

Plastic Deformation, Mechanical and Adhesive Properties of Bio-Plastic Material

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ABSTRACT

Given the added need for eco-friendly material, environmental scientists are constantly on the look-out for new solutions. In this respect, biodegradable polymer proved to be a promising one. The Selfix material, being a bio-plastic, is biodegradable and, unlike other plastic products, can be considered feasible for the industry as a smart material capable of biodegrading at the end of its life cycle. Using Selfix, waste paper can be re-used, thus eliminating the need for recycling and helping to reduce the CO₂ emissions. The present paper develops 3D models with Selfix material to offer benefits such as easy-cutting and sticking properties in a way that can be educational for children. We examine the mechanical properties of this material using tensile testing, laser-cutting, CNC milling, surface roughness and also scanning electron microscope or SEM.

Keywords: Scanning Electron Microscope (SEM); Computer Numerical Control (CNC); heat shape mould; mechanical properties of bio plastic; waste management; adhesives behaviour; biodegradable polymers.

INTRODUCTION

With the new environmental policies and legislation implemented in different parts of the EU, landfills are being slowly eliminated in this part of the world. Up to now, the main ways to deal with waste included incineration, energy recovery comprising gasification pyrolysis and composition, as well as separating and reusing as a second option. Lately, numerous governments have introduced new innovative ways as regards the environment [1, 2].

Therefore, with the aim to keep the environment safe and regulate the use of natural sources, certain countries have started to introduce new policies. Among these, the UK has come up with a series of tools and approaches such as trading systems, environmental taxation, and voluntary agreements intended for large companies to reduce paper and cardboard waste, for example. There, paper and cardboard, which can be collected, recycled and reused easily, constitute the material that is predominantly left over as waste in commerce [3, 4].

In line with these efforts, a new material created by the Selfix Technology Company in UK may be used as recycled paper and cardboard for producing 3D objects and boxes. The present research attempts to demonstrate the Selfix technology as well as find further solutions for similar environmental problems and examine the potential effects [5].

Selfix is produced from a combination of polylactide (PLA), Poly-3 hydroxybutyrate (PHB), cellulose, and starch (C₆H₁₀O₅), all available in large quantities from natural sources and having the ability to absorb humidity. One can obtain biodegradable adhesives with novel adhesion behavior from these materials when exposed to water, with no eventual harmful impacts on the environment. In detail, a smart polymer comes in the shape of a thin plastic sheet, which shows adhesive behavior when wet by water, and can be used to glue cardboards, paper and wood. Interestingly enough, Selfix can be shaped into any desired form or dimensions. As a non-toxic biodegradable product, it is also characterized by a

low melting temperature and begins to soften up at about 60°C. The applications for this material are numerous, namely for home use, in prototyping, jewellery, toy-making, mould formation, and many others. The Selfix material can be turned into mould within two minutes – that is when it begins to gradually harden. The material, though, can be heated again and again for continuous work. Selfix is ideal for creative work and adding entertainment to education, regardless of the target group, apart from the applications in 2D and 3D design and modelling [5, 6].

The samples of Selfix (Figure 1) are examined and tested using different techniques in the following sections.

TECHNIQUES AND PROCEDURES

The first experiment involved a tensile test as a means to determine the mechanical properties and behaviors of this material using axial loading. The tensile test was applied to stretch a sample to the breaking point and to see the extent of such stretch elongation. In this way, it was possible to calculate the stress (σ) from the load



Fig. 1. Selfix material disk

and the strain (ϵ) from the extension in the form of plotting nominal stress against nominal strain or as true stress against true strain. These relations vary in each graph and are controlled by a computer software for monitoring and registering the outcomes [7, 8, 9].

Here, like many other cases and materials, laser cutting exposes the material to heat from a laser beam controlled with CorelDraw software [10].

Apart from the laser, CNC milling – again a common technique in various complex operations such as slot cutting, planning, drilling, re-bating, routing, etc. – operates on 3-axes and comprises a surface moving horizontally along the X and Y axes, and vertically along the Z axes for depth [11, 12].

The surface roughness measurements were conducted to identify the kind of interaction between the material and the surroundings as well as to predict the mechanical performance, ideal roughness, and surface qualities in the machined material [13, 14].

Here, again, these estimates were carried out using software for the centre-line average (CLA) and Roughness average (Ra). For this purpose, a surface profilometer was used with a contact stylus to achieve the maximum accuracy and efficiency. Once the surface analysis was complete, other factors were also determined through the comparison of all the peaks and valleys with the mean line [15, 16].

The scanning electron microscope (SEM), using a targeted beam of high-energy electrons, produces an array of signals on the surface of the samples. As an outcome of the interaction between the electrons and the surface of the sample, these signals contain the data pertaining to outer morphology or texture, chemicals available, crystalline formation, and the orientation of the material within the specimen [17, 18].



Fig. 2. Tensile testing machine & laser cutting machine



Fig. 3. CNC milling machine & surface roughness measurement

RESULTS AND DISCUSSION

Results of tensile testing for specimens from selfix plastic material

As stated earlier, in the lab, the CorelDraw software was employed to make a drawing of the Selfix plastic specimens for subsequent laser cutting and tensile testing. These were carried out to reveal certain mechanical and adhesive characteristics. Figure 5 and 6 shows the specimens from a Selfix plastic disk and the sample broken after test.

The initial results point to the stress and strain curve as well as the mechanical properties of the specimens for Selfix plastic disk (Table 1 and Graph 1).

Figures 7 and 8 show the sheets cut from the Selfix which are bound together with no difficulty by simply wetting the material and sticking them together, ultimately to determine the adhesive qualities. The second result was related to the stress and strain curve as well as the specimen properties of the sheets put together by wetting (Table 2 and Graph 2).



Fig. 4. Scanning electron microscope in the lab

Figures 9 and 10 show sheets of specimen when glued to cardboard and upon completing the tensile tests to reveal the adhesive qualities. Here, a break can be spotted in the cardboard without any tear signs on the Selfix plastic sheet.

