PFANF8 (2003) 5:73-80

Failure Analysis of Tire Tread Separations

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(Submitted 28 April 2003; in revised form 27 June 2003)

In-service catastrophic radial tire failure is often a separation of the tread and outer steel belt from the tire casing and inner steel belt. These separations generally occur in the field at high temperature and high speed. This paper presents a catalog of surface characteristics that define the various types of rubber cracking that take place during a tire belt-leaving-belt separation. A mechanism that explains the generation of the rapid tearing surface is used to detail the variation found in forensic examinations.

Keywords: delamination, rubber tearing, separation, tire, tread

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Introduction

Tire failure analysis is often focused on the mechanism of the separation of the tread and outer steel belt from the tire casing and inner steel belt. The analyst must determine the point of origin of the separation from the appearance of the fracture surfaces. Smith[1] described the microscopy of tire tread pieces gathered from roadsides in Arizona, California, and New Mexico. However, it is often the case in actual forensic investigation that the tire tread pieces are not recovered, leaving the analyst to deal with examining the exposed outer surface of the inner steel belt. This situation accentuates the importance of understanding the appearance of the tire casing fracture surface. Also, in field tread separation events, the fracture surfaces can often be confounded by pre-tear polishing, post-separation skidding, and impact damage.

The objective of this paper is to document the appearance of the outer skim surface of the inner steel belt after a tread separation. Daws[2] characterized four general types of fracture surfaces found on tire belt-leaving-belt separations by producing those surfaces in a laboratory setting. These four surface types were defined as edge cracks, initiation zone, rapid tearing region, and termination point. The appearance of these surfaces correlated extremely well with those found on tires that had experienced belt-leaving-belt separations in actual field service.

This paper expands on the four characteristic surface types by developing the mechanism by which the fracture surface is generated in the rapid tearing region. The mechanism is used to explain the various ways in which the characteristic surface in this type of tearing can be developed.

General Discussion

The modern steel-belted radial tire incorporates two steel belts, with twisted steel cord embedded as reinforcement in the rubber of the tire. Figure 1 shows a tire that has been sectioned to show the steel belts and their position on the casing body ply cords. As seen in Fig. 1, the steel wires of the inner and outer steel belts are laid in different directions in order to provide a reinforcement of the tread area. The resulting rubber-steel composite carries the loads associated with the road contact of the vehicle on which it is mounted. In the inflated and undeformed state, any portion of the tire's tread and steel belt system will normally have a compound curvature. When the tread and steel belt system comes in contact with the road, the geometry must conform to the road surface. This imposed geometry creates a shear strain between the inner and outer steel belts. The strain is due to the asymmetry inherent in each

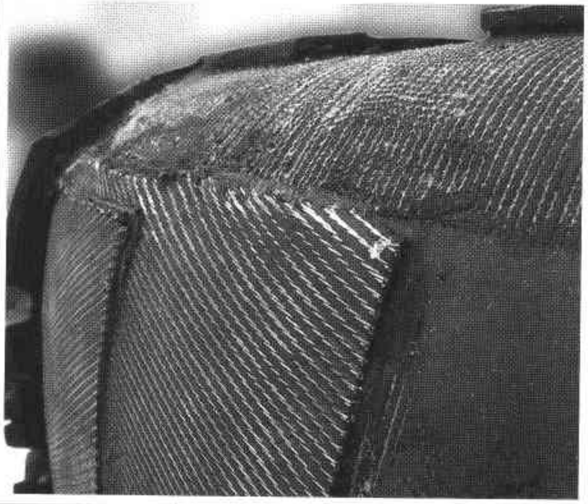

Fig. 1 *Radial tire cutaway showing the steel belt reinforcement system*

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of the steel belts and is a result of the different orientations of the steel wires relative to the tire centerline. The corresponding shear stress in the rubber between the steel belts depends on many variables, but it is essentially a cyclic stress that has the potential to cause a fatigue failure that begins at the edge of the outer steel belt.

The edge of the steel belt is also a critical location in the tire because the rubber is not bonded to the steel at the ends of each steel wire. In tires, the bond between the rubber and the steel is created during vulcanization and depends on excess sulfur in the rubber reacting with copper to produce crystals of CuS on the surface of the wire. To provide the copper, the steel wires are first plated with brass. The wires are then covered with rubber in a calendering operation. The resulting sheets are then cut on a bias to produce strips of steel belt material. Therefore, no bond is possible at the cut ends of the wires because the cut ends were not plated with brass. The lack of bonding ensures the development of microcracks at the belt edge.

