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Loop formation mechanism in the Air-Jet texturing process

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Abstract
A brief introduction to the air-jet texturing process is given, with reference to similarities between air-jet textured yarns and spun yarns, differences between them and stretch yarns, and developments in texturing nozzles. Researches undertaken at various universities on the investigation of the loop formation mechanism are reviewed. An alternative explanation of the loop formation mechanism is offered by detailed reference to current research in the Department of Mechanical Engineering at Loughborough University of Technology, this being based on high-speed photography and flow measurement methods applied mainly to the standard core HemaJet produced by Heberlein of Switzerland. It is argued that the suggested mechanism applies generally to all texturing nozzles.

1. The Air-Jet texturing process

1.1 Characteristics of the process
The majority of texturing methods comprise a simple mechanical distortion during heat treatment of the thermoplastic filaments giving them a common characteristic of high extensibility under quite low loads, due to their very open structures. In contrast, the air-jet texturing process is a purely mechanical texturing method which uses a cold air stream to produce loopy bulked yarns of low extensibility, and these more closely resemble spun fibre yarns in their appearance and physical characteristics.

The air-jet texturing process is by far the most versatile yarn texturing method in that it can "blend" filaments together during processing. This greater versatility offers the texturiser greater scope. Moreover the feed yarns need not be restricted to the synthetics, with their good thermoplastic properties.

Although the air-jet texturing process has to date achieved only marginal commercial progress and industrial acceptance, there are currently many signs of growing interest in it due to its unique characteristics as a textured yarn. Optimistic forecasts predict that air-jet yarns will replace approximately 20% of the present spun yarns by the year 2000, and they have the potential to replace another 20% of the polyester filament yarns which are textured today by the false-twist method [1].

1.2 Air-Jet textured yarns
Any yarns made from synthetic fibres are largely aimed to be competitive with yarns made from the older established natural fibres by simulating spun staple yarns. Yarns produced by the air-jet technique are unique in that they more closely simulate spun yarn structures; whereas the bulkiness of stretch yarns decreases with the degree of tension imposed on them, the form of air textured yarns can be made to remain virtually unchanged at loads corresponding to those normally imposed in fabric production and during wear. This is due to the "locked-in" entangled loop structure attributed to air-jet textured yarns. Air-jet textured yarns again more closely resemble conventional ly spun yarns in that the yarn surface is covered with fixed resilient loops, and these serve the same purpose as the protruding hairs in spun yarns by forming an insulating layer of entrapped still air between neighbouring garments.
Since air-jet yarns more closely resemble conventionally spun yarns than do the stretch yarns, the future competition could be between air-jet yarns and conventional spun natural fibre or mixed fibre yarns. Along with desirable properties such as high abrasion resistance, higher tenacity, more uniform structure, low gloss, low pilling, and greater bulk for equal fineness, the conversion costs also favour the air-jet texturing process [1, 2].

### 1.3 Developments of texturing nozzles

The development of industrially used texturing nozzles was reviewed by Acar [3]. Despite the dissimilarities in the design of the nozzles, the underlying principles of all texturing nozzles have remained unchanged because the essential requirement is to create a highly turbulent and asymmetrical air flow to disturb overfed filaments at supersonic speeds.

![Fig.1 Schematic diagram of the standard-core HemaJet nozzle.](image)

For example the design of Heberlein's standard-core HemaJet, one of today's best known nozzles, is such that a supersonic, turbulent and asymmetric flow is created by mixing the flow from three small staggered air inlet nozzles into the main flow channel of the nozzle (fig. 1). In other types of texturing nozzles, e.g. the more recent Du Pont Taslan types, this is achieved by other possible arrangements such as asymmetric air passage holes or gaps on one side of the nozzle and a converging-diverging section attached to the downstream flow part of the texturing nozzle assembly.

The developments in nozzle design since the process was introduced in the early 1950s have led to:

i. increased texturing speeds from 50 to 500 m/min;
ii. reduced air consumptions from about 20 to 14 m³/hr (Taslan) and 12 m³/hr (standard-core HemaJet);
iii. better yarn quality; and
iv. elimination of the necessity for a pre-twisted supply yarn.