Finally, the third related result concerns stress and strain curves as well as the adhesive qualities of the samples stuck on cardboards. Accordingly, one can observe that the Selfix plastic sample maintains strength better than the cardboard. With additional improvements, this material is expected to become even more durable; hence, other applications and extended use in different areas is possible. The Table 3 highlights the precise



Fig. 5. Cut specimens from Selfix plastic disk by laser cutting

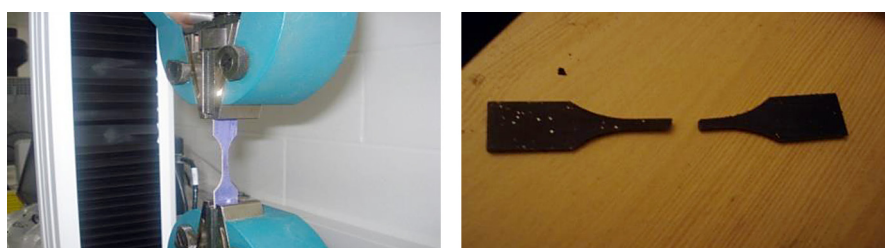


Fig. 6. The specimen in machine & the specimen broken after test

dimensions of the Selfix plastic sheet(s) stuck to cardboard and used for tensile testing (Graph 3).

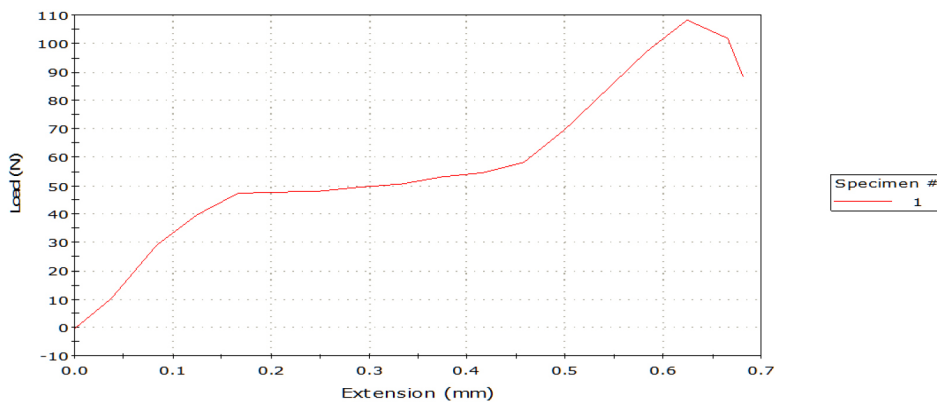
Analysis of tensile test results

In the Graphs 1, 2 and 3 of tensile test, all specimens show a relative and acceptable bonding strength. Since Selfix is an adhesive, numerous forms of testing can be carried out to measure its quality; among them, peel testing is best applied to determine adhesive properties. Here, the strength in bonding between the bio polymers available in various mixtures with cardboard helps

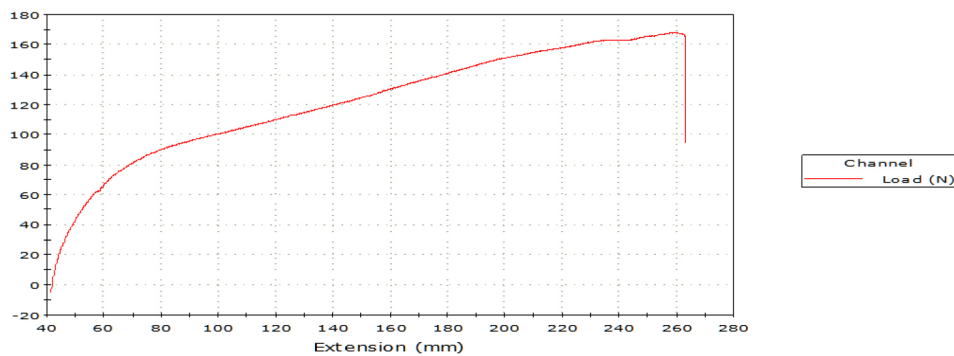
with high levels of resistance against pressure, causing the bond to last longer than expected. As per the curves, one can observe various characteristics, all due to the sheet being highly elastic and modulus and the disk being low in these regards given flexibility and collapse factors.

Results of laser cutting on selfix material

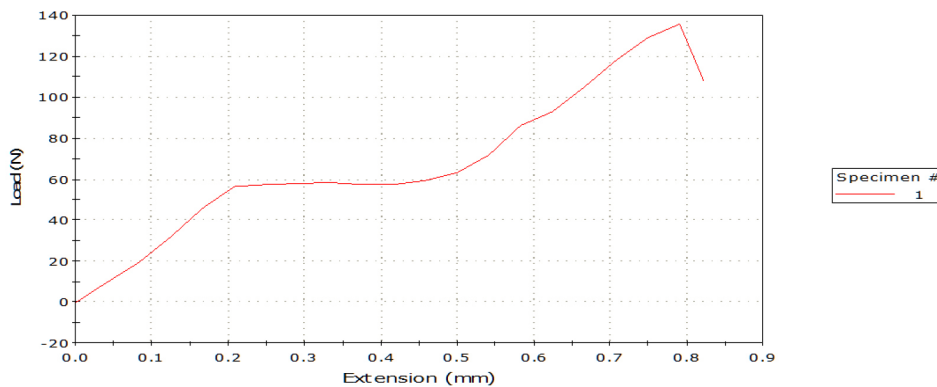
For laser cutting, various settings were tested to find the best one for the Selfix plastic material. On the basis of our observations, the ideal speed



Graph 1. Extension vs load specimen for Selfix plastic disk



Graph 2. Extension vs load specimen for Selfix plastic sheet sticking them together



Graph 3. Extension vs load specimen for Selfix plastic sheet with cardboard

Table 1. Dimensions and mechanical properties of specimen for Selfix disk

Specimen label	Thickness (mm)	Width (mm)
Selfix plastic disk	19.63000	20.00000
Length (mm)	Area (cm ²)	Maximum Extension (mm)
40.00000	3.92400	0.68079
Tensile stress at Maximum Extension (MPa)	Maximum Load (N)	Extension at Maximum Load (mm)
0.22485	107.20584	0.62358

