Laser-Dyeing for Sustainable Textile Design

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Keywords: CO_2 Laser, Textile Design, Colouration, Dyeing, Wool, Sustainability.

Abstract

Current industry standards for dyeing woollen textiles use high temperatures and long processing times to aid dye diffusion. The consumption of water, energy and chemicals used in dyeing and finishing processes have been identified as key challenges to sustainability within the textile industry. This paper furthers the discussion of a recently developed digital laser-dyeing technique for woollen textiles. The research examined the effect of infrared laser irradiation, as a pre-treatment to dyeing 100% wool and its potential as a design tool for textile processing. Analysis of the dye performance properties of treated wool substrates and potential sustainability advantages of the technique are presented. Laser modification of the outer cuticles of wool fibres was found to remove and disrupt the hydrophobic surface. Therefore, after laser treatment, an increased rate of dye diffusion may be expected. By offering this technique as an alternative solution to traditional wet processing, the potential has been found to increase environmental sustainability through significant reduction in energy and wastewater effluent. In addition, the CAD controlled laser provides the advantage of accurate and targeted processing, allowing design and surface patterning capabilities.

Introduction

Improving sustainability of the clothing and textile industry has been widely documented as a priority with textile dyeing and finishing processes recognised as one significant area of environmental concern [1-3]. Recent advances in sustainable dyeing processes have addressed the issue of water consumption through new waterless dyeing technologies that have been developed for all-over colouration on cotton [4] and synthetic textiles [5,6]. The use of CO_2 lasers as a dry process, also offers positive implications for reduction of wastewater and processing time of textile production in comparison to traditional wet finishing methods [7]. These advantages have been beneficial to denim manufacture in creating laser-faded effects on denim [7,8]. As such CO_2 laser use has become increasingly commonplace in the textile industry [9].

The effect of both UV [10,11,13] and IR [12,14] laser irradiation have been reported to increase dye absorption properties of synthetic polymer substrates, resulting in improved dye performance [11,12,14] and a reduction in temperature of the dyeing process [15]. On woollen substrates, laser irradiation has been shown to reduce felting and shrinkage properties [16], while UV irradiation improved dyeability [15]. Very few studies have discussed the possibility of design outcomes of laser enhanced dyeing, from targeting specific areas of the textile substrate [17,18]. The effect of CO_2 laser irradiation on surface and dyeing properties of wool substrates was investigated by the author showing the CO_2 laser as an effective surface design tool for wool [19]. The aims of the following investigation were to ascertain the functional and performance properties properties of the laser-dyeing technique on wool, and for results to be analysed in relation to potential sustainability benefits.

Experimental

The following conditions and equipment were used throughout this research for laser processing, dyeing, testing and analysis of the work. Each experiment was repeated a total of three times and the mean and standard deviations recorded.

Materials. A pre-scoured woven 100% wool, plain weave fabric, with a mean fibre diameter of 19.7 microns, supplied by Drummond Parkland (Huddersfield, UK) was used throughout the experiment. Samples measuring 40mm x 12mm at a weight of 1.25g were used for testing purposes.

Laser. A Synrad carbon dioxide (CO_2) source laser producing a continuous wave beam in the far infrared spectrum with a maximum power of 100 Watts and a wavelength of 10.6μm was used to harness the photothermal properties to modify woollen fibres. All experiments were carried out with the laser beam in focus on the surface of the textile substrate. Winmark software was used to mark raster shapes at a resolution of 100dpi. The window of laser processing parameters to cause effect on the material properties for wool was expected to be small. This was confirmed experimentally to range between 50-60kW/cm^2. Below this, insufficient energy density is delivered to the fabric to allow a phase change to occur. Above this, pyrolysis negatively impacts material properties. Therefore, laser irradiation of fabrics was carried out at power densities of 51kW/cm^2, 54kW/cm^2, 57kW/cm^2 and 60 kW/cm^2 and an untreated control at 0kW/cm^2. Five mark-passes ensured even processing of the substrate surface, at a constant laser scanning speed of 5000mm/s.

