining experimental setup: (**a**) fixturing of the cutting tool and workpiece, (**b**) the relative position of the main cutting edge to the workpiece (orthogonal setup), (**c**) the interpretation of uncut chip thickness (h) during orthogonal machining

epoxy system (epoxy monomer: modified bisphenol A/F resin; hardener: modified cycloaliphatic amine hardener; produced by Ipox Chemicals). The components were mixed at room temperature with a mixing ratio of 100:33. The curing process was carried out at room temperature for 24 h, and then a post-curing process was applied at 80 °C for 2 h in a Heraeus UT20 drying oven. The epoxy sheets were cut into 30 × 20 × 6.5 mm workpieces for the machining experiments with a Mutronic Diadisc 5200 cut-off saw. The Charpy impact test specimens were also notched with the same cut-off saw. The ageing was performed in Gestitz 2824, Hungary, for one year. Hungary has a typical continental climate with hot, dry summers and mildly cold, snowy winters [28]. The average annual precipitation across Hungary is 600 mm, the temperatures vary between – 10 and + 30 °C, and the average hours of sunshine vary between 1 700 h and 2 100 h a year [28, 29]. Therefore, a significant polymer degradation was expected during one year of ageing.

The tensile strength and Young modulus of the epoxy specimens were measured by a Zwick Z020 universal tensile tester machine equipped with a 5 kN tensile head according to the ISO 527-1:2019 standard. Five tensile specimens were tested in the case of both materials; the testing speed was set to 5 mm/min. The Charpy impact strength was tested with a Ceast Resil Impactor Junior with a 2 J hammer on five notched specimens of each material according to the MSZ EN ISO 179-1:2010 standard. Shore D hardness was measured according to the MSZ EN ISO 868:2003 standard with a Zwick/Roell H04.3150.000 hardness tester. All the material tests were performed at room temperature and 48% relative humidity. Digital optical microscopy images of the fractured surfaces of the mechanical tests (i.e., tensile test and Charpy impact test) were taken with a Keyence VHX-5000 optical microscope (equipped with a VH-Z20UT VH Zoom Lens with DIC 20x-200x).

Considering the time-consuming preparation of the aged epoxy specimens, the machining experiments were designed using the 2^k full factorial design. The ageing time (A), cutting speed (v_c), and uncut chip thickness (h) as continuous factors were selected to be varied each on two levels, as it is shown in Table 1. Each experimental run was repeated

Table 1 Factors and their levels

Factors		Levels	
		1	2
Ageing time	A (year)	0	1
Cutting speed	v_c (m/min)	10	20
Uncut chip thickness	h (mm)	0.1	0.2

three times to gain sufficient information on the variances. The analysis of variance (ANOVA) was conducted at a significance level of 0.05.

3 Results and discussion

3.1 Material properties

The tensile strength, Young modulus, impact strength and shore D hardness of the aged and freshly manufactured epoxy resins were measured each five times. The tensile curves of the epoxies can be seen in Fig. 2a. It can be clearly seen on the diagrams that the characteristics of the epoxy's tensile curves did not change significantly after the ageing process; however, the strength of the aged epoxy decreased; and the aged tensile specimens were broken at lower strain and stress values. The calculated tensile strengths (σ) of the freshly manufactured and aged epoxy resins are 55.02 ± 7.168 MPa and 14.14 ± 4.090 MPa, respectively. One-way ANOVA results show that the ageing time has a significant influence (F-value = 122.68; P-value = 0.000) on the tensile strength, i.e. the means differ significantly. However, the Young modulus (E) is insignificantly influenced (F-value = 3.2; P-value = 0.111) by the ageing time. The main effect plots of ageing time on the tensile strength and Young modulus are shown in Fig. 2. The tensile test-induced fractures (Fig. 2b) suggest that the freshly manufactured epoxy has a brittle nature as the fractured surfaces are segmented with many craters as a result of the rapid crack propagation during failure. The aged epoxy has a ductile fracture behaviour; the torn and yielded fracture surface suggests that the failure happened in the plastic deformation region of the stress-strain curve.

The Charpy impact strength (KC) of the aged specimens decreased by ~70% compared to the freshly manufactured epoxy specimens'; the ANOVA also showed a significant (F-value = 106.77; P-value = 0.000; $\alpha = 0.05$) effect of the ageing on the impact strength. The Charpy impact test-induced fractures are shown in Fig. 3. These fractures have the same characteristics as the fractured surfaces of the tensile specimens (shown in Fig. 2): freshly manufactured Charpy specimens have a brittle, crack-propagated failure on the surface, while the aged Charpy specimens have a ductile characteristic with a much smoother, torn surface.

