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Examination of Thermal Damage Simulated on Natural, Blended and Synthetic Clothing by Two Different Thermal Sources

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KEYWORDS

Forensic Textiles, Flame Damage, Thermal degradation, Fibre Analysis, SEM, Microscopy

ABSTRACT:

Introduction: Forensic examination of burned or charred clothing plays a crucial role in incidents related to arson, accidental fires, homicidal burn incidents, and electrocution. This field provides valuable acumens into fire dynamics, ignition sources, and the sequence of thermal events. Different textile fibres respond differently to thermal exposure depending on their composition and structure. By identifying the characteristic damage patterns generated by various thermal sources, forensic experts can identify the probable origin and mechanism of clothing damage in such cases.

Objectives: To examine and compare the thermal degradation patterns of different clothing fabrics when exposed to two distinct thermal sources, and to identify characteristic damage features that can assist in determining the source of thermal damage during forensic investigations.

Methods: Twelve types of clothing fabrics covering natural, synthetic and blended fabrics were selected for analysis and were subjected to controlled thermal exposure under two experimental conditions: (i) direct flame exposure using an LPG Bunsen burner and (ii) spark-induced exposure using an arc welding apparatus. Microscopic examination was conducted to observe the morphology of thermal damage, and fifteen distinct fibre damage characteristics were documented. Statistical analysis was performed using Analysis of Variance (ANOVA) to evaluate the influence of fabric type and damage parameters on the observed thermal effects.

Results: The statistical analysis revealed a significant effect of fabric type on flame-induced damage ($F = 214.34 > F_{(crit)} = 2.01$), indicating that different fabrics exhibit distinct responses to direct flame exposure. In contrast, spark-induced damage showed significant variation based on damage parameters ($F = 15.16 > F_{(crit)} = 2.58$) rather than fabric type, suggesting that the mechanism and extent of damage in spark exposure differs from that of direct flame. Microscopic examination demonstrated observable variations in damage morphology across fabric types and thermal sources.

Conclusions: The study demonstrates that different thermal sources produce distinguishable damage patterns in clothing fabrics, and these variations can be statistically validated. The findings provide useful forensic indicators for differentiating between flame-induced and spark-induced damage, thereby aiding in the reconstruction of fire-related incidents and determination of the source of clothing damage in forensic investigations.

1. Introduction

Textile evidence plays a crucial role in forensic investigations, particularly in cases involving fire-related incidents such as arson, homicide, and accidental fires [1]. Clothing recovered from such crime scenes often bears characteristic damage patterns that can provide critical information about the circumstances surrounding such an incident [2]. In arson investigations, victims and suspects play a significant role in the repository of evidentiary material alongside human remains [3]. Suspects frequently present with characteristic ignition-related injuries arising from procedural lapses, and these injuries often show a direct relationship to the physio-chemical properties of the accelerant involved; for example, the high volatility of gasoline commonly

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results in rapid flash-fire burns. Simultaneously, clothing and footwear demonstrate distinct patterns and distributions of thermal degradation. Systematic examination of the location, extent and morphology of such damage provides essential interpretive data for reconstructing ignition dynamics and overall arson behaviour [4].

Textile damage serves as a valuable piece of evidence since most crimes are committed by individuals wearing clothing [5]. Consequently, in cases such as arson or an acid attack, there is a likelihood that the clothing may sustain thermal damage from the fire or from the Molotov cocktail, which can cause flames to come into close contact with the clothing, or it may experience chemical damage from corrosive splashing back onto the perpetrator [6], [7]. Nevertheless, there seems to have been less work reported on thermal damage to textiles. Leung and Halliday investigated the effects of flash burning on the material. Flash burning results where the vapor from a volatile flammable liquid (such as petrol) mixes with the surrounding air, creating a cloud, and the ignition of this vapor cloud will result in a flame front that flashes through. Items exposed to this flash front may then be subjected to directional heat damage, such as clothing and/or shoes, and the extent of this damage can be dependent upon the susceptibility of the fabrics themselves (melting points, thermal capacities, etc), the duration of contact between the items and the flash front, and the amount of flammable vapor [8]. Flash front is also encountered when exposed to detonations or explosions, but it is clear that there is very limited research in this area [7].

Burning behaviour of clothing and textiles can serve as valuable forensic indicators by aiding in distinguishing between accidental and intentional burning [9], [10]. The morphology of thermal damage including the size, shape, and distribution of holes, the presence or absence of melting, and the characteristics of burnt edges can reveal important information about the heat source, duration of exposure, and environmental conditions during the fire event [11].