### 2. Review of the research investigations on the mechanism of loop formation

Little published information has been available regarding how the texturing effect is achieved, and particularly how the air flow is related to the mechanism of loop formation. One of the authors, G. R. Wray undertook research (UMIST 1963 to 1966) based on the Taslan Type 9 jet which was the most universally used nozzle at that time [4, 5]. He explained the loop formation by a false-untwisting theory according to which the rotational nature of the turbulent air stream in the wake of the feed needle first convoluted the overfed filaments into U-shaped waves which in turn snarled into looped coils owing to the twist liveliness of the slack-ended filaments. This theory presupposed that a vortex-shedding action was occurring into the venturi to cause the observed rotations of the textured yarns.
In 1970 research undertaken at Loughborough University by H. SEN [6] under G. R. WRAY's supervision, led to a more satisfactory interpretation of the bulking action of the air-jet texturing. A dynamically similar scaled-up model of Taslan Type 9 jet showed that the yarn structure inside the nozzle was open and the bulking action was seen to occur at the nozzle exit. This research used "Schlieren photography" to show that shock waves occurred at the nozzle exit; it also verified by measurement that periodic shedding of the vortices in the wake of yarn feed needle could not exist at the highly turbulent operational speeds of the air flow. SEN concluded that the previously suggested false-untwisting vortex mechanism was invalid, although the overall principle of bulking by a temporary removal and reassertion of the twist was still applicable. He suggested an alternative mechanism of loop formation:

The highly turbulent air flow blows the overfed feeder yarn out of the nozzle, and thus causes the portion of the yarn immediately following it to be in high tension. At the exit of the nozzle, the yarn changes its path abruptly as it is withdrawn at a right angle to the jet axis. Due to the momentum of the blown out yarn, the end of the yarn being withdrawn from the nozzle exit is subjected to an alternating force at right angles to its axis. As a result of this, a false-un-twisting effect is created such that it untwists the portion of the parent yarn inside the nozzle and thus its structure is opened. Then when the opened overfeed yarn is blown out, the extra available filament lengths snarl into a looped and entangled state at the nozzle exit under the extremely violent (turbulent) nature of the flow.

In 1975, V. R. SIVAKUMAR [7] interpreted SEN's findings in a slightly different way and he extended the research into the use of a nozzle based on the principles of Taslan Ty-pe 10 jet, but still using pre-twisted feed yarns. He verified the existence of shock waves in the flow by theoretical means and concluded that shock waves play a very important role in loop formation by forming a "pressure barrier" and "retarding" the filaments at their place of occurrence. He claimed that: when a pre-twisted parent yarn is overfed into the nozzle it comes under the influence of the air-flow, and it is suddenly retarded when it is forced against this pressure barrier. This causes the tension in the twist-lively yarn to decrease suddenly to cause snarling of the individual filaments. When these snarled filaments are subjected to the turbulence caused by the shock waves, they are entangled with each other and held together by inter-filament friction and the reasserted twist when the yarn is wound up. Therefore, all the hypotheses to date have been based on the assumption that the feed yarns are pre-twisted. Consequently they are invalid for current processing technologies where no pre-twist is involved and yet good quality textured yarns are produced at higher speeds with relatively reduced air consumption rates.

Some attempts have been made to improve the understanding of the events that occur during texturing of zero-twist yarns by today's texturing jets. G. BOCK [9] and G. BOCK and J. LUNENSCHLOSS [8, 10] have recently attempted to describe the loop formation mechanism. They gave evidence of asymmetry in the flow and argued that this asymmetry alters the forces acting on the separated individual filaments, which in turn cause longitudinal displacement of the filaments with respect to each other. However they are of the opinion that the loop formation mechanism is based on the retardation of filaments by shock waves although they have apparently advanced little further than the tentative descriptions of loop formation and texturing offered by SIVAKUMAR [7] to interpret SEN's observations of shock waves [6]. They also argued that there is a force within the stream which causes the filaments to change their directions of travel, otherwise the bending of the filaments would not be possible, and they concluded that this bending force is due to the pressure barrier or pressure variations caused by the shock waves. The validity of such mechanisms based on the deceleration of the filaments by shock waves and changing the direction of the filaments by such forces existing in the flow, will be discussed in Section 3.
3. Further studies of the process