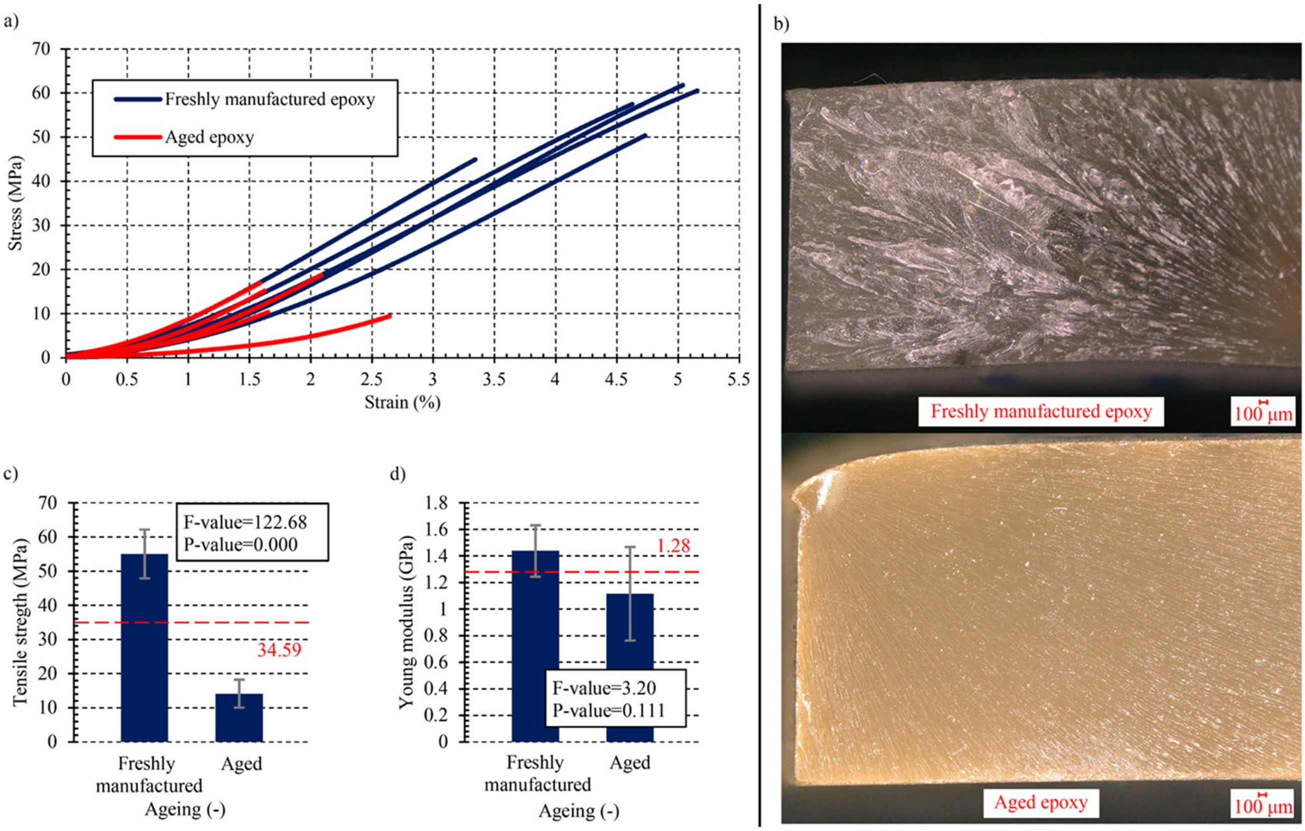


Fig. 2 **a** Tensile curves, (**b**) tensile specimens' representative fractured surfaces, main effect plots of epoxy ageing vs. material properties (with a symmetric error bar of two times the corrected sample standard deviation): (**c**) tensile strength, (**d**) Young modulus