Table 2. Dimensions and mechanical properties of specimen for Selfix plastic sheet sticking them together

Specimen label	Width (mm)	Area (mm ²)	Maximum load (N)
Selfix plastic sheet which, sticking together	15.00000	6.00000	168.12
Extension at Maximum Load (mm)	Tensile stress at Maximum Load (MPa)	Modulus (E-modulus) (MPa)	Comment
259.40908	28.02070	41.03	-
Load at Maximum Tensile stress (N)	Extension at Maximum Tensile stress (mm)	Extension at Break (Cursor at break) (mm)	Load at Break (Cursor at break) (N)
168.12421	259.40908	76.57576	87.43249

Table 3. Dimensions and mechanical properties of specimen Selfix plastic sheet with cardboard

Specimen label	Thickness (mm)	Width (mm)
Selfix plastic material	10.00000	23.00000
Length (mm)	Area (cm ²)	Maximum Extension (mm)
43.00000	2.30000	0.82248
Tensile stress at Maximum Extension (MPa)	Maximum Load (N)	Extension at Maximum Load (mm)
0.46972	135.60186	0.79157

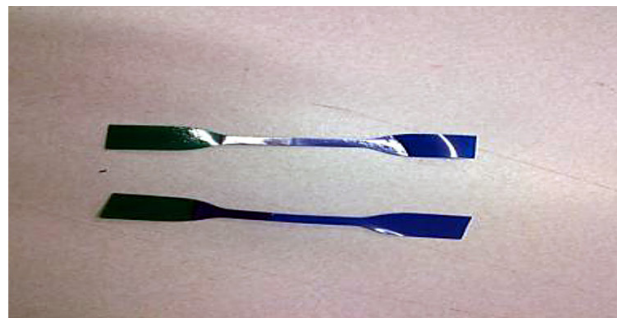


Fig. 7. Another specimen after remove from Selfix plastic sheet



Fig. 8. Selfix plastic sheet pieces which sticking them together

is 4% with 75% power. However, once tried in terms of manufacturability, the material started to melt and fuse. Because cutting with laser involves the concentration of high-density beams on the samples, excessive heat is generated upon the point of contact (Figure 12 show some shapes which were cut in different setting).

The Figure 13 represent the shapes created with laser and under different conditions. Among its other uses, Selfix appears in toys and other educational tools for children. With Corel Draw,

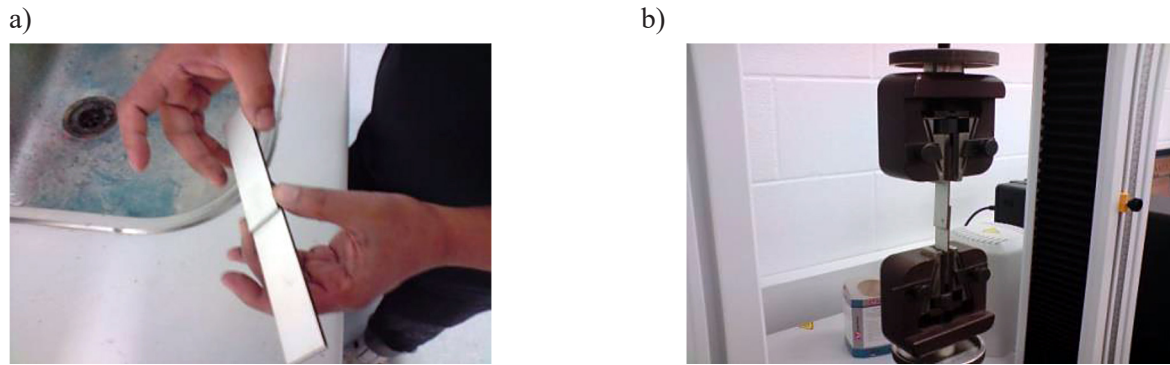


Fig. 9. a) Wetting the Selffix plastic to sticking with cardboard, b) Specimen for Selffix plastic with cardboard in machine



Fig. 10. Selffix did not break, in contrast to the cardboard (adhesion property for Selffix plastic)



Fig. 11. Focusing gauge of laser cutting



Fig. 12. Cut square shape and circle shape of Selffix plastic

such gear in different sizes were designed and cut with laser. In these gears, Selffix plastic can also serve as an adhesive to join parts for the transfer of motion from motor or pedal to any other part.

Analysis of laser cutting results

One has to note that laser may not be the best option to cut Selffix as the substrate can burn and, hence, necessitate further cleaning of

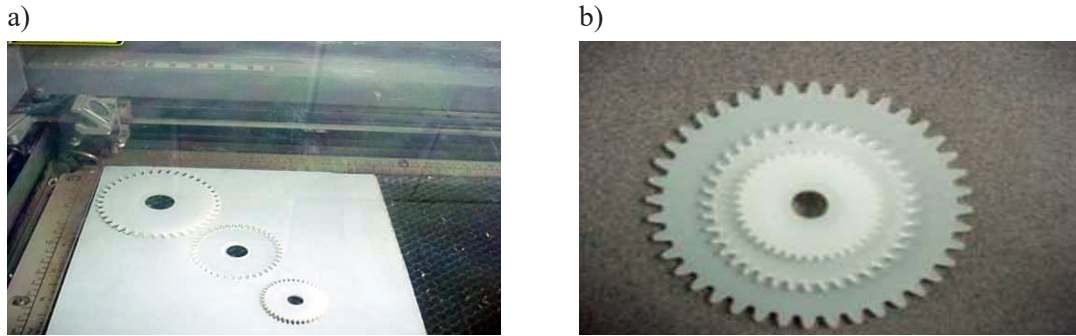


Fig. 13. a) Cutting gears from Selfix plastic by laser cutting, b) Three gears stuck together by using the adhesion behaviour



Fig. 14. The drilling in vertical position & Selfix disk after cut



Fig. 15. Square shapes from selfix disk & square shapes with dust

the edges before any later use. This is due to Selfix sheets being highly prone to heat, quickly melting as a result. For this reason, ideal sizes could not be achieved when cutting the piece, despite the ease of cutting itself. A less powerful beam was also tried and applied, but with no satisfactory outcome.

