Loop formation mechanism in the Air-Jet texturing process

M. Acar, A. J. Alexander, R. K. Turton, G. R. Wray

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 underta-ken at various universities on the investigation of the loop formation mechanism are reviewed. An alternative explana-tion of the loop formation mechanism is offered by detailed reference to current research in the Department of Mechani-cal Engineering at Loughborough University of Technology, this being based on high-speed photography and flow mea-surement methods applied mainly to the standard core HemaJet produced by Heberlein of Switzerland. It is argued that the suggested mechanism applies generally to all tex-turing nozzles.

1. The Air-Jet texturing process

1.1 Characteristics of the process

The majority of texturing methods comprise a simple mechanical dis-tortion during heat treatment of the thermoplastic filaments giving them a common characteristic of high ex-tensibility under quite low loads, due to their very open structures. In con-trast, the air-jet texturing process is a purely mechanical texturing method which uses a cold air stream to pro-duce loopy bulked yarns of low extensibility, and these more closely re-semble spun fibre yarns in their ap-pearance and physical characteris-tics.

The air-jet texturing process is by far the most versatile yarn texturing method in that it can "blend" fila-ments together during processing. This greater versatility offers the tex-turiser greater scope. Moreover the feed yarns need not be restricted to the synthetics, with their good ther-moplastic 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 fila-ment 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 es-tablished 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 bulki-ness of stretch yarns decreases with the degree of tension imposed on them, the form of air textured yarns can be made to remain virtually un-changed 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 en-trapped still air between neighbour-ing garments.

Since air-jet yarns more closely re-semble 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 ab-rasion 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 under-lying principles of all texturing noz-zles have remained unchanged be-cause the essential requirement is to create a highly turbulent and asym-metrical air flow to disturb overfed filaments at supersonic speeds.

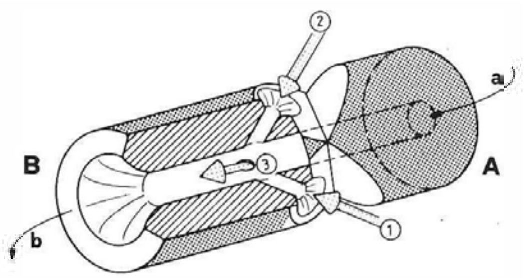


Fig.1 Schematic diagram of the standard-core HemaJet nozzle. 1, 2, 3: Air inlets; A: Yarn entry of nozzle; B: Yarn exit of nozzle; a: Feed yarn; b: Textured yarn

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 pos-sible arrangements such as asym-metric air passage holes or gaps on one side of the nozzle and a con-verging-diverging section attached to the downstream flow part of the tex-turing 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 noz-zle at that time [4, 5]. He explained the loop formation by a false-untwisting theory according to which the ro-tational nature of the turbulent air stream in the wake of the feed nee-dle first convoluted the overfed fila-ments into U-shaped waves which in turn snarled into looped coils owing to the twist liveliness of the slack-ened filaments. This theory presup-posed 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 interpreta-tion 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 noz-zle exit. This research used "Schlieren photography" to show that shock waves occurred at the nozzle exit; it also verified by mea-surement 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 pre-viously suggested false-untwisting vortex mechanism was invalid, al-though the overall principle of bulk-ing by a temporary removal and reassertion of the twist was still appli-cable. 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 ab-ruptly 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 al-ternating 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 ex-tremely violent (turbulent) nature of the flow.

In 1975, V. R. SIVAKUMAR [7] inter-preted 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 impor-tant role in loop formation by forming a "pressure barrier" and "retarding" the filaments at their place of occurr-ence. He claimed that: when a pre-twisted parent yarn is overfed into the nozzle it comes under the influ-ence of the air-flow, and it is sudden-ly retarded when it is forced against this pressure barrier. This causes the tension in the twist-lively yarn to de-crease 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. There-fore, all the hypotheses to date have been based on the assumption that the feed yarns are pre-twisted. Con-sequently they are invalid for current processing technologies where no pre-twist is involved and yet good quality textured yarns are produced at high-er 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, 1 OJ have re-cently attempted to describe the loop formation mechanism. They gave evidence of asymmetry in the flow and argued that this asymmetry al-ters the forces acting on the sepa-rated individual filaments, which in turn cause longitudinal displacement of the filaments with respect to each other. However they are of the opin-ion that the loop formation mechan-ism is based on the retardation of filaments by shock waves although they have apparently advanced little further than the tentative descrip-tions of loop formation and texturing offered by SIVAKUMAR [7] to inter-pret 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 fila-ments 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 decelera-tion of the filaments by shock waves and changing the direction of the fila-ments 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 con-tribution 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 sin-gle head texturing machine (schematically shown in fig. 2), which was purpose designed and built at Loughborough University of Technology to give maximum flexibil-ity to the processing parameters.