The presence of microcracks in a location where cyclic stresses are present guarantees that there will be some level of growth of the microcracks. In normal tire design, the growth rate, and the size, of these cracks remains very small throughout the useful life of the tread. However, in some cases, especially where the tire has been operated in an overloaded or underinflated state, microcracks have the opportunity to grow rapidly and lead to premature failure of the tire. In these cases, one of the more common failure modes is where the tread and outer steel belt separate from the casing and inner steel belt. This mode of separation is commonly known as a *belt-leaving-belt separation.*

In creating tire belt-leaving-belt separations in a laboratory setting, several observations were noted by Daws.[2] First, the tire casing never lost pressure during the separation event. Second, the laboratory tread separations always generated two triangular flaps at the region of initiation. This flap pair consisted of one flap, formed by a triangular piece of tread and outer steel belt bounded by a wire of the outer steel belt, that opened in a direction opposite to the direction of rotation of the tire. The second of the flaps was adjacent to the first along the same outer steel belt wire and opened in the tire's direction of rotation. The two triangular flaps were always bounded by an initial separation line that followed one of the wires in the outer steel belt. The first of these flaps has been called a "leading edge flap" because its triangular end at the tire shoulder points in the direction of tire rotation. The second flap is normally called a "trailing edge flap" for similar reasons. Another observation was that the leading edge flap propagates at a much higher velocity than the trailing edge flap, due primarily to contact of the flaps with external surfaces. Also, the tearing of the flaps from the tire casing normally begins when the flap widths approach the width of the attached tread.

Fracture Surface Observations

General

Daws[2] cataloged four main types of fracture surfaces. The first of these was the surface associated with circumferential cracks on both edges of the two steel belts. These edge cracks initiate at the belt edge in all steel-reinforced radial tires. The second type of crack surface cataloged was associated with the centrifugal forces generated by the flaps at the initiation of the belt-leaving-belt separation process. The third crack region cataloged was associated with the rapid tearing of the tread and outer steel belt away from the inner steel belt. The fourth crack region was associated with the final separation. Examples of each of these surfaces are shown in this paper, followed by a detailed discussion of the rapid tearing process.

Edge Crack Generation

Smith[1] called the circumferential cracks "ring tears" and associated them with small-scale cyclic deformations of the belt edges. These edge cracks propagate radially* into the skim rubber between the two steel belts. It is recognized generally that the rate of propagation of these cracks accelerates as the depth of the crack increases. Further, minute variations in geometry that result from the process of building tires and statistical variation always present in the crack initiation and development processes cause the cracks to initiate at different times and develop with different initial growth rates. For

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*In this text, the radial direction is taken to lie along the casing body ply cords in the plane of the casing. The circumferential direction is taken normal to the radial direction in the plane of the casing.

these reasons, the depth of the circumferential cracks around the tire is variable.

Figure 2 shows a photograph* of edge cracks that were generated in the laboratory. The smooth surface in the lower third of the figure is a region that had been cut with a knife in order to facilitate rapid separation in the laboratory. The cracks grew from this knife-cut region toward the centerline of the tire. The edge cracks have a characteristic ridge appearance and are oriented vertically in Fig. 2. The definition of these cracks is very sharp because they were generated in seconds in the laboratory setting, as opposed to a field tire failure where the crack growth generally takes place over years. Figure 3 shows a micrograph of a small region of the edge cracks. Beach marks running perpendicular to the direction of crack growth can be clearly seen. These beach marks denote the crack tip or front at a particular time in the crack development sequence. Note that the beach marks terminate at what appear to be ridges or radially oriented steps. These ridges separate regions where the crack growth from each initiation point occurs on a slightly different path within the bulk of the skim rubber. The radial tear ridges are also the predominant visual aspect of the edge tears.