2. Thermal Degradation Behaviour of Textile Fibres

The thermal degradation of textile fibres has been extensively studied in the context of fire safety and material science [10]. The response of fibres to heat and flame is fundamentally determined by their chemical composition and molecular structure and they can be broadly categorized into natural, synthetic and blended fibres [12]. Galaska et.al. reported that Cotton typically scorches at around 150 °C, while wool begins to decompose at a slightly lower temperature of about 130 °C [13]. However, leather shows decomposition in the range of 160°C to 165 °C, indicating a slightly higher thermal tolerance compared to other natural fibres. Among synthetic materials, acrylics begin to soften and stick between 204°C to 254 °C, melting at still higher temperatures, whereas nylon 6 displays a clear melting point near 215°C. Many researchers reported that polyester melts at comparatively higher temperatures, approximately 249°C to 290 °C, reflecting its strong thermal stability while rayon, a semi-synthetic fibre, decomposes between 150°C to 204 °C, overlapping partially with natural fibres. In blended fabrics such as cotton-polyester mixes, the thermal behaviour reflects a combination of the individual fibre properties, often showing scorching of the cotton component first, followed by melting of the polyester at higher temperatures [8], [14], [15], [16], [17]. Shufen et al studied the thermal behaviour of polyurethanes and they found that Polyester-polyurethane was thermally more stable than polyether-polyurethane [18].

3. Methods

For this study, twelve different types of clothing were selected based on the prevalence of usage and availability. For each fabric type, rectangular swatches measuring 10 cm x12 cm were prepared. All samples were stored in controlled environmental conditions (22 ± 1°C, 45–55% relative humidity) for at least 24 hours before testing to ensure consistent moisture content. The samples were then subjected to controlled thermal exposure by two different sources (details of the sources are given in Tables 1 and 2). The changes in the physio-chemical properties were observed and recorded using a digital Compound Microscope (magnification range

10X–40X), which was used to examine the morphology of damage, including hole formation, edge characteristics, and fibre surface changes. Further, the samples were subjected to Scanning Electron Microscopic examination using Nova Nano SEM at the Sophisticated Instrumentation Centre, Dr. Hari Singh Gour University, Sagar, Madhya Pradesh, for higher

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magnification and better resolution. The recorded data were statistically analysed using two-way analysis of variance (ANOVA) to evaluate the individual effects of fabric type and damage parameters on flame-induced and spark-induced damage, with significance determined by comparing calculated F values against corresponding critical F values at a 95% confidence level.

Table 1: Experimental conditions (Direct Flame damage)

Flame Source	Laboratory-grade LPG (liquefied petroleum gas) Bunsen burner with adjustable air intake
Flame Temperature	approximately 900–1000°C
Distance from flame tip	1.5–2 cm above
Flame Exposure Duration	3 to 10 seconds
Room Temperature	22 ± 1°C
Sample Size	10 cm × 12 cm swatches; replicates of five (n=5)

Table 2: Experimental conditions (Spark Damage)

Spark Source	Arc Welding Apparatus
Distance from spark source	*5 cm away from the machine*
Material of rod	*Mild steel*
Room Temperature	22 ± 1°C
Sample Size	10 cm × 12 cm swatches; replicates of five (n=5)

4. Results

Two-way ANOVA was used to assess the influence of clothing type and damage parameters on thermal degradation inflicted by direct flame and welding spark exposure across natural, blended and synthetic clothing. For flame-induced damage, a statistically significant effect of clothing type was observed (F = 214.34 > Fcrit = 2.01) as shown in Table 3, indicating that different clothing types responded distinctly to direct flame exposure depending on fibre composition. In contrast, the effect of damage parameters under flame exposure was not statistically significant (F = 0.58 < Fcrit = 2.58), suggesting consistency in the manifestation of damage features once combustion occurred.

Two-way ANOVA was used to assess the influence of clothing type and damage parameters on thermal degradation inflicted by direct flame and welding spark exposure across natural, blended and synthetic clothing. For flame-induced damage, a statistically significant effect of clothing type was observed (F = 214.34 > Fcrit = 2.01) as shown in Table 3, indicating that different clothing types responded distinctly to direct flame exposure depending on fibre composition. In contrast, the effect of damage parameters under flame exposure was not statistically significant (F = 0.58 < Fcrit = 2.58), suggesting consistency in the manifestation of damage features once combustion occurred.

Table 3: ANOVA for Flame damage across samples

SS	*df*	*MS*	*F*	*F crit*
152.406645	11	13.85515	214.343	2.014046
0.150356667	4	0.037589	0.581515	2.583667

On the contrary, spark-induced damage did not show a statistically significant dependence on fabric type (F = 1.07 < Fcrit = 2.01) as shown in table 4, whereas damage parameters exhibited a significant effect (F = 15.16 > $F_{(crit)}$ = 2.58), demonstrating that the nature and intensity of damage characteristics varied primarily with the mode of spark interaction rather than fibre composition alone.