As to the Selfix disk, acceptable results were obtained in comparison to other sheet samples. Despite a repeated experiencing of burn on the disk, the resistance proved to be greater than in the sheet. Laser cutting went smoothly, with reduced time to manufacture due to speedy shaping of the profile. The disk sample was more workable due to particle distribution and bonding being robust and uniform

in comparison to the sheet sample. Another highlight during this process was that no dust was formed and the tool remained stable regardless of the machining speed, thus enabling safe and clean operations.

Results of milling machine on selfix material

Milling was applied to the Selfix material to cut shapes, which were later compared to those cut by laser. For this purpose, the surface roughness was assessed using an SEM.

The Figures 14 and 15 show the square shapes formed using a milling machine with proper feed rate used in the workshop.

Analysis of the milling results

It was observed that while cutting Selfix by a milling machine, the substrate material was deformed on the surface and, hence, needed to be removed from the edges on the Selfix material. The milling operations were also applied and tested on the Selfix disk, which caused the entire machine to shake due to its hardness. In addition, cutting at higher speeds generated a lot of heat within the contact zone between the tool and the work piece. Dust was also formed as a result of milling.

Under normal conditions, coolants are applied to reduce heat within the contact zone; yet, given the biodegradable nature of this polymer, such an application could result in sticking of the piece to the work bench or other unanticipated formations. This limitation makes cutting Selfix even more challenging.

The samples made during the research were found to have satisfactory surface finish and pleasant appearance. Above all, the amount of time spent to produce them was much less than in the case of other materials. It can be stated that combining Selfix with calcium carbonate can be a useful way to reduce the operation time.

Results of surface roughness measurement

In the lab, many points were marked on the Selfix surface after cutting. The process to measure surface roughness was carried out with a stylus-type instrument in order to examine the texture. The Figure 16 show the stylus measurements for the points marked for laser cutting as well as those for milling.

The following measurement parameters were applied in this work:

- Ra: Roughness average
 - Rz: (DIN) Mean peak-to-valley height
 - Rz: (ISO) Ten point height
 - Rmax: Maximum peak-to-valley height
 - Rt: Vertical height between max/min
 - Ry: Maximum roughness depth
 - Rq: RMS of roughness average
 - Rp: Maximum peak height
 - Ssk: Skewness
 - Kku: Kurtosis
- Rq: calculated by taking the root mean square in the series of measurements of deviations from the centerline; and
 - Rz: the average of the five highest and the five deepest valleys within the sampling length, measured from a line parallel to the mean line.

The results are commonly obtained from the graphs; however, in lab settings, these calculations are conducted by the computer. The Graphs 4–7 show us how measure many points for surface of the Selfix material. First point for Selfix by milling machine.

Selfix milled sample

For surface roughness, the amplitudes of peak were investigated. If the graph appears in a straight line, it means that the surface is smooth. However, these graphs reveal large amplitudes of peaks, indicating roughness.

Graph 4 shows milled surfaces along the thickness at position one.

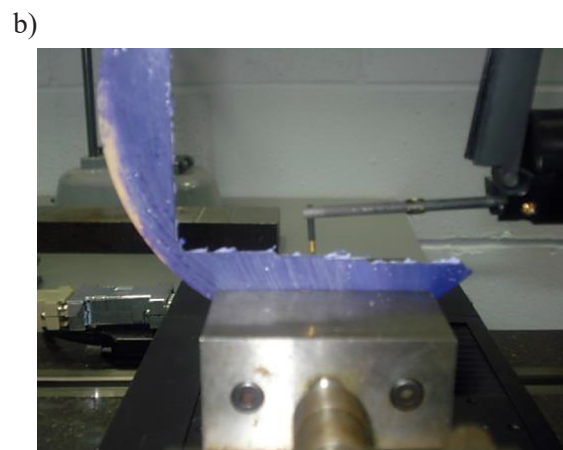
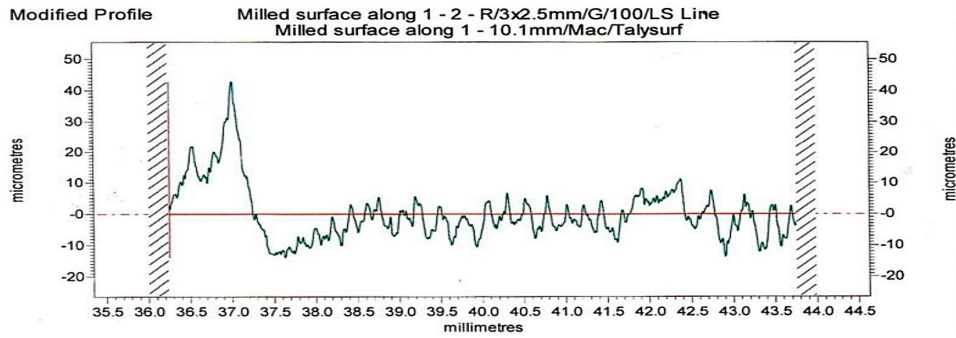
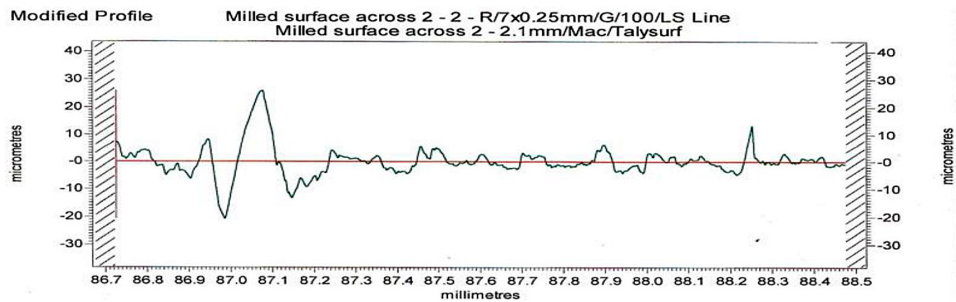