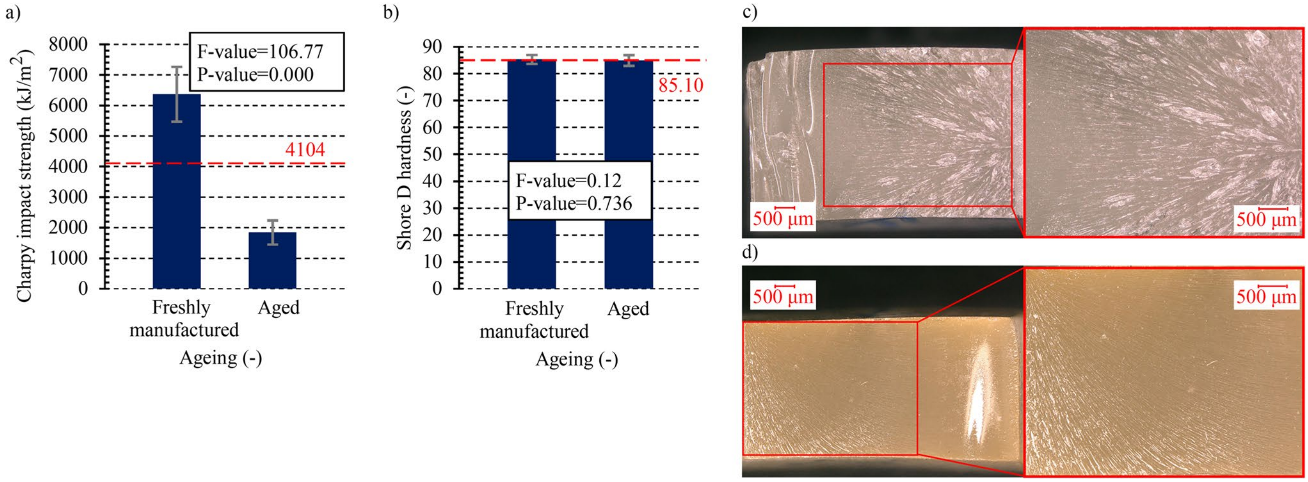


Fig. 3 Main effect plots of epoxy ageing vs. material properties (with a symmetric error bar of two times the corrected sample standard deviation): (**a**) Charpy impact strength, (**b**) Shore D hardness, Charpy impact tests induced fractured surfaces of the (**c**) aged and (**d**) freshly manufactured epoxy resins

The main effect plot of ageing time on the Charpy impact strength is shown in Fig. 3a.

The Shore D hardness values' change is negligible; only an ~ 0.5% decrease can be observed in the case of aged specimens; therefore, the effect of ageing is insignificant (*F*-value = 0.12; *P*-value = 0.736; $\alpha = 0.05$) on the hardness of the epoxy. The main effect plot of ageing time on the Shore D hardness is shown in Fig. 3b.

The measured and calculated material properties are summarised in Table 2. The means of the measured material properties are illustrated in Figs. 2 and 3. The results suggest that during ageing (i.e. UV exposure, moisture and humidity, temperature fluctuation, etc.), the mechanical properties of the epoxy deteriorated, which can refer either to the weakening of covalent chemical bonds between the polymer chains in the crosslinking network (as a result of e.g. UV exposure) or the macroscopic damage of the material (initiation of cracks in the material as a result of e.g. temperature fluctuation).

3.2 Characteristics of cutting force

The cutting force (F_c), which is able to characterise the material removal, is considered to be the maximum of the measured $F_x(t)$ function, while the specific cutting force (k_c) is calculated according to Eq. (2) [30].

$$k_c = \frac{F_c}{h \cdot t} \tag{2}$$

where h denotes the uncut chip thickness, and t is the thickness of the epoxy specimen. The numerical experimental results are listed in Table 3.

Representative cutting force diagrams suggest that the cutting force is significantly smaller in the case of aged epoxy resins than in the case of freshly manufactured epoxies. The main effect of the factors on the specific cutting force can be seen in Fig. 4, and relating ANOVA tables in Table 4. The results show that the influence of the ageing time on the k_c

Table 2 Material properties of the applied epoxy resins, where σ denotes the tensile strength, E is the Young modulus, and KC denotes the Charpy impact strength

No.	Freshly manufactured epoxy				Aged epoxy			
	σ (MPa)	E (GPa)	KC (kJ/m²)	Shore D (-)	σ (MPa)	E (GPa)	KC (kJ/m²)	Shore D (-)
1	50.39	1.148	7.124	83.7	10.36	0.903	1.867	83.3
2	57.49	1.434	5.368	85.8	9.44	0.600	1.356	87.7
3	60.54	1.377	6.618	86.1	18.76	1.307	2.395	85.8
4	44.93	1.630	7.246	85.2	16.99	1.333	1.615	86.0
5	61.78	1.597	5.467	85.7	15.18	1.434	1.984	81.7
Mean	55.02	1.437	6.365	85.3	14.14	1.115	1.843	84.9
s^2	7.168	0.194	0.897	0.951	4.090	0.352	0.392	2.380

Table 3 Experimental design table, where v_c is the cutting speed, *h* is the uncut chip thickness, *A* is the ageing time, *t* denotes the thickness of the epoxy specimen, F_c is the cutting force, k_c is the specific cutting force, *Ra* is the average surface roughness, and *Rz* is the roughness depth