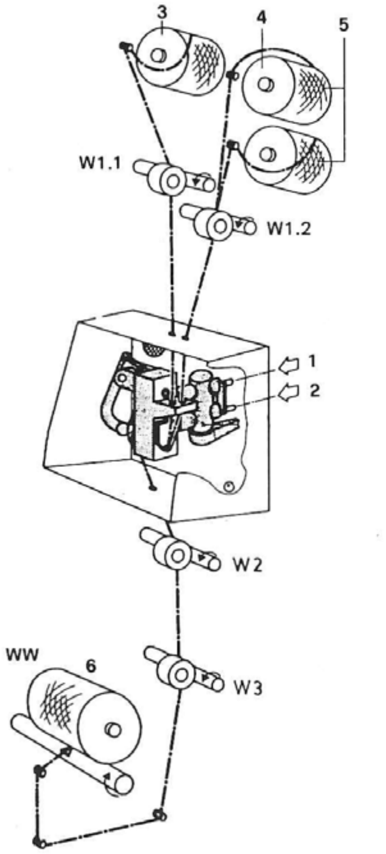


Fig. 2 Diagram of the purpose-built single-head texturing machine. 1: Water; 2: Compressed air; 3: Single yarn; 3/4: Core/effect; 5: Parallel; and 6: Take-up

3.1 Air flow and its effects on the filaments

Axial velocities of the undisturbed air flow were measured by using a dy-namically similar, linearly 4-times scaled-up model of the HemaJet tex-turing nozzle. Modelling was re-quired because the minute size of the actual texturing nozzle made the use of measuring probes impractic-able due to their interference with the flow. Velocity measurements in gen-eral showed that air flow is super-sonic at the exit region of the nozzle at working pressures used in tex-turing.

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

High-speed photographs of filaments that were left free in the air flow rather than being turned at right ang-les to the jet axis show that these are separated and dispersed across the nozzle due to the effects of the turbu-lent 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 fila-ments which have excess lengths free to travel within the air flow.

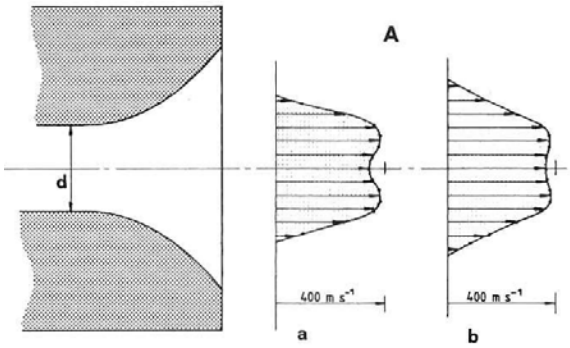


Fig. 3 Axial velocity profiles: a distribution of air velocity. a) at the exit plane; b) at one diameter away from the exit plane

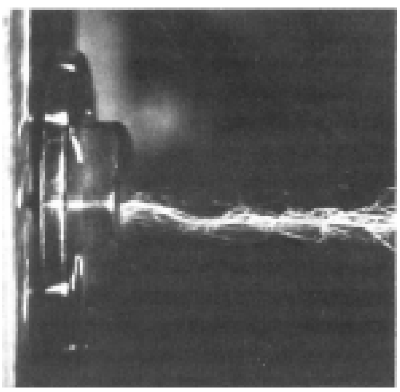


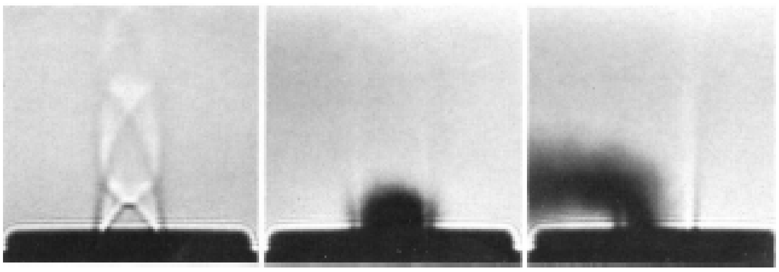
Fig. 4 Filaments left free in the air flow

It can be argued that the separated filaments at different locations in the nozzle are under the effect of different drag forces which are propor-tional to the square of the local air velocity. Therefore at any instant, some filaments move relatively fas-ter than the others resulting in a lon-gitudinal 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 fi-laments 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. Ob-servation 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 exist-ence of shock waves was also theoretically proved by Sivakumar [7] in 1975 with Taslan 10. Recently shock waves have also been ob-served by Bock [9] with a Taslan 14 jet. In all of these flow visualizations the air flows were free of any interfer-ence by the filaments themselves. Naturally during actual texturing con-ditions, 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 di-rections 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 decelera-tion of the filaments by the shock waves, and the possibility of chang-ing the direction of the filaments by any forces existing in the flow due to these shock waves were found to be very unlikely.