Figures 4 and 5 show the zone of edge cracking in tires that experienced field service** tread separa-

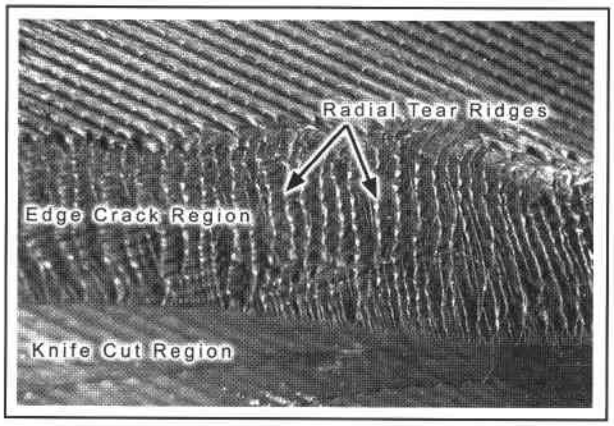

Fig. 2 *Edge cracks created in a laboratory tire tread separation*

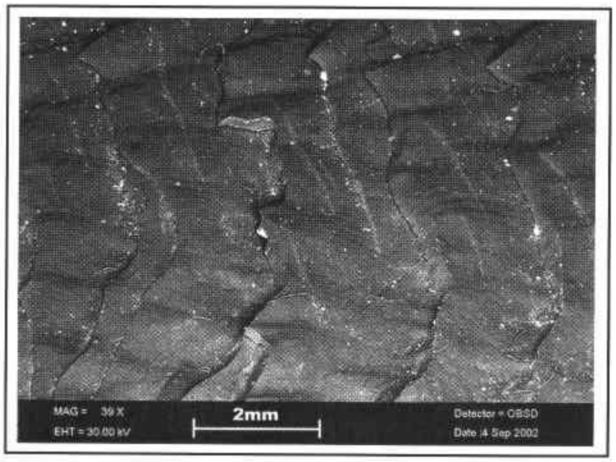

Fig. 3 *Micrograph of edge cracks showing beach marks and radial tear ridges*

Fig. 4 *Sample of edge cracks occurring in a field tire tread separation (serial side)*

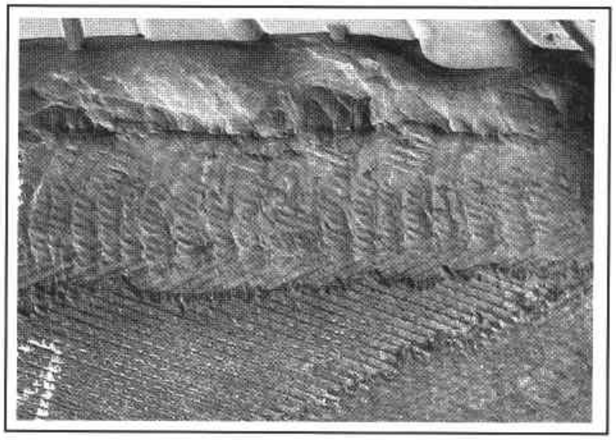

Fig. 5 *Sample of edge cracks occurring in a field tire tread separation (opposite serial side)*

*In all the surface photographs shown, the radial direction is vertical, while the circumferential direction is horizontal.

**In field service, tires may be mounted in several ways. All tires have a serial number, required by the Department of Transportation (DOT), molded into one of the sides. This side of the tire, usually denoted by the Serial Side (SS), can be mounted facing either in or out on the vehicle. In all photographs of field service tires in this paper, the Serial Side is at the bottom of the photograph, and the Opposite Serial Side is at the top. It is normal for tires to have the DOT serial number on the opposite side of the tire from the decorative, or white wall, side. Therefore, the Serial Side of the tire is normally mounted facing inward on the vehicle.

tion. In Fig. 4, the edge cracks grew from the Serial Side belt edge upward toward the tire centerline in the same manner as those in Fig. 2. In Fig. 5, the edge cracks grew from the Opposite Serial Side belt edge downward toward the tire centerline. The edge cracks grow from the edge of the outer steel belt into the skim rubber between the two steel belts, and they normally occur simultaneously on both sides of the tire. Because the initial fatigue crack growth rate in field tires is very low (many orders of magnitude lower than that found by Daws[2] in laboratory experiments), polishing of the edge crack surfaces due to relative movement of the crack surfaces normally occurs. The relative movement of the crack surfaces is caused by the strains generated when the tread is in road contact during each rotation. This polishing reduces the sharpness of the radially oriented tear ridges that characterize these cracks.