No.	Factors			t	Responses				
	v_c	h	A		F_c	k_c	Ra	Rz	Rz/Ra
	(m/min)	(mm)	(year)	(mm)	(*N*)	(*N*/mm^2)	(μm)	(μm)	(-)
1	20	0.2	0	6.73	49.19	36.54	41.23	194.80	4.72
2	20	0.2	1	6.38	44.87	35.17	37.40	192.27	5.14
3	10	0.2	1	6.60	58.03	43.97	35.93	171.97	4.79
4	20	0.2	1	6.75	43.55	32.26	45.35	220.00	4.85
5	10	0.2	0	6.33	201.93	159.51	34.29	173.57	5.06
6	10	0.1	0	6.67	70.10	105.09	0.76	9.30	12.29
7	10	0.1	1	7.28	55.59	76.36	0.59	6.47	10.96
8	10	0.1	1	7.02	49.34	70.28	0.49	5.80	11.84
9	10	0.2	0	5.21	60.00	57.58	34.64	195.83	5.65
10	10	0.1	0	5.95	71.81	120.69	7.72	54.57	7.07
11	20	0.1	0	5.68	50.97	89.74	4.04	35.63	8.81
12	20	0.1	0	5.10	45.47	89.15	1.10	14.40	13.13
13	20	0.2	0	6.38	87.22	68.36	38.30	182.77	4.77
14	10	0.2	1	6.84	65.73	48.05	45.28	208.80	4.61
15	10	0.2	0	5.91	184.63	156.20	38.81	189.93	4.89
16	20	0.1	0	6.48	53.71	82.89	6.93	48.43	6.99
17	10	0.2	1	6.70	214.43	160.02	50.65	215.43	4.25
18	20	0.2	1	6.39	71.76	56.15	35.32	166.90	4.73
19	20	0.2	0	5.60	98.04	87.53	38.37	186.50	4.86
20	10	0.1	0	6.26	63.86	102.02	0.89	9.67	10.86
21	20	0.1	1	6.21	5.93	9.54	3.29	21.63	6.58
22	20	0.1	1	6.12	46.24	75.55	17.28	95.00	5.50
23	20	0.1	1	6.83	49.65	72.69	21.26	109.23	5.14
24	10	0.1	1	6.43	33.68	52.38	0.57	7.53	13.29

is the most significant (*F*-value = 5.85, *P*-value = 0.028), followed by the cutting speed (*F*-value = 5.68, *P*-value = 0.030). The influence of the uncut chip thickness (i) on the cutting force is significant (*F*-value = 7.34, *P*-value = 0.015), and (ii) on the specific cutting force is not significant, as it was expected based on Eq. (2). The main effect plots show that the larger the cutting speed, the smaller the specific cutting force. The larger cutting speed results in a larger cutting temperature-induced material softening and a larger rate of deformation-induced decreases in the ultimate elongation to fracture [22]; the larger speed will, therefore, lower the cutting energy needed for chip removal. The main effect plot of ageing time confirms that the older the epoxy resin, the significantly lower the specific cutting force is. This is in good agreement with the material testing results (Table 2).

3.3 Characteristics of the machined surfaces

The characteristics of machined surface roughness is analysed through the *Ra*, *Rz* and *Rz/Ra* measures. The calculated surface roughness parameters are listed in Table 3. The main effects of the cutting speed, uncut chip thickness and ageing time on the average surface roughness and the roughness depth can be seen in Fig. 5. The nominal results show that the larger the cutting speed and the ageing time, the slightly larger the *Ra* and *Rz* parameters. However, these effects were found to be insignificant at the significance level of 0.05. The influence of the cutting speed on the *Ra* is often parabolic [25, 31]; therefore, the influence of the v_c should be investigated in the future on more than two levels and a wider scale (e.g. five levels according to the central composite inscribed (CCI) experimental design plan, using an advanced machine tool which can provide at least 40,000–50,000 mm/min max. speed along one of the horizontal axis). On the other hand, the influence of the uncut chip thickness on the analysed surface roughness indicators is significant (*F*-value = 272.74, *P*-value = 0.000 for the *Ra* and *F*-value = 255.95, *P*-value = 0.000 for the *Rz*), as shown in Table 5. The larger the uncut chip thickness, the significantly larger the surface roughness. Tapoglou and Makris [32] observed a similar trend in the influence of uncut chip thickness on the *Ra* when machining polyether ether ketone (PEEK). It is well known that the chip cross-section significantly influences the second moment of area; thus, the