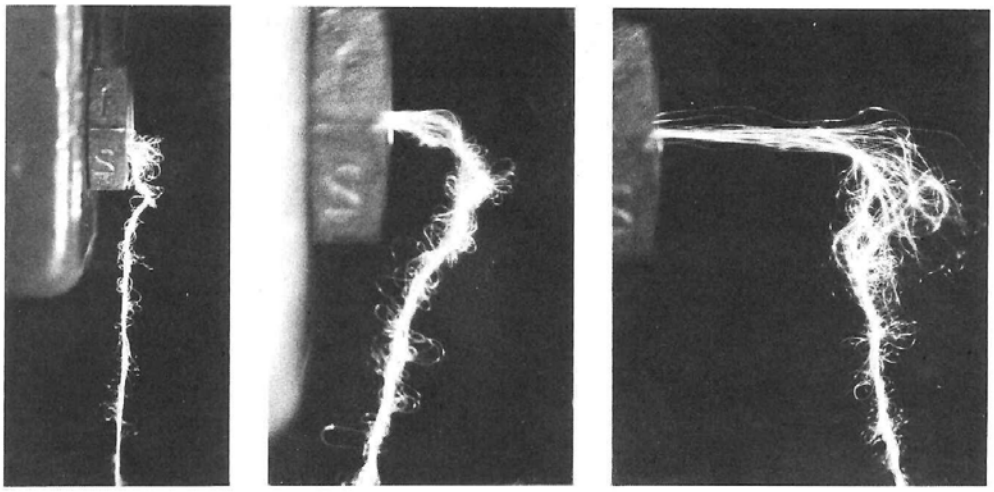
(a) (b) (c)

Fig. 5 "Shadowgraphs" from Taslan nozzle at a working pressure of 8 x 105 N/m2 (gauge). A) with free undisturbed air flow (no yarn in the nozzle), b) and c) with disturbed air flow (yarn present in the nozzle)

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 proces-sing with the actual HemaJet textur-ing nozzle. A general analysis of these showed that texturing starts in the outlet of the nozzle and it is com-pleted at the immediate exit area out-side 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 fila-ments occupy the lower half of the nozzle outlet. It also shows that the tension in the textured yarn is suffi-ciently high to pull the yarn close to the nozzle exit in a straightened form. When the yarn is textured with-out 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 for-mation (Fig. 6c) was observed to oc-cur very frequently in dry texturing and is adversely compared to fig. 6a which typifies wet texturing condi-tions.



(a) (b) (c)

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).

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 dis-placement of the filaments relative to each other is expected and very poor loop formation takes place in such cases.

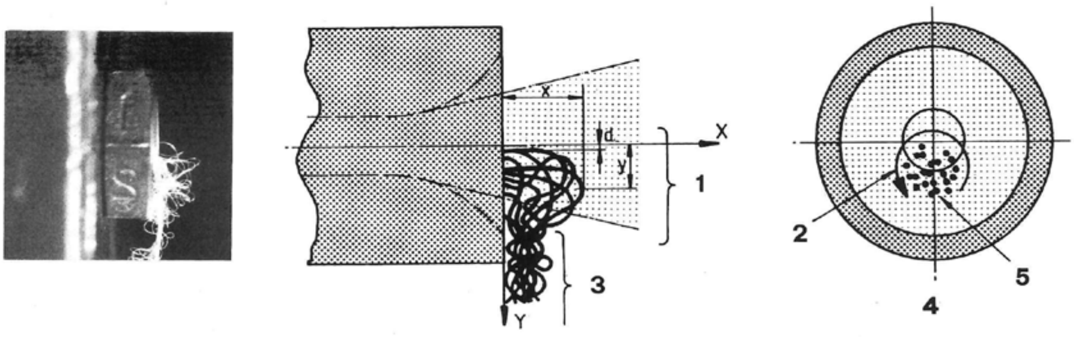


Fig. 7 Schematic representation of the separated swirling fila-ments as they emerge from the nozzle; 1. Entanglement zone; 2. Swirl; 3. Textured yarn; 4. Exit from nozzle; 5. Spread-out bundle of filaments

In order to give more insight to the loop formation mechanism, 100 still photographs of each dry and wet tex-turing run were taken and individual-ly analysed. As shown in Fig. 7, the point remotest from the nozzle exit plane at which loops were instan-taneously being formed was mea-sured 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 fila-ment in the emerging bundle was al-so measured.

