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Impact Behavior of Corner Cracked Spring Steel Under Varied Material Condition and Service Temperature

H. A. Vinaya Kumar
Assistant Professor, Department of Mechanical Engineering, N.D.R.K. Institute of Technology, Hassan, India

***Abstract*: Spring is a critical and prominent piece of material in an automotive. During the service it has to function in several typical environmental conditions. Also, a wide variety of loads will come on the spring during functioning. Because of its exotic properties, the spring steel is used as the spring material. Due to continuous operation and the influence of environmental effects, wide variety of flaws in different orientations will induced in the spring. Under such circumstances the prediction of the useful life of the spring with the pre-existing flaws, is quite a challenging task. It is well known that the springs a highly susceptible to the bending loads. In the present experimental analysis the influence of service temperature and the flaw orientation on the impact behavior has been investigated.**

***Keywords*: Spring Steel, Corner Crack, Impact Behavior, Multi-layer Coated, Carburized, Impact Energy.**

1. Introduction

Increasing competition and innovations in automobile sector tends to modify the existing products or replacing old products by new and advanced material products. A suspension system of vehicle is also an area where these innovations are carried out regularly. More efforts are taken in order to increase the comfort of user [1]. Spring steel is used widely in the motor vehicle industry and many general engineering applications. Suitable for applications that require high tensile strength and toughness. Typical applications include crankshafts, steering knuckles, gears, spindles and pumps. During the last two decades, considerable efforts have been made in the development of high-performance spring steels to meet the needs for the weight and cost savings in the automotive industry [2]. The highest quality level of spring steel requires the appropriate fine grained microstructure, without segregations, large inclusions and surface defects [3].

A manufacturer of spring steels must provide a technical steel description in their production program. Namely, the durability of the springs is limited by plastic deformation, fatigue and fracturing. From this point of view, the use of spring steel with the following properties is recommended: high ductility and toughness at operating, good hardenability that provides the required mechanical properties, even at the maximum dimensions [4].

Springs are based on Hooke's law which states that "deflection is proportional to load". They are fundamental mechanical component that form the basis of many mechanical systems. A spring is defined as an elastic body, whose function is to distort when loaded and to recover to its original shape when the load is removed [5]. Suspension springs of ground vehicles are subject to high static and cyclic loads [6]. The leaf springs bend and slide on each other allowing suspension movement [7]. Parabolic springs are subjected to cyclic compression and tension load when the heavy vehicle runs on the road. In industry, only manufacturer manages to test the fatigue life of these springs using constant amplitude loading. This is because non constant amplitude proportional loading fatigue test is time consuming and adds more cost [8]. Valve springs are subjected to dynamic and impact loading during the valve opening and closing events [9].

A large variety of springs is made from one of several grades of carbon or alloy steels and is used in different components for the purpose of absorbing loads. Helical coil springs are generally manufactured from rods, which are coiled in the form of helix. Fatigue is the most common mechanism of failure in springs. Fatigue fracture generally initiates at the surface and the resolved tensile stresses cause further growth of the developed cracks and lead to premature failure of the springs. Other common causes of failures include overstressing, design deficiencies, material defects, processing errors and unusual operating conditions. In certain cases more than one cause can contribute to failure [10]. Helical compression springs are made of oil-hardened and tempered spring steel wire, stainless spring steel wire and patented-drawn spring steel wire. After drawing, the wire is coiled in a spring coiling machine. The residual stress developed in the spring wire during the cold shaping then has to be relieved by a tempering stage as the next step in manufacture [11]. The leaf spring should absorb the vertical vibrations and impacts due to road irregularities by means of variations in the spring deflection so that the potential energy is stored in spring as strain energy and then released slowly. So, increasing the energy storage capability of a leaf spring ensures a more compliant suspension system [12].

Cracks often develop in the corners of a structural member due to high stress concentration factor in those areas. If one can calculate the rate of crack growth, an engineer can schedule inspection accordingly and repair or replace the part before failure happens. Moreover, being able to predict the path of a crack helps a designer to incorporate adequate geometric tolerance in structural design to increase the part life. While producing durable, reliable and safe structures are the goals of every aerospace component manufacturer, there are technical challenges that are not easy to be solved [13].