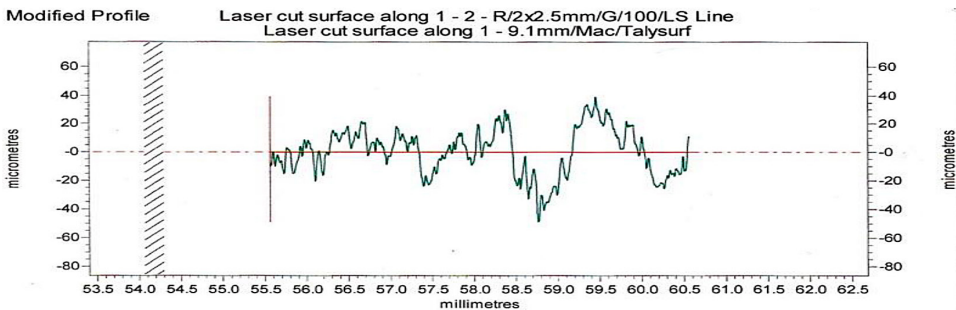
Fig. 16. a) The stylus measurement the points for laser cutting,
b) The stylus measurement the points for milling machine



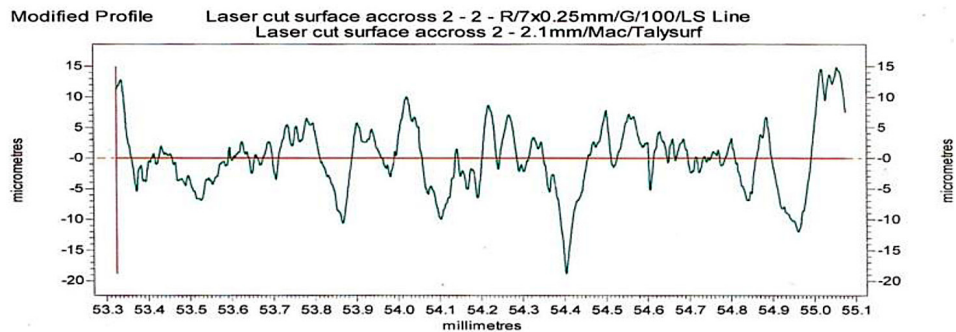
Graph. 4. Surface roughness at first point for milling machine: Ra 6.2633 μm
 Rp 1max 42.8392 μm Rv 1max 13.9342 μm Rt 56.7735 μm Rp 20.2148 μm Rv
 12.7285 μm Rz(DIN) 32.9433 μm RS 178.72 μm RSm 576.92 μm



Graph. 5. Surface roughness at second point for milling machine: Ra 3.4600 μm
 Rp 1max 26.0129 μm Rv 1max 20.6561 μm Rt 46.6690 μm Rp 9.6734 μm
 Rv 8.2705 μm Rz(DIN) 17.9438 μm RS 55.29 μm RSm 215.29 μm



Graph. 6. Surface roughness at first point for laser cutting: Ra 13.1081 μm
 Rp 1max 39.3216 μm Rv 1max 48.7201 μm Rt 88.0416 μm Rp 30.3790 μm
 Rv 36.3858 μm Rz(DIN) 66.7648 μm RS 119.30 μm RSm 764.83 μm



Graph. 7. Surface roughness at second point for laser cutting: Ra 4.0921 μm
 Rp 1max 14.9212 μm Rv 1max 18.7721 μm Rt 33.6932 μm Rp 9.3429 μm
 Rv 9.5427 μm Rz(DIN) 18.8855 μm RS 48.59 μm RSm 119.05 μm

More milled surfaces

These surfaces are related to the other side of the cutter. Given the lower levels of vibration here, the surface appears to be much smoother across the thickness at position two (Graph 5).

Laser-cut samples

We attempted to apply 0.8 mm and 0.25 filters, but achieved no satisfactory results. Moreover, there is a disadvantage in using 2.5 filter, in that it takes away too much of the traverse length. The evaluation length is a multiple of the filter or sample length. As a 2.5 mm filter was applied, the measurement was 7.5 mm long over a 10 mm traverse length. With only 9 mm available, the length will be 0.5 mm.

Laser surfaces (along the thickness at position one) – Graph 6.

The edge is at an angle, which makes it necessary to approximately align the machine to it across the thickness at position two (Graph 7).

As per the results, one can obtain the approximate average maximum profile as the difference between the heights of the ten highest peaks and the ten deepest valleys. This shows us the surface texture on limited-access areas having either high peaks or low valleys.

A datum marked on the surface allows for the precise location of the surface 3D maps and 2D surface profiles to be accurately pinpointed, thus allowing us to compare the parent surface and replica.

Figures 17–20 show meshed axonometric and photo simulation as well as a pseudo-colour Image for the surface of Selfix material after cutting with a milling machine and laser.

Analysis of surface roughness measurement results

As per the cutting effect on the Selfix surface according to the graphs, the specimen roughness was found to vary depending on the location. For instance, at the first point for milling machine, the surface roughness stands at 6.26 µm and at the second point, 3.46 µm. In the case of laser cutting, this value at the first point is 13.10 µm and 4.09 µm at the second point. Upon comparison, the laser-cut surfaces reveal more roughness in contrast to the milling machine, and can also be compared between the average for value of surface roughness at these points.