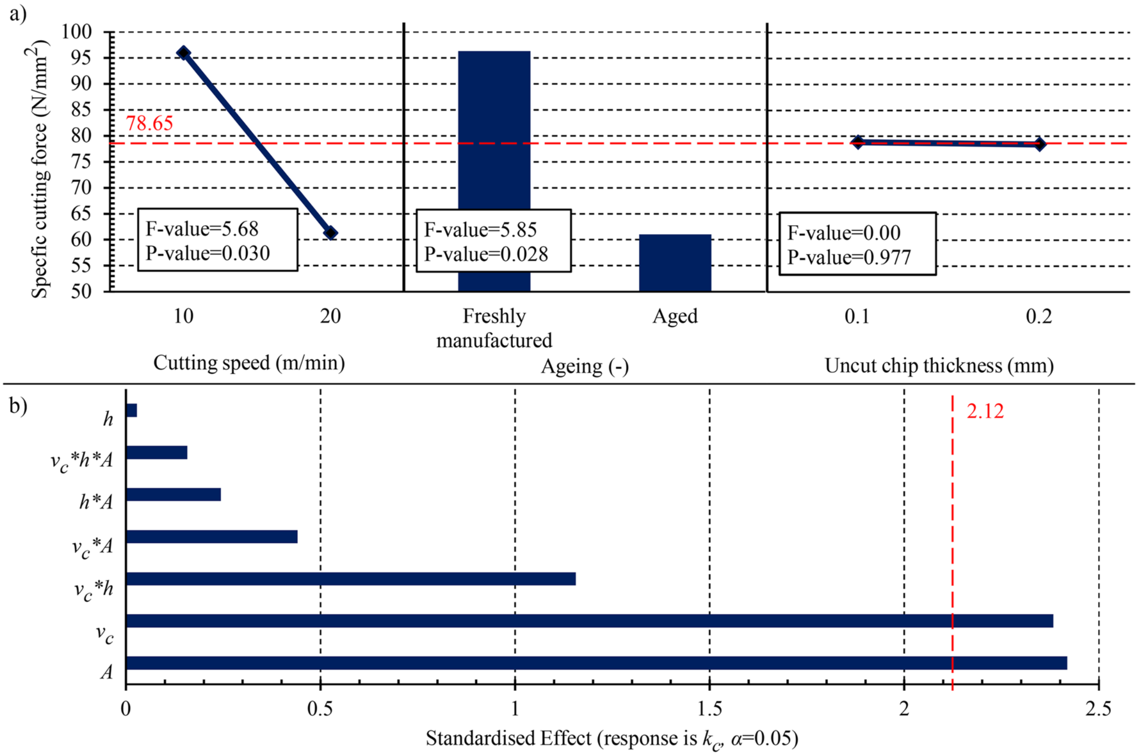


Fig. 4 **a** Main effect of the cutting speed (v_c), uncut chip thickness (h) and ageing time (A) on the specific cutting force (k_c) and the (**b**) Pareto chart of the standardized effects of factors and their interactions on the k_c

Table 4 Analysis of variance (ANOVA) tables for the F_c ad k_c response values

Source	DF	F_c (*N*)				k_c (*N*/mm^2)			
		Adj SS	Adj MS	*F*-value	*P*-value	Adj SS	Adj MS	*F*-value	*P*-value
Model	7	31577.7	4511.1	2.34	0.076	16740.1	2391.44	1.88	0.140
Linear	3	27570.4	9190.1	4.76	0.015	14682.9	4894.3	3.84	0.030
v_c	1	9701.7	9701.7	5.03	**0.039**	7230.1	7230.14	5.68	**0.030**
h	1	14164.9	14164.9	7.34	**0.015**	1.1	1.06	0	0.977
A	1	3703.8	3703.8	1.92	0.185	7451.7	7451.7	5.85	**0.028**
2-way interactions	3	3997.6	1332.5	0.69	0.571	2025.4	675.14	0.53	0.668
$v_c \cdot h$	1	3693.2	3693.2	1.91	0.185	1701.3	1701.3	1.34	0.265
$v_c \cdot A$	1	116.7	116.7	0.06	0.809	248.2	248.23	0.19	0.665
$h \cdot A$	1	187.7	187.7	0.1	0.759	75.9	75.89	0.06	0.810
3-way interactions	1	9.7	9.7	0.01	0.944	31.8	31.76	0.02	0.876
$v_c \cdot h \cdot A$	1	9.7	9.7	0.01	0.944	31.8	31.76	0.02	0.876
Error	16	30866.2	1929.1			20373.5	1273.34		
Total	23	62443.9				37113.6			

energy needed for chip removal; therefore, the epoxy resins are expected to behave more brittle than ductile. This transition in material behaviour from ductile to brittle will result in a more fractured machined surface; thus, a rougher surface.

Representative machined 3D surface profiles of freshly manufactured and aged epoxy resins at various uncut chip thicknesses and cutting speed values can be seen in Fig. 6.

The influence of the uncut chip thickness on the machined surface can be clearly seen; furthermore, the slight effect of the cutting speed is also visible. Significantly deeper craters are visible on the surfaces machined at the larger h, while the surface is smoother at the smaller h. The 3D microscopic images confirm the insignificance effect of the A on the surface quality. These results suggest that there is no significant influence on the machining of aged