The level of performance of components in service depends on several factors such as inherent properties of materials, load or stress system, environment and maintenance. The reason for failure in engineering component can be attributed to design deficiencies, poor selection of materials, manufacturing defects, exceeding design limits and overloading, inadequate maintenance etc. Therefore, engineer should anticipate and plan for possible failure prevention in advance [14].

Oil quench and temper process offer enormous advantages to the heavy duty spring production because its treatment results can reveal optimum combination of toughness and ductility, and also improves fatigue life. The material used was a commercial grade of heavy duty spring steel. In the hardening process, selective alloy was heated up to its austenitizing temperature, 870°C, and quenched in oil. After that, tempering was done at 450°C increased by 50°C to 550°C for each tempering time (1 hr, 2 hr, and 3 hr) interval. The experimental results revealed that mechanical properties of selective alloy were significantly changed by temper treatment. By increasing the tempering time and temperature, hardness and ultimate tensile strength are gradually decreased and ductility was improved. Moreover, rather interesting condition is observed in elastic properties and endurance limit at 450°C and one-hour tempering condition, and this state is the optimum condition for spring production [15].

Coating or paint layers are often applied to the surfaces of polymeric, metallic, or composite structures. Coating layers are used for many reasons such as for protection, for decoration, for a barrier, or to provide unique surface properties. If the coating fails, it may cease to provide its function and the system has therefore failed. Failure here is not in the sense of structural failure, but rather failure of the intended purpose of the coating. For example, a cracked paint layer ceases to provide an attractive surface appearance. Coatings are not used for their loading bearing contributions. As a result, when a coated structure is subjected to loads, cracks typically develop within the coating before the substrate fails. Coating cracks usually initiate and rapidly propagate throughout the entire thickness of the coating. When the crack reaches the coating/substrate interface, it has several alternative failure modes [16]. Coatings are frequently used to increase the resistance of substrate against corrosion, wear, fatigue or to serve as protection for metallic components at high temperatures, but they are not used for their loading bearing contribution. Two extreme cases are: soft compliant coating on a stiff substrate, and hard brittle coating on a compliant structure. Principal failure modes of coatings are cracking and delamination [17].

Surface engineering may be defined as the design of engineering to improve their performance in service. This can be achieved by surface treatments, which can provide combinations of surface and bulk properties unobtainable in a single material. A ceramic on a metal, for example, can give extreme hardness at the surface, while maintaining acceptable fracture toughness throughout the section. The surface treatments may involve coating, chemical modification or physical processing. Coating processes, such as electroplating processes, produce a discrete layer of a new material with a sharp interface at the substrate. Chemical modification techniques, such as nitriding, provide a diffuse layer of a foreign element with no definitive interface. Physical processes, such as grit blasting, change the surface profile but not the chemical composition [18].

2. Material and Experimentation

The experimentation has been carried out on spring steel material EN-47. The specimen preparation and experimentation were carried out according to ASTM standards. The mechanical properties of EN-47 spring steel material have a hardness of 99 HRC, yield strength of 640Mpa, density of 7.85g/cc and modulus of elasticity 205Gpa.

A. *Material*

EN47 Spring Steel is chromium vanadium type spring steel. Spring Steel is used widely in the motor vehicle industry and many general engineering applications. Suitable for applications that require high tensile strength and toughness. Typical applications include crankshafts, steering knuckles, gears, spindles and pumps.

B. *Material Conditions*

Conditions selected in this project are,

(i) Normal condition
(ii) Coated condition
(iii) Coated then heat treated condition
(iv) Carburized condition

C. *Specimens Preparation*

In this project, material used is EN 47 Spring Steel. Specimens are prepared according to the ASTM Standard. Impact test and three point bending test are conducted. The Charpy impact test is conducted for Single Side Corner V-Notch specimen (SSCN specimen), Double Side Corner V-Notch specimen (DSCN specimen), Triple Side Corner V-Notch specimen (TSCN specimen) and Single Side Flat V-Notch specimen (SSFN specimen).