The average for milling machine:

$$\frac{6.26 + 3.46}{2} = 4.86\mu\text{m}$$

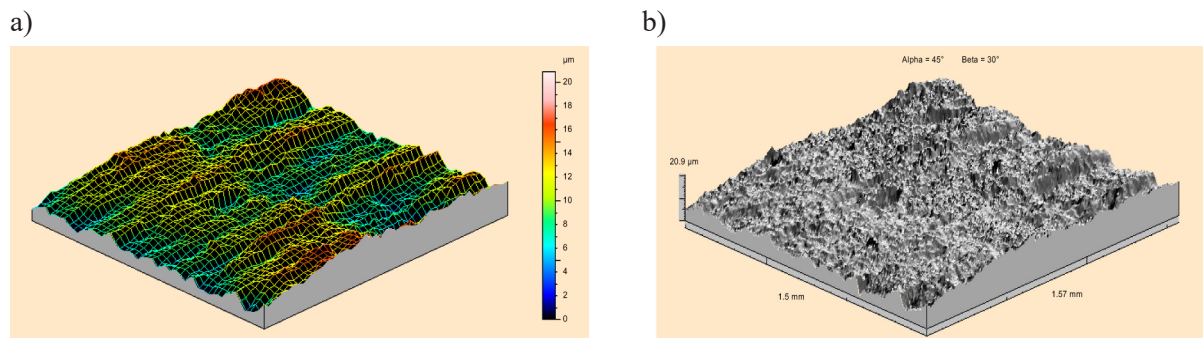


Fig. 17. Selfix milled sample: a) Meshed axonometric at point for milling machine, b) Level of surface photo simulation at point for milling machine

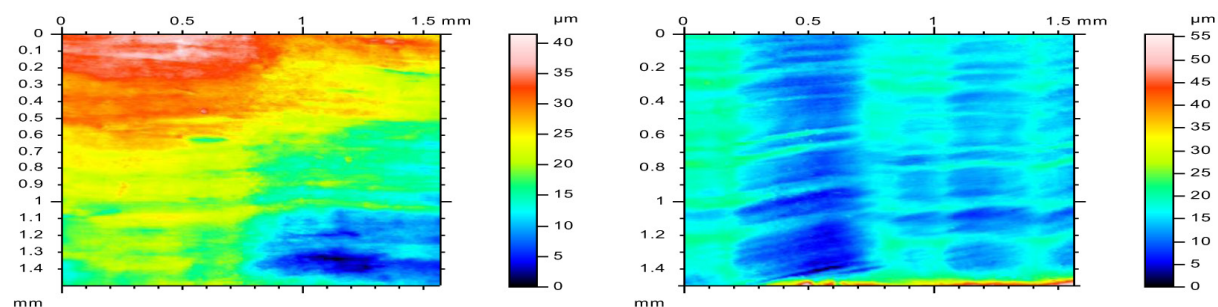


Fig. 18. Pseudo colour image at point for milling machine

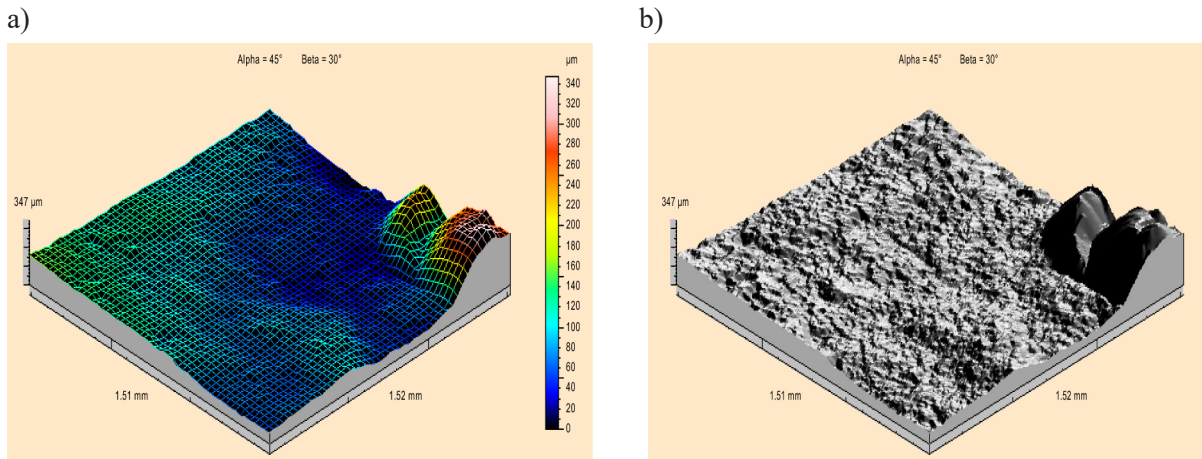


Fig. 19. Selfix laser cut sample (position 2& 3D scan): a) Meshed axonometric at point for laser cutting, b) Level of surface photo simulation at point for laser cutting

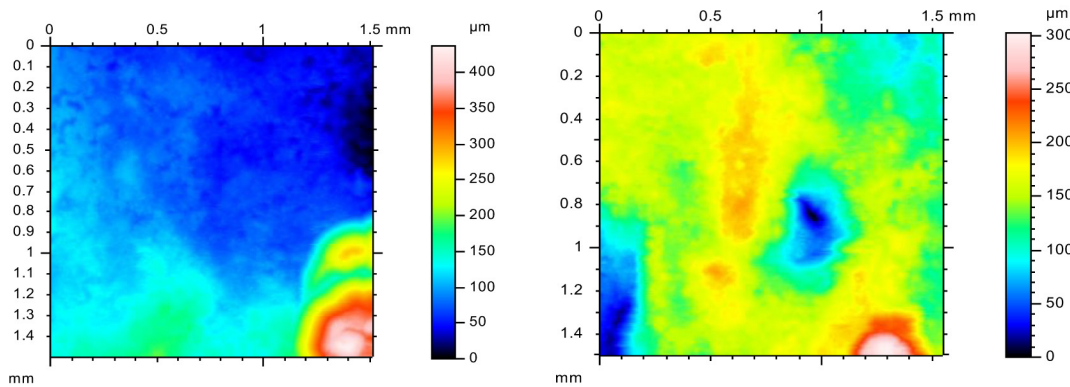


Fig. 20. Pseudo colour image at point for laser cutting

The average for laser cutting:

$$\frac{13.10 + 4.09}{2} = 8.59\mu\text{m}$$

The results show greater roughness on the surface cut by laser. Apart from this, the images for meshed axonometric, photo simulation and pseudo color reveal the signs of melting at the strength joint surface. It can be concluded that the burns by laser cutting or deformation by milling machine on the surface of Selfix material need to be addressed to achieve better and higher-strength surface quality. The surface roughness model is based on mechanical analysis, and hardness and surface deformation depend on the type of material.