Dyeing. An Ahiba infrared dye machine was used allowing controlled temperature and agitation throughout the dyeing process. Dyeing occurs by adding dye, fabric sample and auxiliaries in airtight cylinders with each fabric sample occupying it's own vessel. Concentrations of chemicals used during the dye process were expressed as a percentage on weight of fibre (owf). The dye recipe used Lanasol Blue CE Reactive dye from Town End Dyes, UK, at a 4% dye concentration and the auxiliaries as recommended by the manufacturer [20]. In the procedure used, fabric undergoes a 15-minute pretreatment at 50^{o}C in a 1:100 liquor ratio containing 2% owf acetic acid, 5% owf sodium sulfate, 1% owf Albegal B and water. Dye was then added and the dye bath warmed to 80^{o}C for 30 minutes. Finally 1% owf ammonia was added and processed at 80^{o}C for a further 15 minutes. After dyeing, the samples were removed from the dye bath, rinsed and allowed to air dry.

Figure 1 shows a schematic for dyeing the wool samples. Test temperatures of 80^{o}C were used throughout this study, held for a reduced overall dyeing time (Fig.1, line b). Line a, (Fig.1, line a) shows the standard procedure for optimal dyeing conditions, as described by the manufacturer [20], where the dye bath is held at a peak temperature of 100^{o}C for 90 minutes. An approximation of the energy saved during the dyeing process was estimated using the schematic in figure 1, on the assumption that the power required to heat the dye bath will be proportional to the temperature, and Energy = Power x Time. The relative energy

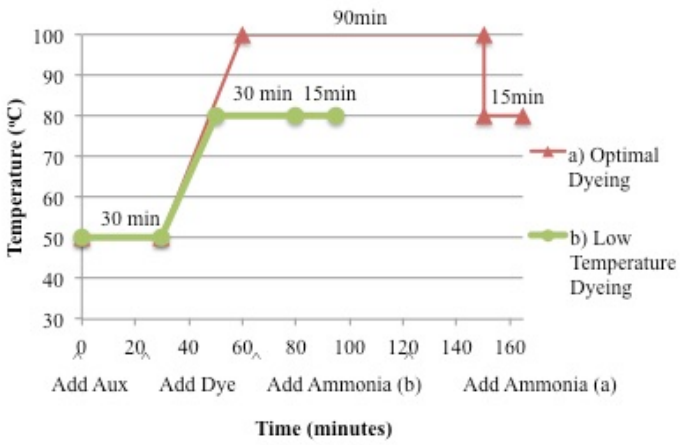

Figure 1 Dyeing Schematic for Reactive Dye comparing optimal dyeing conditions for wool with low temperature dyeing conditions used after laser irradiation.

saving can be approximated from the difference in the areas under each curve. Where A_a is the area under graph line a and A_b is the Area under graph line b (Fig.1).

$$\% \text{ Energy Saving} = 100 \times (A_a - A_b) / A_a \quad (1)$$

Microscopy. A Nikon Optiphot optical microscope at a magnification of 10x and a Phenom Scanning Electron Microscope (SEM) at a magnification of 5000x were used to analyse the effect of laser irradiation on individual textile fibres.

Dye Exhaustion. Dye Exhaustion is the percentage of dye absorbed by the fabric from the dye bath solution. In this experiment a Unicam SP1800 UV/visible spectrophotometer was used, set at 610nm, the maximum absorbance wavelength specific to the chosen dye. Three absorbance measurements were taken from each exhausted dye bath and an average was used to calculate Exhaustion (%E) using the following equation (Eq.2). Where Abs_0 is absorbance of the original dye bath solution at a wavelength of 610nm and Abs_1 is absorbance of the remaining dye bath liquor after the dyeing process has taken place.

$$\%E = 100 \times (Abs_0 - Abs_1) / Abs_0 \quad (3)$$

Colour Fastness. The standard test method BS EN ISO-C10: 2007 was used to determine the effect of washing on colour fastness of the laser irradiated, dyed samples. A multi fibre strip was attached to each sample, which was then agitated under controlled conditions of time and temperature in a soap solution. After rinsing and drying, colour change of the fabric sample and the staining on the adjacent fabric were assessed by comparison to the original fabric. A value from 1 to 5 was awarded using the appropriate grey scales, where 5 is no loss of colour or no staining. Colour fastness to rubbing under both wet and dry conditions was determined by the BS EN ISO 105-X12: 2002 standard test method. Test samples were rubbed with a dry cloth and a wet cloth using a crockmeter, which provided a constant rubbing pressure of 9N. The staining of the rubbing cloths was also assessed using a grey scale.