Table 1
Chemical composition of EN 47 Spring Steel

Components	C	Mn	Cr	V	Si	P	S
Wt%	0.45 to 0.55	0.50 to 0.80	0.80 to 1.20	0.15% min	0.50% max	0.06% max	0.06% max

Conditions selected in this project are normal condition, coated, coated then heat treated and carburized. In coated condition, specimens are multi layer Coated (two layers) by electrolytic coating process. One layer is Nickel of 10µm and is followed by another layer is Chromium 5µm. In coated then heat treated condition, coated specimens are heat treated to temperature 125^{0}C for 45 minutes. Carburizing is a heat treatment process of adding carbon to the surface. Carburizing is done by exposing the normal condition specimens to a carbon rich atmosphere at 900^{0}C temperature and allows diffusion to transfer the carbon atoms into specimen up to the depth of 1mm.

Fig. 1. SSCN Specimen

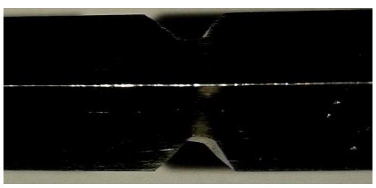


Fig. 2. DSCN Specimen

Fig. 3. TSCN Specimen

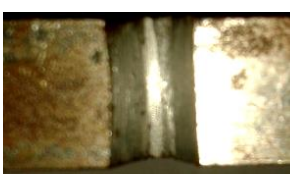


Fig. 4. SFCN Specimen

D. Experimentation

The experimentations are carried out in order to investigate of Impact behavior. Charpy Impact Test Procedure is as follows.

Ensure knife edge is assembled and the column of the striker is set to 141^0 47” of fall angle. Set the pointer to the maximum capacity and freely release the hammer to determine any friction losses. ASTM standard test piece of overall length of 55 mm square cross section of 10 mm side with central V-Notch of 3 mm depth is placed on the machine anvil in a simply supported manner and such that it is on the tension side (Notch is facing away from the striking edge). The striker is lifted and clamped to have initial potential energy of 300 Joules and the needle is set to 300 Joules, the maximum capacity. The striker is released free to striker the specimen. The absorbed energy is read on the scale as indicated by the pointer. Apply the safety breaker to stop the oscillation of the striker.

3. Results and Discussions

A. Material

Fig. 5 shows Impact Energy vs. Temperature of Single Side Flat Notch specimen (SSFN specimen). SSFN specimen in normal condition has less impact energy at 0^{0}C compared to SSFN specimen in normal condition at room temperature (25^{0}C) because fracture toughness of the material is less at 00C compared to room temperature. Impact Energy gradually decreases at 50^{0}C and become constant till 100^{0}C. But impact energy increases at 200^{0}C.

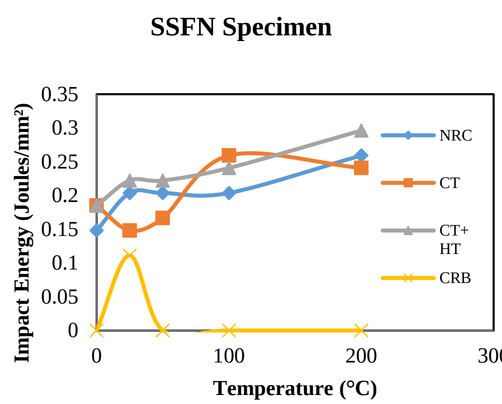


Fig. 5. Effect of service temperature of SSFN specimen on Impact Energy.

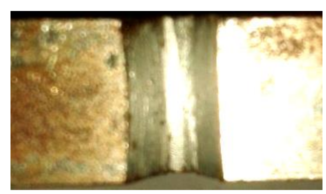
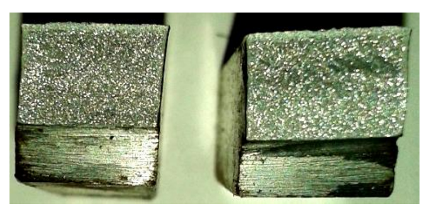


Fig. 6. (i) Before SSFN specimen failure.



(ii) After SSFN specimen failure.