The surface roughness is useful in determining the quality of the bond of the polymer with other materials. The type of bonding is an essential factor that influences the physical, mechanical and aesthetics of the substance. A composite is a kind of engineered material that consists of particular fillers in a soft matrix. Here, the

matrix material is Selfix and filler material used for enhancing properties is calcium carbonate. It was found that the quality of the bond improves with a decrease in the filler material. The reason behind this improvement is the covalence, and the bonding between the molecular chains of the polymer and material molecules when they come into contact.

Scanning electron microscope results

According to the SEM observations, images were taken from the structure of the Selfix sample on the cut edges in order to accurately determine the particle distribution (Figure 21). On the basis of the results, it was found that Selfix contains other compounds. Other images, taken to capture the microstructural features, appear in the following for three different materials on the cut edges.

Analysis of sem results

From the images captured with the SEM, one can see that pure Selfix looks well as regards the

a) Material - Selfix blended with Calcium Carbonate:

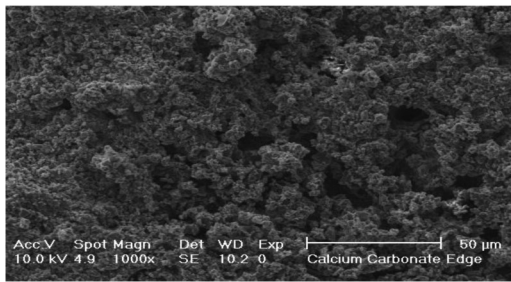


Image 1.at 1000x

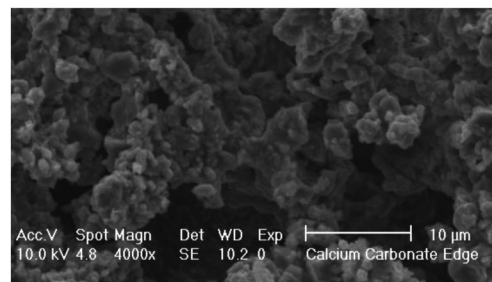


Image 2 at 4000x

b) Material –Selfix blended with wood flour.

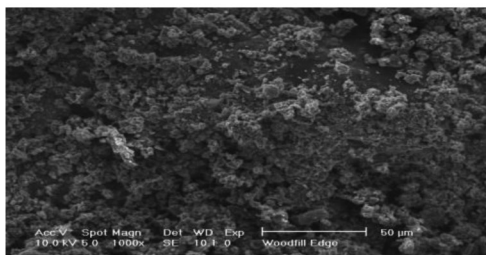


Image 3 at 1000x

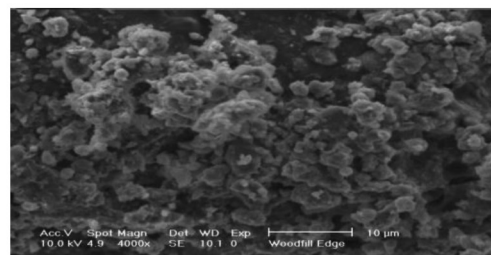


Image 4 at 4000x

c) Material – Pure selfix with green pigment.

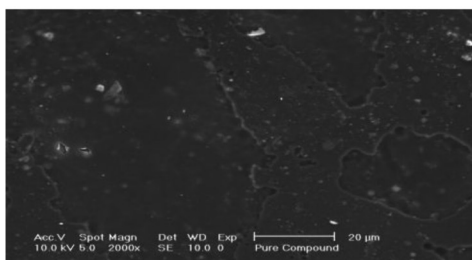


Image 5 at 2000x

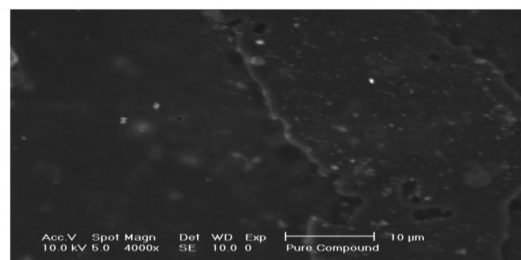


Image 6 at 4000x

Fig. 21. Structure of the Selfix sample

material uniformity, but once it is blended with fillers such as calcium carbonate, uniformity decreases as a result of pores formed during molding. Other factors having impact on uniformity include selecting inappropriate die in the extrusion machine, wrong temperature settings during the extrusion process, and improper mixing or combination with fillers. All of these can cause particle distribution to become coarse in the case of biodegradable materials.

Apart from this, it was observed that calcium carbonate and wood flour go well in combination with Selfix and produce an acceptable mix, satisfactory surface finish, and also added tensile strength. Otherwise, wood fillers are not mixed

properly with the Selfix material matrix, wood traces can appear unevenly scattered all over the base material. For this reason, this filler is not a proper choice to go with Selfix when it comes to machining. Specifically, common productions processes, namely turning grinding, can generate high amounts of wood powder, thus increasing the health and safety hazards at the same time.

Considering that wood is a good heat conductor, laser cutting burns these particles, creating flame and fume, leading to possible damage to the entire setup or any part of the machine. As these machines are costly to purchase and maintain, from the manufacturing and economic perspective it is not quite logical to make biodegradable

a) Material Sample: - Selfix blended with Calcium Carbonate.