Results and Discussion

Surface Observation. To examine the effect of laser treatment on the surface properties of wool, laser irradiation at increasing power outputs was performed prior to dying the wool

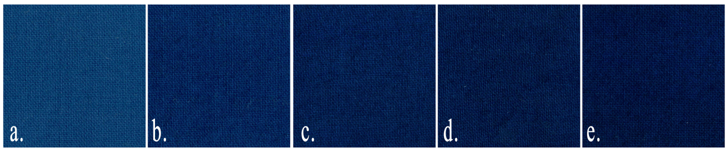

Figure 2 Laser pre-treated, dyed wool samples subject to power densities of a.) 0, b.) 51kW/cm^2, c.) 54kW/cm^2, d.) 57kW/cm^2 and e.) 60 kW/cm^2

with reactive dye. Five squares of 100% wool were laser treated at power densities of 51kW/cm^2, 54kW/cm^2, 57kW/cm^2, 60 kW/cm^2, at 5000mm/s and an untreated, 0kW/cm^2 control. Visually, a change in colour could be seen showing increasingly darker shades of blue as the laser power density increases (Fig. 2).

Figure 3 shows microscopic images of laser treated wool before and after dyeing at increasing laser power densities. 3a shows the untreated control with a consistent, even tone across the fibres. In 3b and 3c however, it can be seen that individual fibres, which have been subject to the laser irradiation, are darker in colour. In micrograph 3c, where a higher power density has been used, the contrast has increased significantly. Increased carbon can be seen in micrograph 3d as a result of pyrolysis, which may be removed by gentle abrasion. As well as degrading fabric structure, this may result in poor colour fastness to washing and rubbing. The results indicate improved dye performance on the surface fibres of wool after laser irradiation up to 60kW/cm^2.

The morphology of the irradiated surfaces was further examined by scanning electron microscopy (SEM) on an area of the wool fabric that had been subject to laser irradiation of 57kW/cm^2 at a velocity of 5000mm/s. The micrograph in figure 4 shows two particular fibre strands of note, labeled A and B. The characteristic scales of natural wool fibre can be seen on Strand A, this strand was not subject to laser irradiation. On Strand B however, the scales on the surface of the fibre appear less pronounced; they have been ablated by laser irradiation. The scales on a woollen fibre are formed from a tough slightly hydrophobic lipid layer. The removal of the scales of a wool fibre allows easier penetration of the dye into the core of the fibre [21]. The darker colour properties seen in figure 2 can be attributed to improved dye absorption by the laser modification of wool fibres. From SEM and optical microscopic evaluation, laser parameter settings suitable for further testing were identified and the effect of laser irradiation on wool fibres has been discussed.

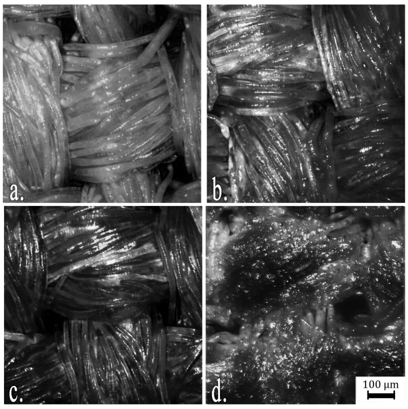

Figure 3 Micrographs 10x magnification of laser irradiated, dyed samples at power densities of a.) 0, b.) 54, c.) 57, d.) 60

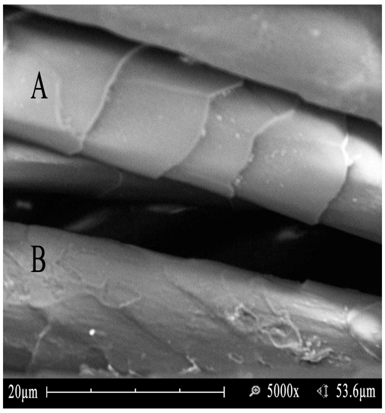

Figure 4 SEM micrograph of laser irradiated wool. a.) Untreated wool fibre, b.) Laser irradiated wool fibre.