SSFN specimen with coated has more impact energy at 0^{0}C compared to SSFN specimen with coated at room temperature (25^{0}C) because fracture toughness of the material is more at 0^{0}C compared to room temperature. Impact Energy gradually increases up to 100^{0}C. At the interface of coated layer and the substrate, micro air gaps are created. When the temperature of SSFN specimen with coated increases, air gaps which is present at interface disappears and coated layers will get properly bond to the substrate. So impact energy of SSFN specimen with coated increases with increase of temperature from 50^{0}C to 100^{0}C. But impact energy decreases at 200^{0}C.

SSFN specimen with coated is heat treated to a temperature 125^{0}C for duration of 45 minutes. SSFN specimen with coated then heat treated has less impact energy at 0^{0}C compared to SSFN specimen with coated then heat treated at room temperature (25^{0}C) because fracture toughness of the material is less at 00C compared to room temperature (25^{0}C). Impact Energy gradually decreases at 50^{0}C and increases from 100^{0}C to 200^{0}C.

SSFN specimen is carburized for depth of 1mm by heated to a temperature 900^{0}C. When specimen is carburized, its grain size increases. SSFN specimen with carburized has less impact energy compared to SSFN specimen with other conditions at room temperature (25^{0}C).

B. *Effect of notch orientation on Impact Energy*

Effect of different notch orientation on Impact Energy is discussed below.

1) *Normal condition*

Double Side Corner Notch specimen with normal condition has more impact energy at 0^{0}C, room temperature (25^{0}C) and 50^{0}C compared to other types of specimen with normal condition as shown in Figure 7. Double Side Corner Notch specimen at 100^{0}C has less impact energy compared to Single Side Corner Notch specimen and more compared to Triple Side Corner & Single Side Flat Notch specimen with normal condition.

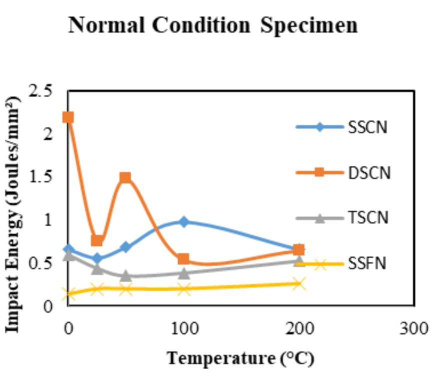


Fig. 7. Effect of normal condition on Impact Energy in different notch oriented specimens.

Double Side Corner Notch specimen has same impact energy at 200^{0}C compared to Single Side Corner Notch specimen more compared to Triple Side Corner & Single Side Flat Notch specimen with normal condition.

(i) Single Side Corner Notch (ii) Double Side Corner Notch

(iii) Triple Side Corner Notch (iv) Single Side Flat Notch

Fig. 8. Fractured surface of SSCN, DSCN, TSCN, and SSFN specimen in normal condition.

2) *Coated condition*

Double Side Corner Notch specimen with coated has more impact energy at 0^{0}C, room temperature (25^{0}C), 50^{0}C and at 100^{0}C compared to other types of specimen with coated as shown in Fig. 9.

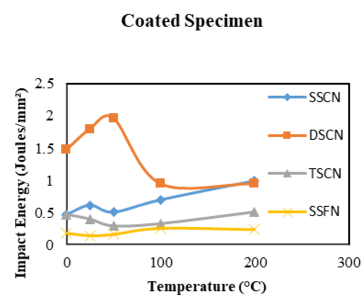
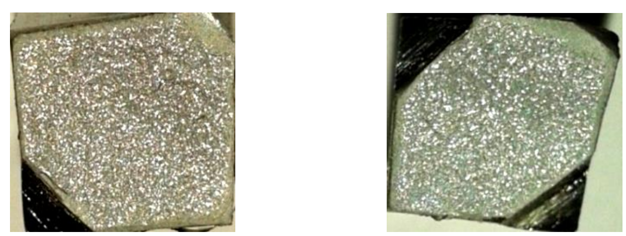


Fig. 9. Effect of coating on Impact Energy in different notch oriented specimens.