Edge crack growth is a complex function of the specific geometric design of the tire, the materials used in the construction of the tire, the accuracy of the construction of the tire, the load, the pressure, the temperature of operation, and other environmental conditions. However, as the cracks progress more deeply into the skim rubber in the radial direction, theory predicts that the crack growth per revolution accelerates. The normal outcome of this characteristic is the generation of one or two large thumbnail-shaped pockets between the two steel belts at some location on the circumference of the tire. These large pockets are generally the locations for the initiation of tread separation in field tires.

Flap Initiation

The region at the point of initiation of the flap tips is torn during operation by centrifugal and contact patch stresses. In this region, distinct beach marks may be observed on one of the flap tip surfaces. These marks go from the separation line to the belt edges at the shoulders of the tire. The beach marks arc around the flap tip, showing that the flap edge along the shoulder of the tire is being pulled farther during each tear than is the flap edge along the separation line. This observation is consistent with the tire having curvature across the tread area. If the flap tip forms over a thumbnail-shaped pocket formed by extending edge cracks, no additional tearing is required to free the flap. Because the edge crack pocket represents a region of belt skim rubber that is already separated at the time the flap is being initiated, there are no beach marks within the edge crack pocket region. In this case, beach marks may or may not be found outside the edge crack pocket region, depending on how large a thumbnail-shaped pocket was present.

Figure 6 shows the initial separation line for flap formation from a tire having a laboratory-created separation. The initial separation line is highlighted for clarity. In this case, both the leading edge and trailing edge flaps were torn loose; that is, there was no edge crack thumbnail pocket under either flap. The result is that there are beach marks emanating from the separation line that define the tear progression of the flaps. The propagation direction of the flap is shown for the flap below the separation line. Figure 7 shows an example of a flap initiation region in a field tire where there was tearing of the flap at the time of the separation. Beach marks can be seen faintly in the surface of the rubber. Figure 8 shows an example of another tire that experienced a separation in field service. Below and to the right of the separation line (highlighted for clarity) is a thumbnail pocket that was developed by the edge cracks growing and linking together under fatigue loading. In this particular case, the edge crack pocket extended approximately 85% of the way across the tire tread area before the flaps formed and the tread and outer steel belt separated. As would be expected, there was a significant amount of polishing at the tire shoulder due to the large interfacial movement that occurs in a pocket of this size. Additionally, the crack surfaces near the tire centerline are distorted. In fact, the flap tips in this case did not generate the characteristic beach marks because once the

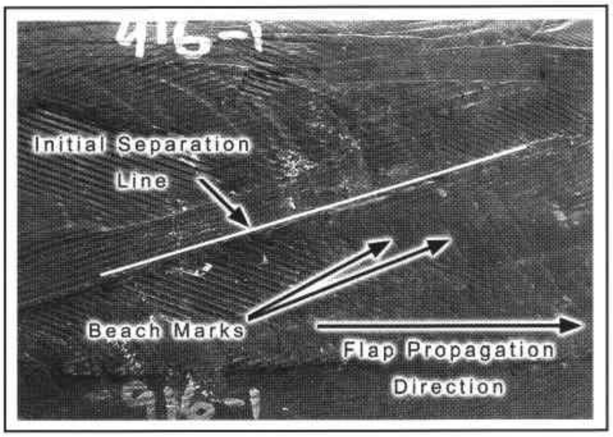

Fig. 6 *Initial flap tearing region occurring in a laboratory tire tread separation*

tread and outer steel belt broke at the tire shoulder, the flap was already separated for nearly the full width of the tire. As seen in the laboratory tire tread separations, rapid tearing of the flap normally begins at the point where the flap width is approximately equal to the tread width. For the tire in Fig. 8, at the time of separation, no further tearing was required to allow the flap to separate completely from the casing and begin to tear away.