In this present paper a further contribution to the understanding of the air-jet texturing process is attempted, based on the work currently being undertaken mainly on the Heberlein standard-core HemaJet, using a single head texturing machine (schematically shown in fig. 2), which was purpose designed and built at Loughborough University of Technology to give maximum flexibility to the processing parameters.

3.1 Air flow and its effects on the filaments

Axial velocities of the undisturbed air flow were measured by using a dynamically similar, linearly 4-times scaled-up model of the HemaJet texturing nozzle. Modelling was required because the minute size of the actual texturing nozzle made the use of measuring probes impracticable due to their interference with the flow. Velocity measurements in general showed that air flow is super-sonic at the exit region of the nozzle at working pressures used in texturing.

A typical distribution of the air velocity outside the nozzle at 7 bar (abs) working pressure is shown in fig. 3. This shows that the velocity distribution is not uniform.

High-speed photographs of filaments that were left free in the air flow rather than being turned at right angles to the jet axis show that these are separated and dispersed across the nozzle due to the effects of the turbulent flow. It was also evidenced that filaments left free in the flow travel at very high speeds compared with the yarn texturing production speed [3]. This is also the case for overfed filaments which have excess lengths free to travel within the air flow.

Fig. 2 Diagram of the purpose-built single-head texturing machine. 1: Water; 2: Compressed air; 3: Single yarn; 3/4: Core/effect; 5: Parallel; and 6: Take-up

Fig. 3 Axial velocity profiles: a) distribution of air velocity. a) at the exit plane; b) at one diameter away from the exit plane

Fig. 4 Filaments left free in the air flow
It can be argued that the separated filaments at different locations in the nozzle are under the effect of different drag forces which are proportional to the square of the local air velocity. Therefore at any instant, some filaments move relatively faster than the others resulting in a longitudinal inter-filament displacement [5]. These filaments are more likely to form loops. Since the filaments change their positions because of the swirling and turbulent flow, an individual filament may go through variations in the drag force acting on it as the process continues, and may have randomly distributed loops along its length.

Fig. 4 which is one of many such photographs clearly indicated that filaments that were left free in the air flow showed no sign of changing their directions at right angles to the jet axis due to any forces existing in the air stream [10].

3.2 Shock waves

Compression shocks are expected in a supersonic free jet when the flow pressure at the exit of the nozzle is less than the ambient pressure. Observation of such shock waves with texturing nozzles goes back to 1970, when Sen [6] visualized the flow with a Taslan 9 jet by using "Schlieren photography". These photographs have only recently been more widely published [3]. The existence of shock waves was also theoretically proved by Sivakumar [7] in 1975 with Taslan 10. Recently shock waves have also been observed by Bock [9] with a Taslan 14 jet. In all of these flow visualizations the air flows were free of any interference by the filaments themselves. Naturally during actual texturing conditions, the filaments are present within the air flow and this would disturb the flow and hence affect the formation of the shock waves. Fig. 5 shows shadowgraphs obtained from a Taslan nozzle. These show shock waves at (a) with a free undisturbed air flow but these were destroyed when filaments were present in the nozzle as shown at (b) and (c) which were photographed from different directions at right angles to each other. Similar observations were made with the HemaJet nozzle. Therefore the validity of the loop formation mechanism based on the deceleration of the filaments by the shock waves, and the possibility of changing the direction of the filaments by any forces existing in the flow due to these shock waves were found to be very unlikely.