(i) Single Side Corner Notch (ii) Double Side Corner Notch

(iii) Triple Side Corner Notch (iv) Single Side Flat Notch

Fig. 10. Fractured surface of SSCN, DSCN, TSCN, and SSFN specimen in coated condition.

But Double Side Corner Notch specimen at 200^{0}C has less impact energy compared to Single Side Corner Notch specimen and more compared to Triple Side Corner & Single Side Flat Notch specimen with coated.

3) Coated then heat treated condition

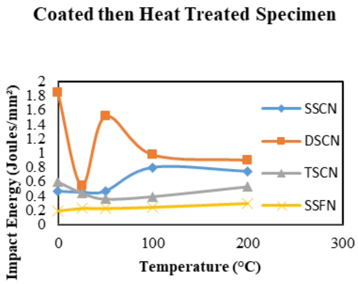
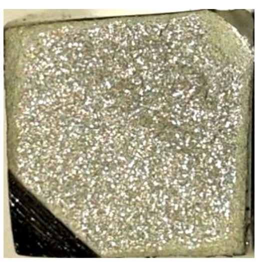
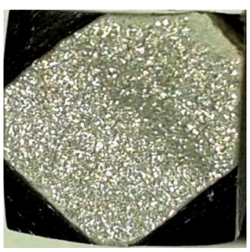


Fig. 11. Effect of coating then heat treating on Impact Energy in different notch oriented specimens.

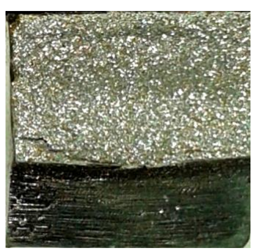


(i) Single Side Corner Notch

(ii) Double Side Corner Notch



(iii) Triple Side Corner Notch



(iv) Single Side Flat Notch

Fig. 12. Fractured surface of SSCN, DSCN, TSCN, and SSFN specimen in coated then heat treated condition.

Double Side Corner Notch specimen with coated then heat treated has more impact energy at 0^0C, room temperature (25^0C), 50^0C, 100^0C and at 200^0C compared to other types of specimen with coated then heat treated as shown in Fig. 11.

4) Carburized condition

Triple Side Corner Notch specimen with carburized has more impact energy at 0^0C, room temperature (25^0C), 50^0C, 100^0C and at 200^0C compared to other types of specimen as shown in Fig. 13.

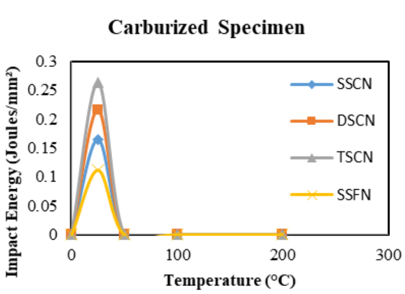
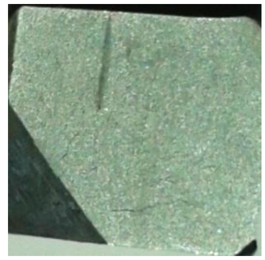
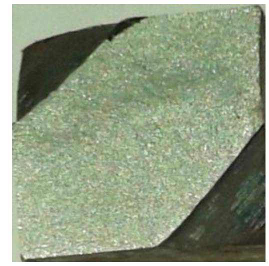


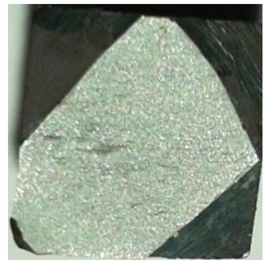
Fig. 13. Effect of carburized on Impact Energy in different notch oriented specimens.



(i) Single Side Corner Notch



(ii) Double Side Corner Notch



(iii) Triple Side Corner Notch

(iv) Single Side Flat Notch

Fig. 14. Fractured surface of SSCN, DSCN, TSCN, and SSFN specimen in carburized condition.

C. Micro mechanism of fractured surface

Fractured surfaces are analyzed by using SEM images.

1) Single Side Corner Notch specimen

The fractured surface of Single Side Corner Notch specimen shows that when the impact force acting on the opposite corner edge of corner notch, the energy absorbed for failure is sufficient to propagation of crack up to middle portion of the specimen as shown in Fig. 15, 16, 17, 18. For complete fracture of the specimen, triggering points are generated at the opposite corner edge of corner crack.