Rapid Tearing

Once the flaps have separated across the entire tread width, the tear crack propagation in the skim rubber between the two belts occurs rapidly. When the leading edge flap contacts external surfaces, the tear propagation rate is on the order of 100 mm/rev or higher.[2] The skim rubber in this rapid tearing region will normally peel close to the inner steel belt on one half of this region and close to the outer steel belt on the other half; the tire centerline separates these two zones. The resulting thick-thin aspect of the skim rubber remaining on the outer surface of the inner steel belt is very distinctive. Figure 9 shows a portion of the rapid tearing region from a laboratory separation. This particular sample was from a trailing edge flap on a right-side tire. Figure 10 shows the rapid tear region on a tire that experienced a field tread separation. The tire was mounted on the left side of the vehicle, and the sample shown in the photograph was produced by the leading edge flap. In both of these photos, the

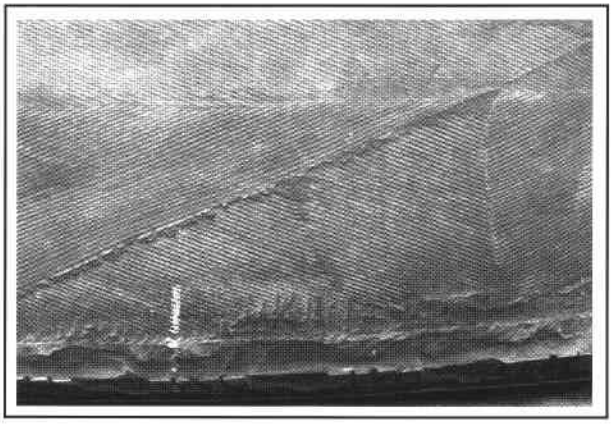

Fig. 7 *Flap initiation region occurring in a field tire tread separation*

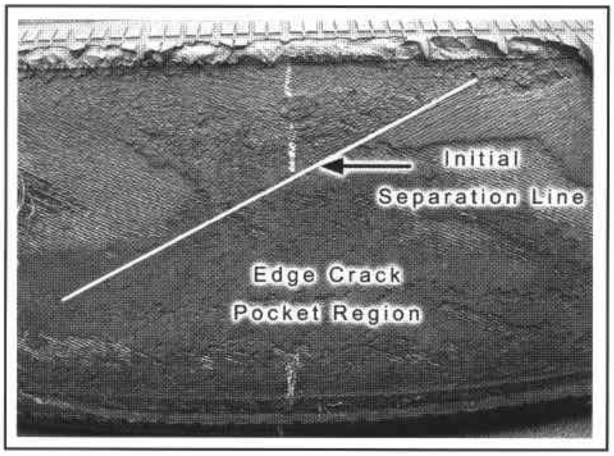

Fig. 8 *Flap initiation region occurring by growth of edge crack pocket under flap in field tire tread separation*

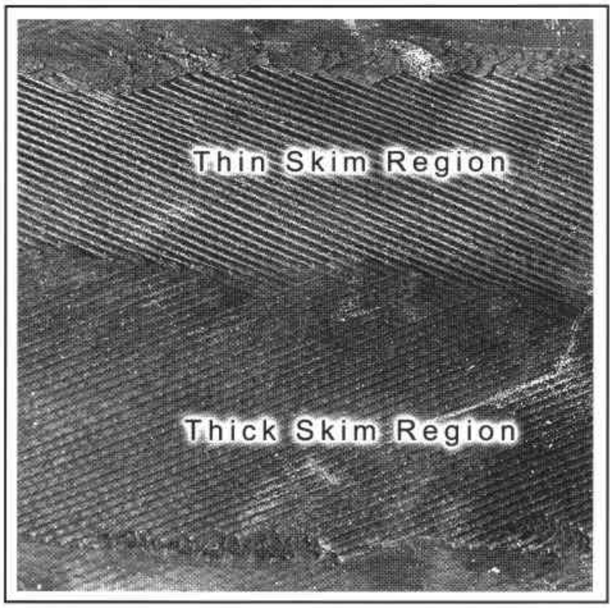

Fig. 9 *Rapid tearing region occurring in a laboratory tire tread separation (trailing edge flap, right-side tire)*

Fig. 10 *Rapid tearing region occurring in a field tire tread separation (leading edge flap, left-side tire)*

impression of the outer steel belt wires created a pattern of lines moving from the tire centerline to the lower left. The impression of the inner steel belt wires created a pattern of lines going from the tire centerline to the upper left. This herringbone pattern is characteristic of the rapid tearing region of a tire tread separation.