![Fig. 5 "Shadowgraphs" from Taslan nozzle at a working pressure of 8 x 10^5 N/m^2 (gauge). A) with free undisturbed air flow (no yarn in the nozzle), b) and c) with disturbed air flow (yarn present in the nozzle) ](image)

3.3 High-speed photography

High-speed still photographs of 400 nanosecond exposure time, and cine photographs at 20 000 frames per second were taken during processing with the actual HemaJet texturing nozzle. A general analysis of these showed that texturing starts in the outlet of the nozzle and it is completed at the immediate exit area outside the nozzle.
Fig. 6a shows a yarn being textured, the supply yarn having been passed through water before being fed into the nozzle. It illustrates that loops are being formed as the filaments emerge from the nozzle and that these filaments occupy the lower half of the nozzle outlet. It also shows that the tension in the textured yarn is sufficiently high to pull the yarn close to the nozzle exit in a straightened form. When the yarn is textured without wetting the filaments, the loop formation is not so effective and the tension in the yarn becomes so low that the textured yarn is blown in a straight direction from the nozzle (fig. 6b and c). In this case no loops are formed at the nozzle exit, the filaments being scarcely separated as they are blown out in a virtually parallel direction along the nozzle exit. This condition of poor loop formation (Fig. 6c) was observed to occur very frequently in dry texturing and is adversely compared to fig. 6a which typifies wet texturing conditions.

![Fig. 6 High-speed still photographs during texturing. A) Wet texturing condition whereby the yarn tension is high; b) Dry texturing condition whereby the yarn tension is low; c) Dry texturing condition with even lower yarn tension than shown in b).](image)

Analysis of high-speed cine-films confirmed that very frequently in dry texturing and only occasionally in wet texturing, the filaments emerging from the nozzle become very un-stable with poor separation and occupy the central part of the nozzle exit where the axial velocity distribution is relatively constant; therefore almost all the filaments are under the effect of an approximately constant drag force, each of them emerging from the nozzle at about the same speed. Thus, no longitudinal displacement of the filaments relative to each other is expected and very poor loop formation takes place in such cases.

![Fig. 7 Schematic representation of the separated swirling filaments as they emerge from the nozzle; 1. Entanglement zone; 2. Swirl; 3. Textured yarn; 4. Exit from nozzle; 5. Spread-out bundle of filaments](image)
In order to give more insight to the loop formation mechanism, 100 still photographs of each dry and wet texturing run were taken and individually analysed. As shown in Fig. 7, the point remotest from the nozzle exit plane at which loops were instantaneously being formed was measured by a horizontal coordinate, \( x \), from this plane and by a vertical coordinate, \( y \), from the nozzle axis. The vertical distance, \( d \), from the nozzle axis to the uppermost filament in the emerging bundle was also measured.

The existence of a point where the filaments are assumed to be "inter-lacing" or "integrating" as suggested by Luenenschloss and Bock [10] was very difficult to determine except when the filaments were blown well away from the nozzle to give poor loop formation. In the case of effective loop formation, e.g. in wet texturing, it was observed that the loops were formed as the filaments emerged from the nozzle, thus keeping the textured yarn close to the nozzle exit by giving a rise to the yarn tension. Therefore it is misleading to explain the loop formation by "interlacing" or "integration" points which are only observed under those poor texturing conditions when filaments are blown well away from the nozzle.

The results of the analysis summarised in Figs. 5a and 5b show that the filaments occupy the lower half of the nozzle exit area in most cases, regardless of whether the yarn is wet or dry textured. They also show that the filaments are pulled further down and closer to the nozzle exit in wet texturing conditions than in dry texturing. The better loop formation achieved in wet texturing shortens the overall length of the textured yarn, consequently increasing the tension in the yarn and pulling the emerging, loop-forming filaments down and against the nozzle (downwards take-off).

### 3.4 Yarn tension

The variations in the average tension in the yarn between the nozzle and the take-up rollers (W2) was evidenced by tension measurements for wet and dry processing. Fig. 9 shows tension variations for wet and dry processing conditions at varying overfeed ratio and illustrates that the average tension in the yarn is much higher when the yarn is wetted before it enters the nozzle. Similar effects are also obtained by varying other processing parameters such as air pressure and production speed. In practice, it is very well known that wetting the supply yarn results in more effective loop formation and hence gives better texturing. These results indicate that the increased tension in the yarn is caused by the shortening if its length resulting from better loop formation.