Dye Exhaustion. Samples irradiated with power densities of 51kW/cm^2 to 60kW/cm^2 were dyed with Lanasol blue reactive dye in controlled conditions. A fully exhausted dye bath would result in insufficient dye remaining in the liquor for adequate absorption readings to be taken using a spectrophotometer. To ensure only partial exhaustion, a high concentration of dye at 4% owf was chosen and the dye bath held at 80°C for 30 minutes. After dyeing, the absorbance of the remaining liquor from each of the five samples was measured using a spectrophotometer and the percentage exhaustion was calculated relative to the initial dye bath concentration before dyeing. The results show an overall increase in exhaustion of the dye bath as laser power increases as seen in the graph (Fig. 5). This indicates a corresponding increased dye uptake by the fabric substrates. At the lower than optimal temperatures of 80°C, exhaustion of dye has increased by a significant 9-10% on all laser treated samples. Laser modification of wool fibres allows more dye to enter the fibres on the laser treated surface. The increased dye exhaustion verifies that a greater affinity for dye is attained.

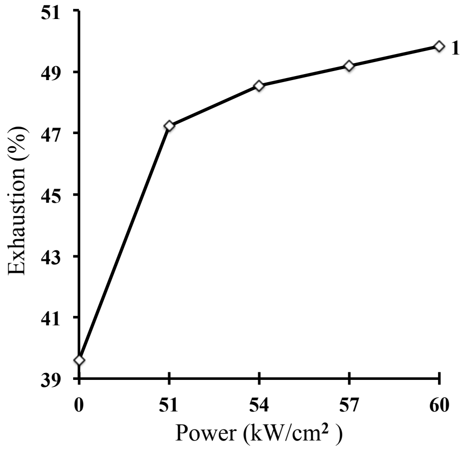

Figure 5 % Exhaustion of Dye from Dye Bath at Increasing Laser Power Densities.

Sample	Power Density [kW/cm^2]	Fastness to Washing BSEN ISO-C10:2007		Fastness to Rubbing BSEN ISO 105-X12:2002	
		Cotton	Wool	Dry	Wet
a	0	4/5	4/5	4/5	4
b	51	5	5	4/5	4/5
c	54	5	5	4/5	4/5
d	57	5	5	4/5	4/5
e	60	5	4/5	4	3/4

Table 1 Fastness properties of laser irradiated and dyed wool.

Fastness Properties. The results in table 1 show that fastness performance has not been negatively affected by washing or rubbing. Fastness results of the laser pretreated samples at the reduced time and temperature are consistent with the dye manufacturers results at the recommended higher dye temperature and time [20]. The untreated control shows slight loss in fastness performance, suggesting that the laser irradiated samples give improved fastness to washing and rubbing at lower temperatures. At the highest laser power density we begin to see a reduction in fastness. This is due to the onset of pyrolysis at higher laser powers as observed under microscopy. Loose burnt debris was removed by the rubbing test (ISO105-X12: 2002). The results show that laser parameters between 51kW/cm^2 and 57kW/cm^2 are suitable for dye uptake improvement without thermal degradation of the woollen fibres.

Laser Pretreatment For Textile Design. The colour difference between treated and untreated areas of the fabric substrate were significant at 57kW/cm^2, showing potential for CAD controlled laser treatment to be used as a design tool/technique. This parameter was used to mark wool fabric with designs consisting of geometric patterns in solid and linear shapes. After dyeing with blue reactive dye, the laser marked areas appeared tonally darker on the surface of the cloth. The resulting samples (Fig. 6) provided a two tone all over pattern and showed that a precise level of detail was achievable. The technique has the potential to be used on woollen textiles of varied constructions and weights that could be suitable for fashion or interior textile applications.