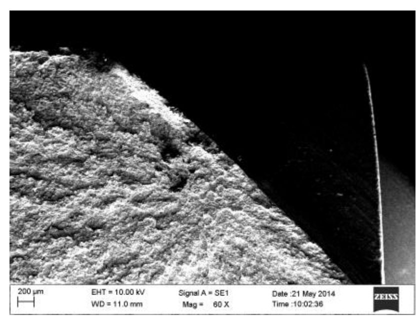


Fig. 15. SEM image of triggering points in SSCN specimen.

So crack will grow in two directions and specimen fails in the middle of fractured surface. Up to the triggering point it is static crack growth. In the middle of fractured surface will stable crack growth and dynamic crack growth at side edges as shown in Fig. 5.9. Energy absorbed for failure is more than Single Side Flat Notch specimen & Triple Side Corner Notch specimen and less than Double Side Corner Notch specimen shown in the Fig. 19.

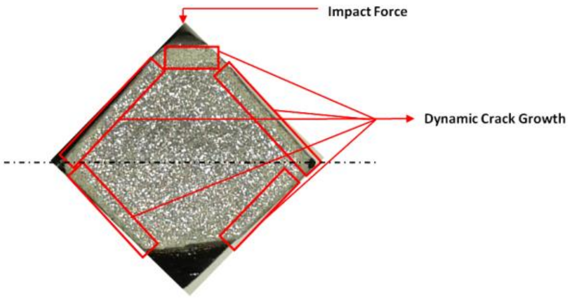


Fig. 16. SSCN specimen with dynamic crack growth.

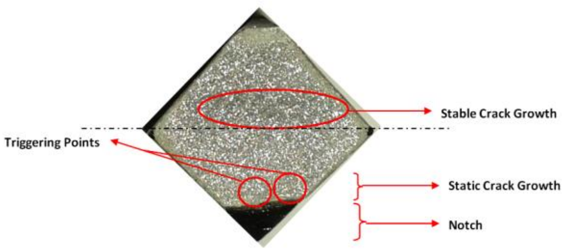


Fig. 17. SSCN specimen with static and stable crack growth.

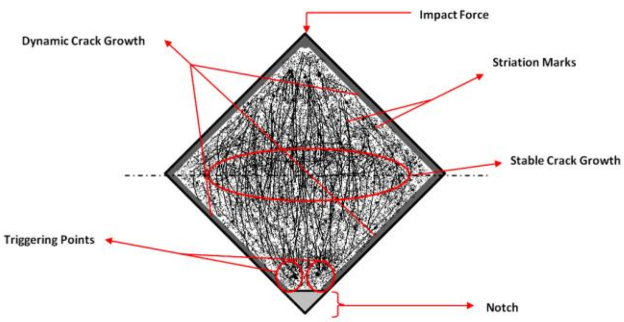


Fig. 18. SSCN specimen with dynamic, static and stable crack growth.

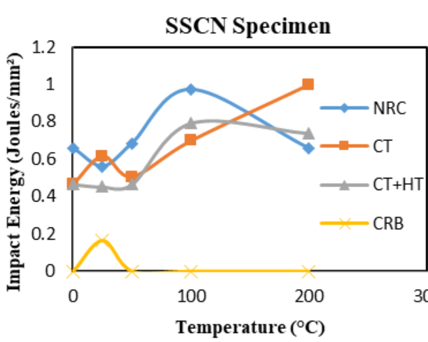


Fig. 19. Impact Energy vs. Temperature of SSCN specimen.

2) *Double Side Corner Notch specimen*

The two opposite corners, edges having the notch and impact force applied at un-notched corner edge. The triggering points are generated at impact force applied corner edge as shown in Fig. 20, 21, 22. Followed by stable crack growth and also triggering point will generate at the opposite corner and large triggering point generated near the impact force acting corner edge.