The direction of propagation of the tear and the tire's rotational direction determine whether the skim remaining on the outer surface of the inner belt will be thick or thin on the Serial and Opposite Serial sides of the tire. As seen in Fig. 9 and 10, the region of thin skim shows wire lines from the inner steel belt in the upper portion of the photographs (the Opposite Serial Side of the tire), while the region of thick skim in the lower portion of the photographs (the Serial Side of the tire) shows wire lines from the outer steel belt.

The locations of the thick and thin skim arise due to the compound curvature of the tire's surface. When the tread and outer steel belt pull from the inflated casing, the edge of the crack forms an arc in the direction of propagation of the tear. This arc has the appearance of a "C," with the open end toward the direction of crack propagation. Figure 11 shows a sketch of the development of this crack front shape. Curved line A´B´C´ is drawn parallel to the tire body ply cords and is therefore perpendicular to the tire centerline. Straight line DEF is a line perpendicular to the centerline of the belt that is tearing off. The crack front, given by line ABC, will follow an arc because the line segments AD, BE, and CF in the separating belt must be of equal length. This geometry occurs because the separated tread and outer steel belt have little or no curvature, while the inflated casing has curvature because of its internal pressure. Therefore, the outer edges of the tread and outer steel belt (points A and C) have to be located farther along the direction of propagation than does the center (point B) at any instant of time.

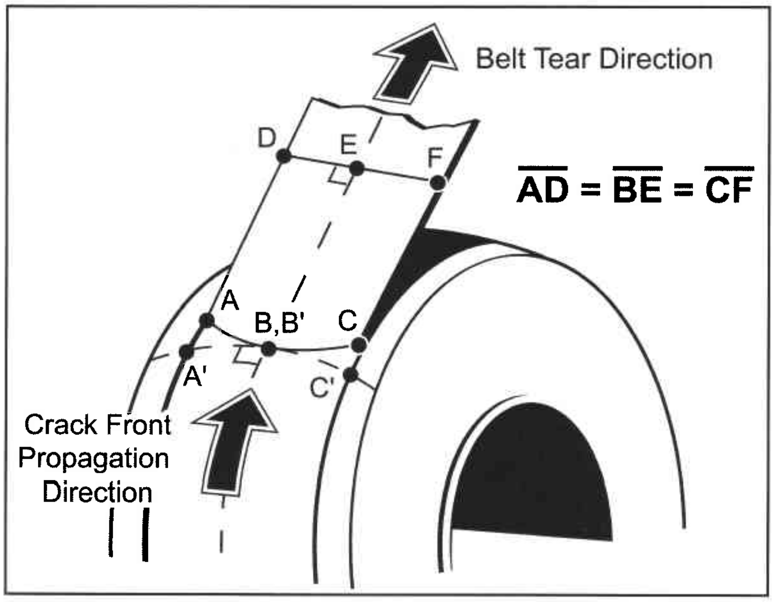

Fig. 11 Sketch showing the shape of the crack front in the rapid tearing region

Figure 12 shows a schematic depicting the orientations of the crack edge and the steel belt wires for a leading edge flap on a normally mounted left-side tire, as was shown in Fig. 10. In this case, the inner steel belt wires appear to pull out of the skim rubber on the Opposite Serial Side of the tire where they align with the edge of the arc of the crack front. The wires of the outer steel belt are more normal to the crack front on this side, so they provide reinforcement for the skim rubber between the belts. The wires of the inner steel belt, by contrast, provide stress concentrations at the advancing crack front. In tires with normal levels of bonding between the rubber and the steel wire, the cracking occurs entirely in the skim rubber; that is, the steel wire in the inner steel belt is not exposed. Thus, the wires remain covered with a thin layer of the skim rubber. In tires where there has been a breakdown of the bond strength between the rubber and the steel wire, the cracks may propagate along the surface of the wire. However, in the case of normal bonding strength, the pattern left in the skim rubber remaining on the casing is a series of furrows that mimic the shape of the inner steel belt wires. The bulk of the skim rubber that was between the two steel belts will be pulled off the casing and stay with the tread and outer steel belt.

On the Serial Side of the tire in Fig. 12, the crack front aligns with the wires in the outer steel belt. The inner steel belt provides reinforcement, and the crack front is influenced by the stress concentrations presented by the outer steel belt wires. The pattern left on this side of the tire will therefore be a series of furrows that mimic the outer steel belt wires. The bulk of the skim rubber that was between the two steel belts remains attached to the inner steel