### 3.5 Conclusions

Air flow has greater asymmetry and swirl inside the nozzle which diminishes outside where it is super-sonic and turbulent with a nonuniform profile. Since the filaments are separated and change their positions across the nozzle at very high frequencies, some of them move instantaneously faster than the others due to the nonuniform velocity distribution. The speeds of the filaments are much
faster than the yarn texturing speed. Shock waves are at least partially disturbed by the fila-
ments which do not change their di-rections of motion due to any forces existing in the air stream. Tensions
are created in the yarn as a natural consequence of loop formation. Such tensions are higher under
good texturing conditions.

Fig. 9 Variations of the average yarn tension based on varying overfeed ratios. A) Yarn
tension [g]; B) Overfeed [%]; 1) Wet texturing conditions; 2) Dry texturing conditions

4. The loop formation mechanism

Usually there are many filaments in a supply yarn, but in order to explain the loop formation
mechanism, it is simpler to consider only a few fila-
ments emerging from the nozzle as shown in fig.
10. At any instant some of these filaments will be moving at faster speeds than others. The free
excess lengths provided by over-feeding the filaments enable the fas-ter moving filaments to slip
and be displaced longitudinally with respect to relatively slower moving filaments. The amount of
this longitudinal dis-place-ment is affected by local forces instantaneously acting on the fila-
ments (including friction) and by the overfeed ratio. The textured yarn is delivered at right angles to the
noz-zle axis and travels at the final yarn production speed (i. e. texturing speed). Since the yarn
length is shortened as a result of loop forma-
tion, this creates a tension in the yarn of a magnitude
determined by the effectiveness of the texturing. Thus on the one hand the emerging fila-
ments are
blown out of the nozzle along the direction of the air flow at much faster speeds than the yarn
texturing speed; on the other hand the tension in the yarn pulls the "leading ends" of the emerging fila-
ments in the direction of the yarn de-livery (i.e. at right angles to the noz-zle axis). Since the
"trailing ends" of the filaments are held within the noz-
ze, these filaments are forcibly bent into
bows and loops. These are then entangled with other instantaneously emerging filaments and
become fix-ed stable loops within the textured yarn structure.

The filaments continually change their position across the nozzle due to the dual effect of the


The filaments continually change their position across the nozzle due to the dual effect of the
turbulent swirling air flow and the tension in-duced by the loop formation process itself. Therefore
different filaments go through this process at different instants and the cycle repeats itself
randomly.

This can be illustrated in fig. 10 which is a simplified schematic dia-gram with only a few filaments
repre-
senting the behaviour of a more complex multi-filament yarn. In fig. 10a filament 1 is the
fastest moving filament having the greatest longitud-inal displacement with respect to all others and
is blown furthest out of the nozzle to form a loose bow or loop. An instant later, in fig. 10b, it is
formed into a fixed loop L 1 within the textured yarn as a result of mutual entanglement of the
filaments. This newly formed fixed loop L 1 increases the tension in filament 1 thereby causing a
change in its position and also contributing to the total yarn tension which is pulling the yarn down closely to the nozzle. Meanwhile filament 2 comes under the action of a greater drag force as a result of changes in the positions of the filaments across the nozzle due to the turbulence and swirl and this now becomes the fastest moving filament so causing it to be blown out and displaced longitudinally with respect to others to form a loose bow or loop. Immediately afterwards whilst filament 2 is being similarly entangled into a fixed loop L2, a further filament 3 commences a similar loop formation process (fig. 10c). Since there are many filaments in an actual supply yarn rather than the five illustrated in fig. 10 several loops are formed at any particular instant and these help each other to be fixed and locked within the yarn structure by mutual entanglement.

This mechanism of loop formation is valid for all types of texturing nozzles, despite detailed differences in their design, because the underlying requirement to create supersonic, asymmetric, turbulent and nonuniform flow is essential for satisfactory texturing.

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