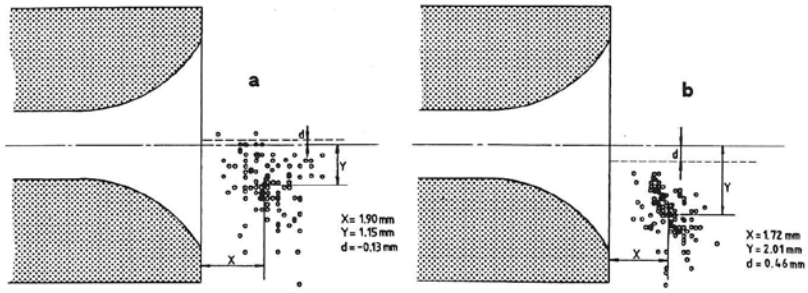


Fig. 8 Results of the analysis of 100 high-speed photographs, a) average values for dry texturing conditions; b) average values for wet texturing conditions

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 fila-ments 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 mis-leading to explain the loop formation by "interlacing" or "integration" points which are only observed under those poor texturing condi-tions 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, re-gardless 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 {down-wards 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 evi-denced 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 be-fore it enters the nozzle. Similar ef-fects 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 forma-tion and hence gives better texturing. These results indicate that the in-creased tension in the yarn is caused by the shortening if its length result-ing from better loop formation.

3.5 Conclusions

Air flow has greater asymmetry and swirl inside the nozzle which di-minishes outside where it is super-sonic and turbulent with a nonuniform profile. Since the fila-ments 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 fila-ments 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.

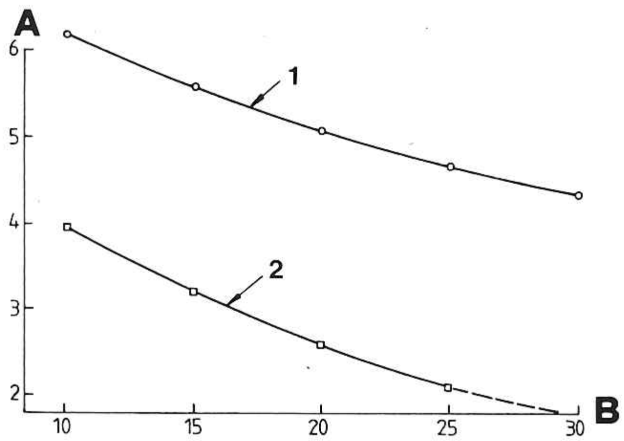


Fig. 9 Variations of the average yarn tension based on varying overfeed ratios. A) Yarn tension [g]; B) Overfeed [%]; 1) Wet texturing conditions; 2) Dry texturing conditions

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-placement 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-zle, 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 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 ten-sion which is pulling the yarn down closely to the nozzle. Meanwhile fila-ment 2 comes under the action of a greater drag force as a result of changes in the positions of the fila-ments across the nozzle due to the turbulence and swirl and this now be-comes the fastest moving filament so causing it to be blown out and dis-placed longitudinally with respect to others to form a loose bow or loop. Immediately afterwards whilst fila-ment 2 is being similarly entangled into a fixed loop L2, a further filament 3 commences a similar loop forma-tion process (fig. 10c). Since there are many filaments in an actual supply yarn rather than the five illu-strated 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.

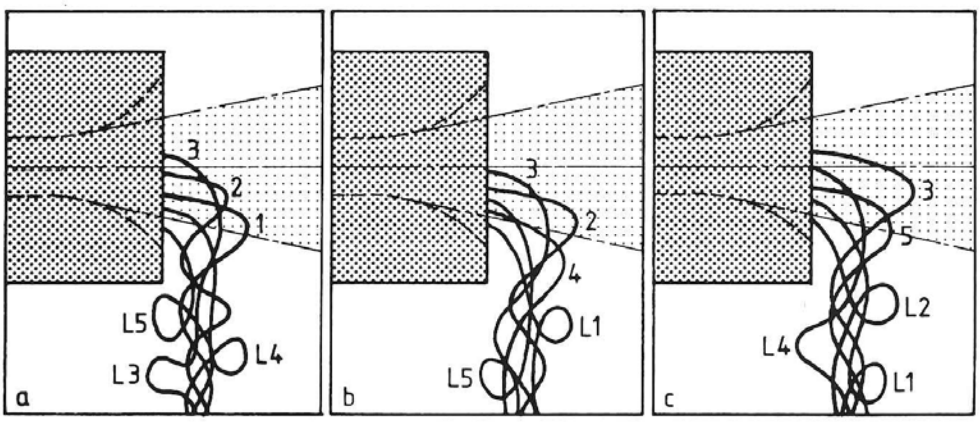


Fig. 1o Schematic illustration of the mechanism of loop formation

This mechanism of loop formation is valid for all types of texturing noz-zles, 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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