Table 4: ANOVA for Spark damage across samples

SS	*Df*	*MS*	*F*	*F crit*
0.072033	11	0.006548	1.070663	2.014046
0.370843	4	0.092711	15.15802	2.583667

The extent of thermal damage seen in the examined clothing was significantly affected by the type and composition of fabric and the heat source. Figure 1 illustrates that materials directly subjected to flames incurred far greater heat damage than those only exposed to sparks from a welding apparatus. The box plot illustrates a distinct disparity in the distribution of damage caused by the two heat sources about warp direction. The presence of fire increased both the median and total damage levels.

Similarly, interaction plot (as shown in Figure 2) was employed to examine the effects of fabric type and heat source on thermal damage. The results indicate that the damage patterns vary significantly among the twelve analysed fabric types. Nylon net, georgette, and quilting

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cotton exhibited greater damage upon exposure to direct flame however all clothing demonstrated less damage when subjected to sparks. The interaction plot indicates a non-parallel trend, signifying an interaction between the fabric type and the heat source. The response of textiles to thermal exposure is contingent upon the fabric type and the heat source employed.

The mean thermal damage quantified for each fabric type was analysed and represented graphically (as shown in figure 3). From this study, it is clear that different fabrics exhibited varying damage pattern outcomes which can be attributed to different fibre composition, manufacturing techniques, and thermal resistance levels. Fabrics composed of synthetic or loosely woven fibres were more susceptible to heat damage.

This study also revealed distinct, composition-dependent damage morphologies under direct flame exposure. Cellulosic fabrics such as quilting cotton and glace cotton exhibited complete carbonisation, ash formation and brittle, friable edges, while blended fabrics showed combined charring and localized melting that can be attributed to the presence of thermoplastic fibres. Synthetic fabrics underwent melting, bead formation and loss of structural integrity, whereas dense denim resisted burn-through and displayed superficial blackening only. In contrast, spark exposure produced localized damage of lower severity, characterized by micro-perforations and small circular holes (~0.4–0.5 cm) rather than extensive burn-through.

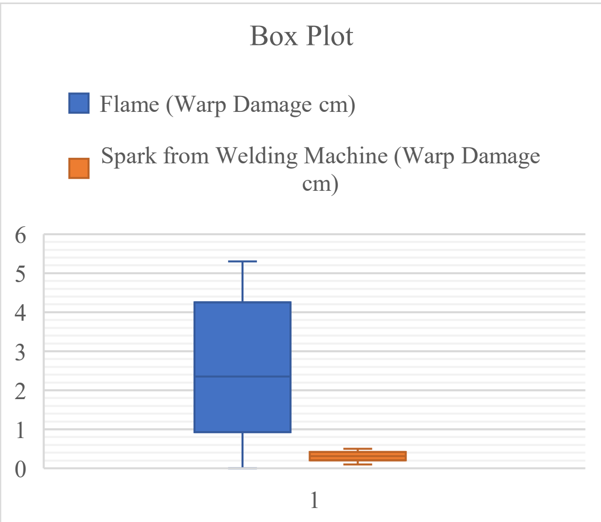

Figure 1. Box Plot of Thermal Damage Caused by Spark and Direct Flame

In Figure 1, Box plot is illustrating the distribution of thermal damage measured in the warp direction (cm) caused by two different heat sources: spark generated from a welding machine and direct flame exposure. The plot demonstrates that fabrics exposed to direct flame exhibited significantly greater damage compared to spark exposure. The central line within each box represents the median, the box indicates the interquartile range (IQR), and whiskers represent the range of observed values.

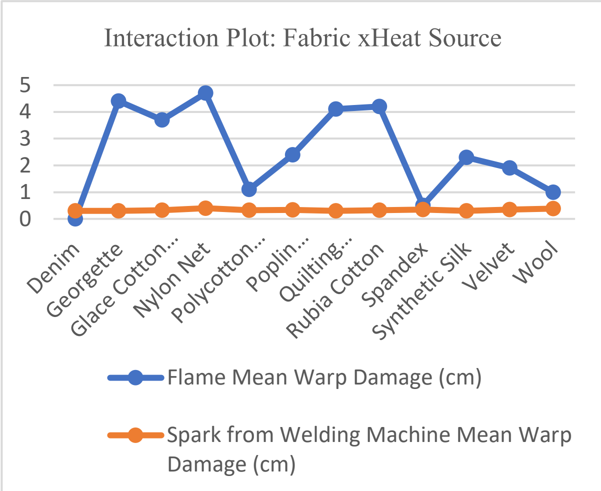

Figure 2. Interaction Plot Showing the Effect of Fabric Type and Heat Source

In Figure 2, Interaction plot is showing the mean thermal damage (warp direction, cm) across twelve different fabric types when exposed to spark from a welding machine and direct flame. The figure illustrates variation in damage response among fabrics and highlights the interaction between fabric type and heat source, indicating that the extent of thermal damage depends on both the material composition and the nature of the heat source.