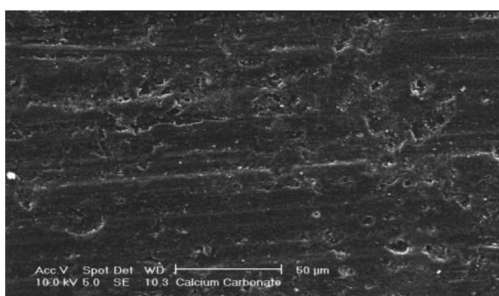


Image 7 at 1000x

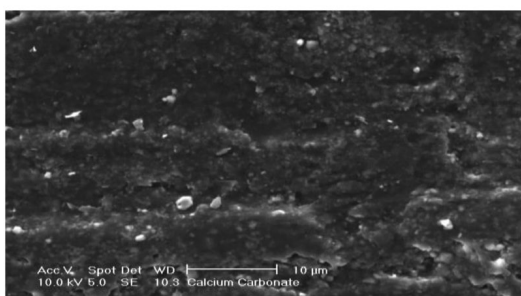


Image 8 at 4000x

b) Material Sample: - Selfix blended with Wood.

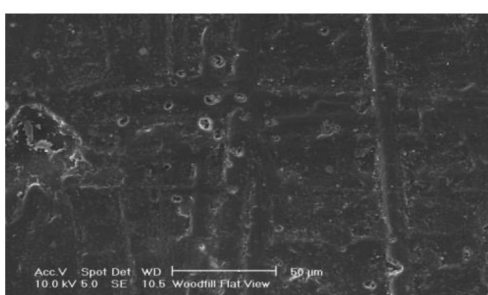


Image 9 at 1000x

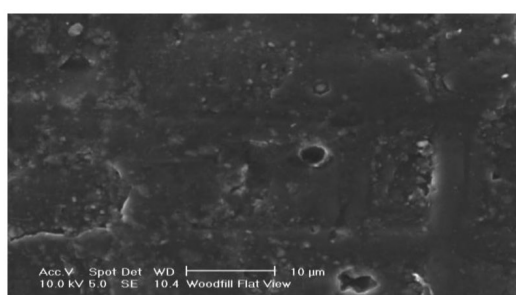


Image 10 at 4000x

c) Material Sample – Pure Selfix with green pigment.

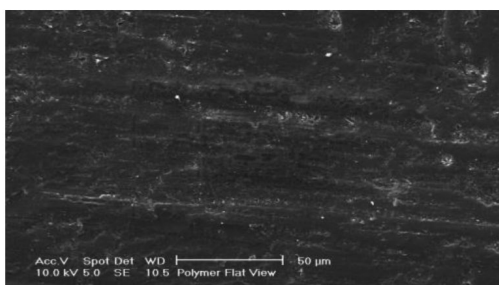


Image 11 at 1000x

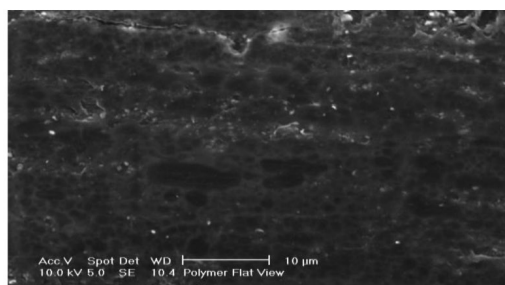


Image 12 at 4000x

Fig. 22. SEM images of sample material on the surfaces

material in this way. Another disadvantage of the wood-blended Selfix is that, once wet, it takes much longer to stick and forms rather weak bonds when compared to the other two biodegradable polymer samples. In conclusion, it can be stated that Selfix in combination with wood is not manufacturing-friendly.

Benefits of innovation with smart material

Selfix offers the specific benefits of making models quickly as well as prototyping, Apart

from these, it has found applications in automata to produce countless shapes and forms, some of which would not necessitate other material to be used with Selfix. Given its self-adhesion quality, it can stick to different materials simply by means of wetting. In the case of educating children, this material can be very useful for many creative activities and also making toys. This can help families in economizing on educational gadgets, helping children to grow more imaginatively by, perhaps, materializing their own ideas into shapes, and even getting the parents involved in activities.

There is no question that Selfix helps with creativity and creates more entertainment while learning. These benefits aside, the disposal of paper and cardboard can be reduced. Selfix can also be applied in making products with added value, or at home to make designs without worrying about waste and toxicity.

Selfix material (biodegradable polymer) as adhesive

In most cases, the main factor in selecting adhesives is their bond quality and the ability to undertake mechanical loading. Another factor is the status of the contact surfaces and its preparation by etching, priming and grinding to remove coarse material, dirt, and grease gathered which can adversely affect the bond strength. These processes take time and require other resources [19].

In this respect, as Selfix was designed to be water-soluble, the free molecules within the material make strong joints with others when drying, thus making Selfix an adhesive in some cases. Apart from this, a thin layer of this material can increase the axial stress resistance against tensile and compressive loading. Another use is improved bonding since almost all the available surface area can be contacted and holes and air pockets avoided. A smooth surface hosts far more free molecules, which ensure proper adhesion, compared to an uneven one [20].

CONCLUSION

Numerous companies are attempting to reduce their carbon footprint by decreasing it in favor of environmental benefits. With this in mind, paper and cardboard can be reused and not disposed of. The present research suggests that Selfix material could be the solution for reusing paper and cardboard and, hence, saving energy and natural resources needed to produce them. Using Selfix to reuse paper and cardboard waste would be beneficial both environmentally and economically, especially in the case of families and, within a larger scale, businesses.

Certain countries, such as the UK, have passed the regulations targeting waste, (CO₂) emission, re-using, and recycling. In line with these efforts, and given the biodegradability of Selfix smart material, it can have a role in governments and environmental groups' initiatives toward environmental preservation.

Finally, it can be stated that Selfix has numerous novel applications for different purposes in education and business. The following may be recommended based on this research outcomes:

- Supporting industrial companies and enterprises that aim at reducing waste, such as Selfix Technology Company;
- Encouraging collaboration between the sector and universities to create the solutions targeting product improvement to reduce the environmental impacts;
- Improving the knowledge transfer capacity and skills in innovative product development in public research organisations along with the measures to promote such awareness and skills among students;
- Encouraging the production of packing material that is eco-friendly and re-useable;
- Conducting further research on Selfix properties for further improvement and 3D modeling to design novel products and shapes; and
- Concentrating on case studies related to waste reduction to find other applications for Selfix and biodegradable materials to that end.

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