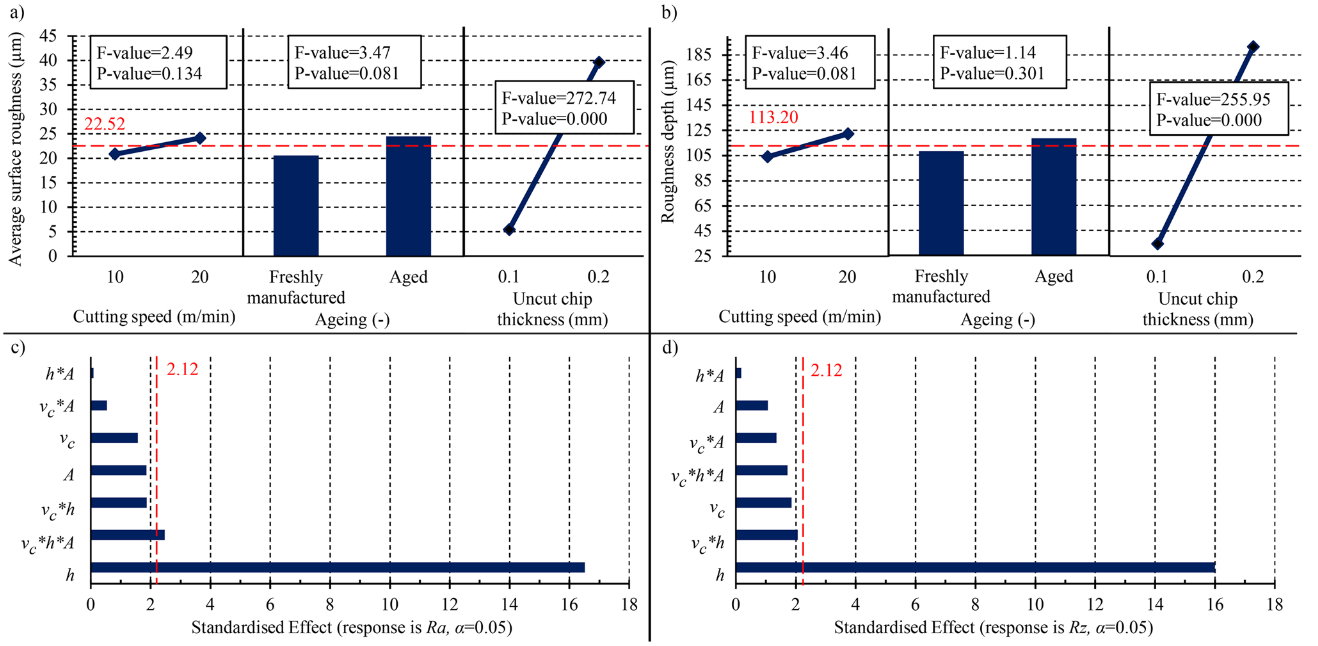


Fig. 5 Main effect of the cutting speed (v_c), uncut chip thickness (h) and ageing time (A) on the (**a**) average surface roughness (Ra) and the (**b**) roughness depth (Rz), and the (**c**, d) corresponding Pareto charts of the standardized effects

Table 5 Analysis of variance (ANOVA) tables for the *Ra* and *Rz* response values

Source	DF	Ra (μm)				Rz (μm)			
		Adj SS	Adj MS	*F*-value	*P*-value	Adj SS	Adj MS	*F*-value	*P*-value
Model	7	7435.57	1062.22	41.23	0.000	155349	22193	38.53	0.000
Linear	3	7180.38	2393.46	92.9	0.000	150090	50,030	86.85	0.000
v_c	1	64.17	64.17	2.49	0.134	1993	1993	3.46	0.081
h	1	7026.85	7026.85	272.74	**0.000**	147439	147439	255.95	**0.000**
A	1	89.36	89.36	3.47	0.081	658	658	1.14	0.301
2-way interactions	3	97.96	32.65	1.27	0.319	3544	1181	2.05	0.147
$v_c \cdot h$	1	90.13	90.13	3.5	0.080	2466	2466	4.28	0.055
$v_c \cdot A$	1	7.62	7.62	0.3	0.594	1058	1058	1.84	0.194
$h \cdot A$	1	0.21	0.21	0.01	0.929	20	20	0.03	0.856
3-way interactions	1	157.24	157.24	6.1	0.025	1715	1715	2.98	0.104
$v_c \cdot h\, A$	1	157.24	157.24	6.1	0.025	1715	1715	2.98	0.104
Error	16	412.22	25.76			9217	576		
Total	23	7847.8				164566			

epoxy resins from the point of view of machined surface characteristics.

Figure 7 shows the measured roughness depth values relative to the average surface roughness values. The characteristics of *Rz/Ra* parameters are similar in both fresh and aged epoxies, i.e. the slope of the fitted line and the nominal value of *Rz/Ra* parameters are 4.9 and 4.7, respectively. This proportion suggests that the dominance of outlier peaks and valleys is not significant, not like it is observable in machined surfaces of fibrous polymeric composites (*Rz/Ra* is between 6 and 16 depending on the number of fibre pull-outs and uncut fibres [33]). The relatively large coefficient of determination values (R^2= 0.9927–0.9952) indicate that the fitting of measurements to the nominal line is appropriate, i.e. the *Rz/Ra* value is independent of the varied factors (cutting speed and uncut chip thickness). It is observable in Fig. 7 that the measurements are mainly located in two regions, namely Region A and Region B. While Region A includes the measurements of surfaces machined with smaller uncut