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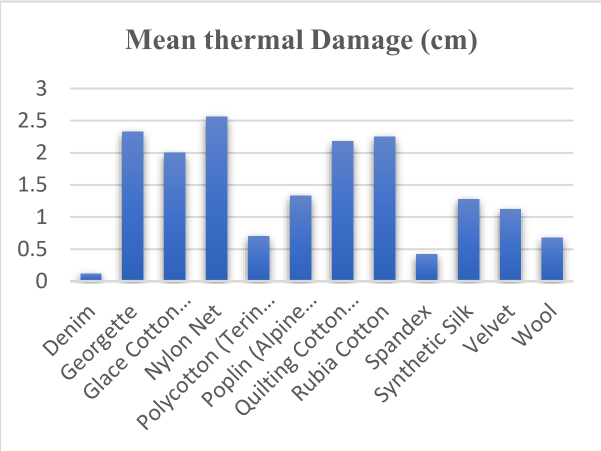

Figure 3. Mean Thermal Damage Observed Across Fabric Types

Figure 3. Bar chart representing the mean thermal damage measured in the warp direction (cm) for each of the twelve fabric types examined in the study. The variation in damage magnitude reflects differences in fibre composition, fabric structure, and thermal resistance properties among the textiles.

5. Discussion

The thermal damage produced by flame and spark exposure could be broadly classified into three fibre-dependent patterns, corresponding to natural (cellulosic and protein), blended, and synthetic fabrics. Cellulosic fabrics such as quilting cotton, glace cotton, and denim showed rapid ignition, extensive carbonisation, grey ash formation, and brittle, friable edges, consistent with the pyrolytic degradation of cellulose [19], [20]. The absence of bead formation and the presence of carbonisation zones (3.6-4.1 cm) indicate sustained combustion and heat propagation beyond the initial contact point, a behaviour well documented for cellulosic textiles [21], [22]. Denim exhibited greater resistance to flame-this can be attributed to its dense twill weave and higher fabric mass, supporting its reported suitability for protective applications [23], [24].

Proteinaceous wool displayed comparatively limited damage, characterized by smaller, irregular holes, minimal ash formation, and a distinctive burnt-hair odour, reflecting its inherent flame resistance [13]. The nitrogen and sulphur containing amino acid structure of wool promotes char formation rather than sustained combustion, resulting in restricted thermal spread [16]. In contrary, synthetic thermoplastic fibres exhibited melting, shrinkage, bead formation and smooth fused edges due to polymer softening below decomposition temperatures [25]. The formation of hard, glossy beads and absence of ash serve as key forensic indicators distinguishing synthetic fibres from natural materials [26]. Nylon net showed extensive hole formation owing to its open mesh structure and complete filament melting, suggesting potential catastrophic failure under thermal stress [27]. Spandex demonstrated a distinct response marked by central blackening, minimal bead formation, and retained structural integrity, consistent with the pyrolytic degradation behaviour of polyurethane fibres [18].

Blended fabrics exhibited heterogeneous damage morphologies reflecting the combined responses of their constituent fibres, with simultaneous carbonisation of cellulosic components and bead formation from synthetic fibres. Features like elongated holes in poly-cotton, attributed to differential fibre shrinkage and mixed ash–bead patterns in Rubia cotton provide valuable analytic indicators for identifying blended compositions [28]. Collectively, these findings strengthen the forensic value of fibre-specific thermal damage patterns for reconstructing exposure conditions, identifying garment composition, and differentiating thermal sources in fire-related investigations.

6. Conclusion

The morphology of thermal damage on clothing can provide information about the wearer's position relative to the fire source, the duration of exposure and the intensity of thermal conditions. For example, the presence of extensive carbonization with large holes suggests prolonged exposure to direct flame, while multiple small perforations may indicate exposure to sparks or flying embers. This comprehensive study has systematically characterized the flame-induced damage patterns across twelve types of clothing, establishing a detailed understanding of how fibre composition and exposure conditions influence thermal behaviour. The findings confirm that each fabric category exhibits distinct morphological and chemical changes under controlled flame exposure, which can serve as reliable diagnostic indicators in forensic investigations. The research not only enhances the interpretive accuracy of

thermal damage on fire-exposed textiles but also provides a robust reference framework for fire reconstruction, differentiating the source of ignition and providing the expert testimony. By emphasizing on the significance of standardized documentation, advanced analytical techniques and real-world validation, this study provides a foundation for a more scientific and consistent approach to forensic textile analysis.

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