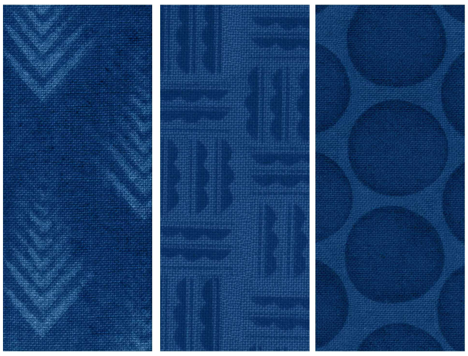

Figure 6 Design Samples: CAD controlled tonally darker areas produced by laser irradiation prior to dyeing.

Discussion of Results. This study found that a CO_2 laser could be used to irradiate wool fabrics prior to dyeing to achieve differential dye uptake across the surface of the cloth. A technique has been derived allowing a pattern to be marked on wool using a CO_2 laser followed by dyeing. After dyeing, the laser-marked pattern appeared tonally darker on the surface of the cloth. Microscopic analysis has shown that laser irradiation removed the outer scales from individual wool fibres on the surface of a woollen textile. It has been discussed how the modification of these scales allowed easier penetration of dye into fibre, so that laser marked areas allowed an improved dye absorption compared to the non-treated areas. Usually, high temperatures and long processing times are required to achieve maximum dye uptake on wool [20], however dye exhaustion results in this study have indicated that dyeing laser pretreated wool at a reduced temperature of 80^{o}C can achieve an elevated level of dye uptake. An optimum power density of $57kW/cm^2$ has been identified. Up to this parameter, laser irradiation was used to control levels of dye uptake to achieve pattern designs, without loss of performance properties of the fabric from washing or rubbing to an ISO standard. The lower temperature and reduced dyeing time was estimated at a significant 54% energy saving when compared to the manufacture's recommended dyeing process.

Advantages for Sustainability and Manufacture. This technique offers sustainable innovation in a number of areas. Laser enhanced dyeing offers potential reductions in energy and wastewater effluent through reduced dyeing temperatures and improved dye performance. Low temperature processing reduces overall dyeing time and temperature from standard practice, displaying potential for an estimated 54% reduction of energy during dye production. The ability to reduce energy used in dyeing by over half would offer exceptional savings with both economical and environmental benefits.

The laser marking operates a remote, non-contact set-up with the ability to place designs on finished products and across garment seams. This also offers potential for manufacturers to customise garment blanks to meet the requirements of retailers and consumers. This kind of responsive manufacture has the potential to reduce surplus stock. Furthermore, combining the functionality of the laser to perform multiple production tasks at once, such as pattern cutting as well as the laser dye technique, would allow additional environmentally sustainable benefits to the process compared to outsourcing each individual stage of the production process, for example, fabric manufacture, screen printing and garment production in addition to storage and transport between these phases. Combining techniques in one stage has potential to offer fast response in today's fast changing market, with easily changed CAD files allowing smaller product runs than financially permitted by exposing individual screens for screen printing or die cutters for product pattern cutting. Therefore, as well as meeting the aim to offer sustainability through reduced temperatures and improved dye performance, laser technology could offer additional advantages through a potential change in production systems.

The laser technology used is commercially available and accessible to small businesses as well as to the larger manufacturer. This means that the techniques developed could be transferred to creative textile businesses including fashion and homeware applications. The results could enable design innovation and customisation to manufacturing and retailing businesses, alongside contribution to developing environmental strategies, thus increasing their competitiveness within the global market.

Conclusion. A novel method of textile surface design for wool has been presented. Additional sustainability benefits and positive impacts for manufacturing have also been discussed. Results have established that an increased dye uptake is achievable on the surface of a wool fabric by laser irradiation. Experiments have shown that CAD files can be used to mark out targeted areas to create specified designs. The reason for the increased dye uptake has also been explained. The tested substrates show high fastness to washing and rubbing, indicating that the dyeing quality meets current industry and consumer standards. It has been shown that the technique reduces overall dyeing time and temperature from standard practice, displaying potential for an estimated 54% reduction of energy during dye production. Further work lies in examining Life Cycle Assessment of laser-dyeing as a proposed tool for textile production.

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