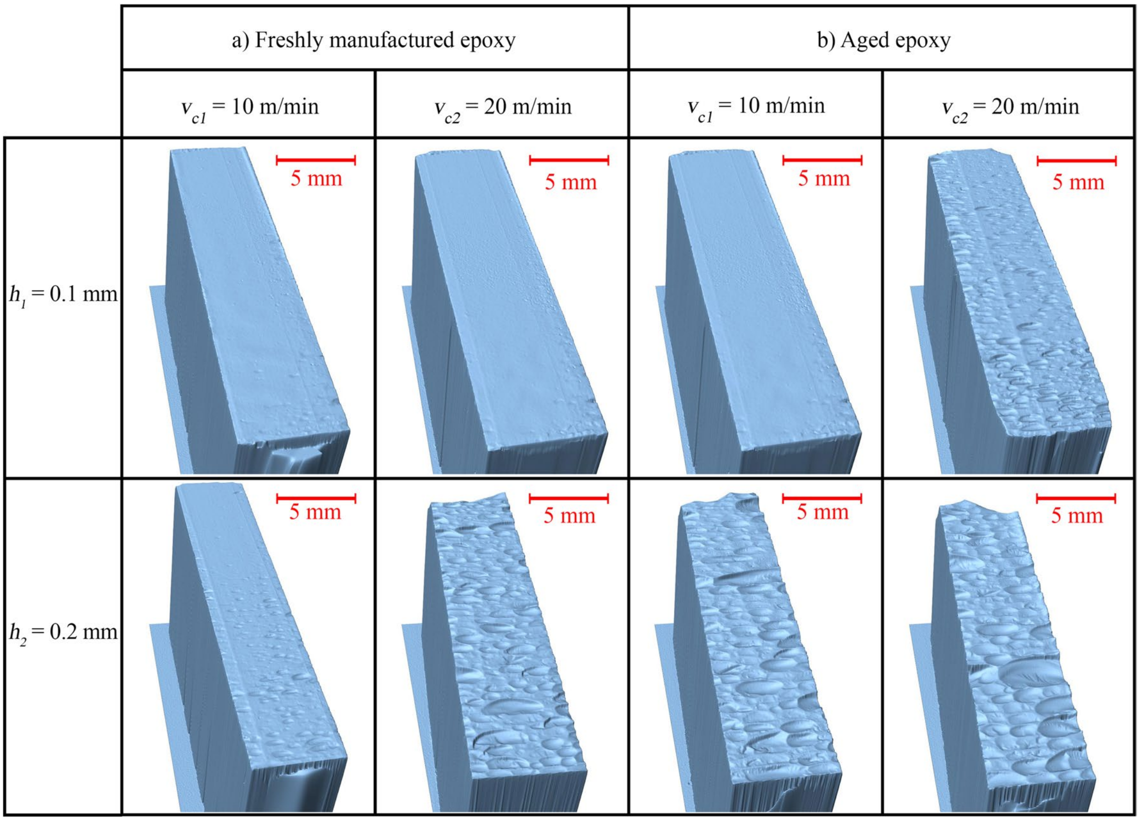
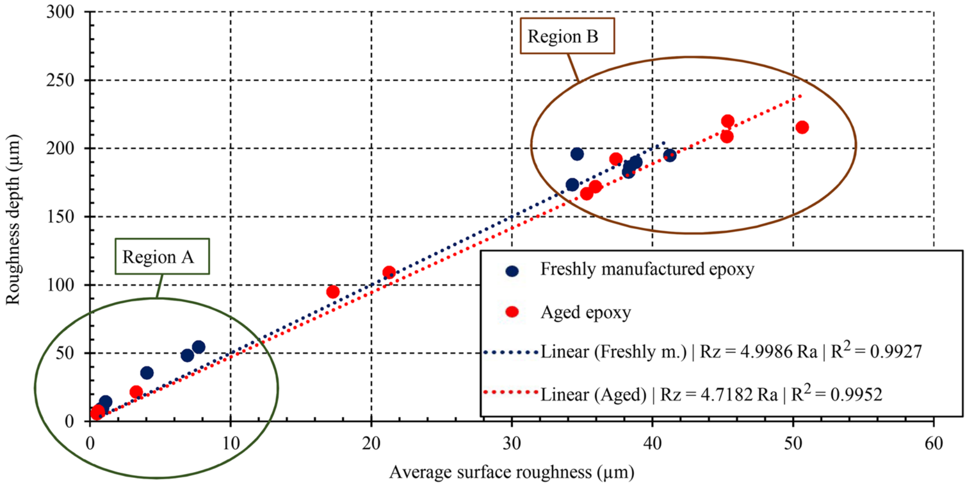


Fig. 6 Representative machined 3D surface profiles of (a) freshly manufactured and (b) aged epoxy resins at various uncut chip thicknesses and cutting speed values

Fig. 7 The ratio of roughness depth (*Rz*) to the average surface roughness (*Ra*) in the case of orthogonal machining of freshly manufactured and aged epoxy resins



chip thickness, Region B corresponds to the experimental results gained through the larger uncut chip thickness values. The significant separation of these regions proves that the influence of the uncut chip thickness on the machined surface characteristics is crucial.

4 Discussion and outlook

The experimental results showed that the tensile and impact strengths of the applied epoxy degraded significantly due to the ageing procedure. Furthermore, the cutting energy needed for chip removal was also found to be smaller in the case of the aged epoxy specimens. These findings are in good agreement, as the lower the strength, the lower the expected resistance of the composite against cutting. On the other hand, the ANOVA results proved that ageing has an insignificant influence on the Young modulus and Shore D hardness. Although ANOVA proves these significances and insignificance of the influences of the analysed factors, the increase of the factor range would affect them, i.e. the significantly more extended ageing and larger range of analysed cutting speed may result in significantly different chip removal and material properties. These are the focus of further investigations.

Current experimental findings are useful for designing and optimising the machining of pure epoxy resins, whether they are freshly manufactured or at the end of the product's life cycle. On the one hand, the results are especially valuable for those manufacturing departments where the existing and used epoxy resin parts must be mechanically machined (hole-making for assembly, edge preparation, etc.) due to renovation or maintenance. According to the experiences gained, a sharper cutting edge is recommended for machining aged epoxy resin, as the material removal resistance is smaller, enabling the cutting edge to be sharper and less robust. Furthermore, the smaller uncut chip thickness (i.e. smaller feed in drilling or milling) is recommended for better surface quality. On the other hand, we propose to widen the cutting tool portfolio of tool manufacturers for providing suitable tool geometries for fresh and aged thermosetting polymers, as a sharper and weaker tool geometry (i.e., larger positive rake and clearance angles, smaller cutting edge radius) would be more beneficial for effective cutting of mechanically degraded aged polymers. However, the cooling may further increase the rigidity of the aged polymers; thus, cooling of aged epoxies is not recommended. This is beneficial because dry conditions are more sustainable than cooling liquids.

Although the current study focuses on the machinability of pure epoxy resins, these results can be applied to the technology planning of fibrous polymeric composites, especially carbon fibre-reinforced thermosetting polymer (CFRP) composites. The finite element analysis (FEA) and optimisation of CFRP composites requires the proper definition of each composite ingredient's material properties and chip removal characteristics, i.e., carbon fibres, non-reinforcing fibres and epoxy matrix. Therefore, knowing the machinability indicators of pure thermosetting epoxy resin is essential in determining optimal machining conditions through FEA.

The result of the study proves the significant difference in chip removal of aged and freshly manufactured epoxy resins; however, there are many limitations that have to be pointed to for further work. For example, natural ageing has the benefit that it is closer to the real load of parts than artificial ageing. However, this is less controllable and, thus, difficult to reproduce. Furthermore, the ageing time was analysed in this study only on two levels (0 and 1 year), which enables us to determine the significance of its influence; however, the proper effect curve till the end of the life cycle of epoxy products (which may be more than 10 years) is still unknown.

The applied machining length (*cc.* 30 mm) was minimised due to material and workspace (measuring range of the dynamometer) limitations; therefore, the cutting temperature couldn't be measured and analysed. The significantly longer machining length may result in enough time for cutting-induced heat generation and conduction, which may have a significant influence on the machining performance and surface characteristics if it approaches the glass transition temperature (T_g) of epoxy resin.

In the future, huge attention will be given to the applications of sustainable technical polymeric materials, as the current thermosetting polymers are irreversible and challenging to recycle or reuse. Polyimine vitrimers were introduced a few years ago that behave like a thermosetting polymer below a vitrimeric transition temperature (T_v) and like thermoplastics above it [34]. These sustainable vitrimers will therefore, possibly replace current thermosetting polymers in the future. Therefore, the cutting mechanisms and properties of vitrimers have to be investigated shortly to support the sustainability aspirations of society and governments. Another future research may be governed by the improvement of the machinability of aged polymers by applying smart particles or fillers.

5 Conclusions

In the present study, the machineability of aged and freshly manufactured pure epoxy resins were investigated through orthogonal machining experiments. Half of the epoxy specimens were aged in a continental climate environment for a year, while the other half was manufactured prior to the orthogonal machining experiments. According to the present study, the following conclusions can be drawn.

One-way ANOVA results show that the ageing time has a significant influence on the tensile strength and Charpy impact strength. However, the Young modulus and the Shore D hardness are insignificantly influenced by the ageing time. The one year of natural ageing significantly degraded the tensile and impact strengths of epoxies by 74.6% and 71.1%, respectively.

The experimental results show that the influence of the ageing time on the specific cutting force is the most significant, followed by the cutting speed. The influence of the uncut chip thickness on the cutting force was also found to be significant. The main effect plot of ageing time confirmed that the older the epoxy resin, the significantly lower the specific cutting force is. This is in good agreement with the material testing results.

It was shown that the influence of the uncut chip thickness on the analysed surface roughness indicators is significant. The larger the uncut chip thickness, the significantly larger the surface roughness. However, the 3D microscopic images confirm the insignificance of the effect of the ageing time on the surface quality. These results suggest that there is no significant influence of the machining of aged epoxy resins from the point of view of machined surface characteristics.

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Data availability Machining of freshly manufactured and aged epoxy resins.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

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