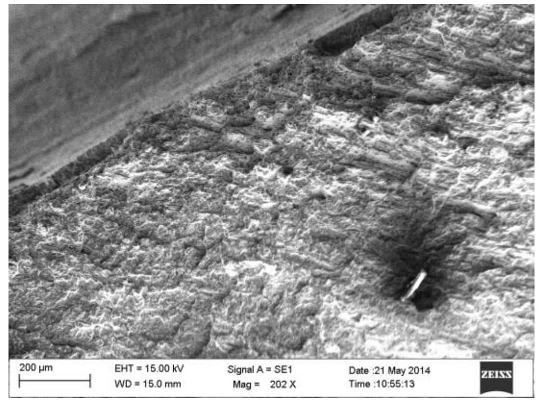


Fig. 20. SEM image of triggering points in DSCN specimen.

The dynamic crack growth at the side edges of fractured surface which are in the opposite direction of impact force applied corner edge. In Double Side Corner Notch specimen, it is too difficult to predict the failure area on the fractured surface. The energy absorbed by this specimen for the failure is very high compared to other three types of specimen as shown in Fig. 23.

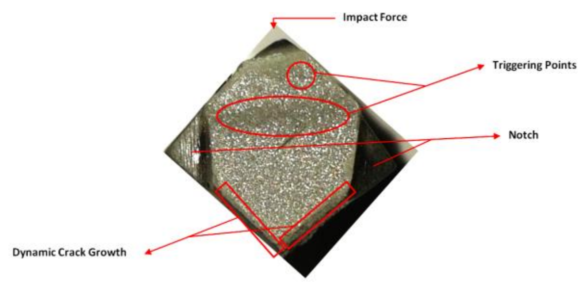


Fig. 21. DSCN specimen with dynamic crack growth

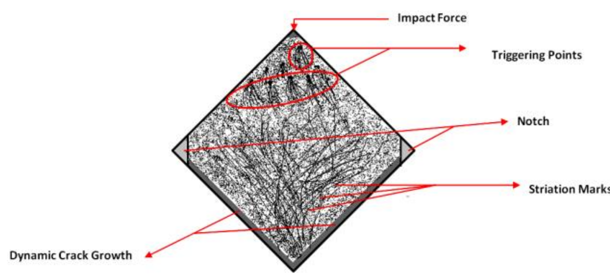


Fig. 22. DSCN specimen with dynamic, static and stable crack growth.

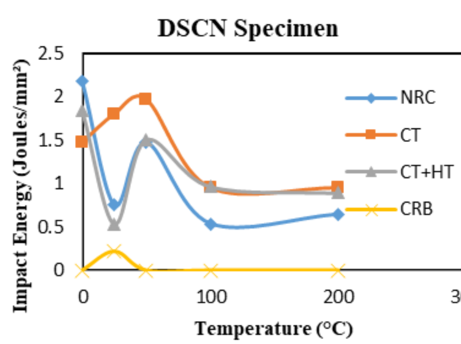


Fig. 23. Impact Energy vs. Temperature of DSCN specimen.

3) Triple Side Corner Notch specimen

The specimen consists of three notches on the corner edges. The impact force is applied to the un-notched corner edge. The triggering points are generated near the notch and also at the impact force applied corner edge as shown in Fig. 24, 25, 26.

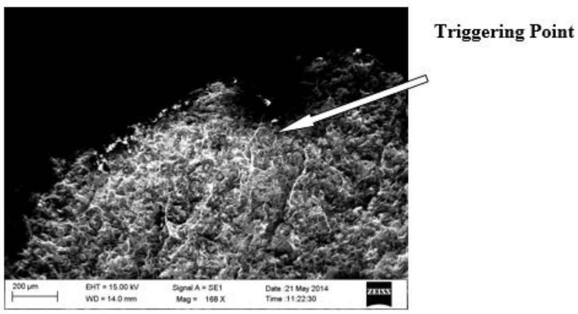


Fig. 24. SEM image of triggering points in TSCN specimen.

The crack will initiate and propagated statically and grows stably. In this case of specimen it is difficult to predict the crack growth during the failure of the specimen. Octahedral shear stress will act on the specimen during the failure. Energy absorbed for failure is more than Single Side Flat Notch specimen and less than Single Side Corner Notch specimen & Double Side Corner Notch specimen as shown in Fig. 27.

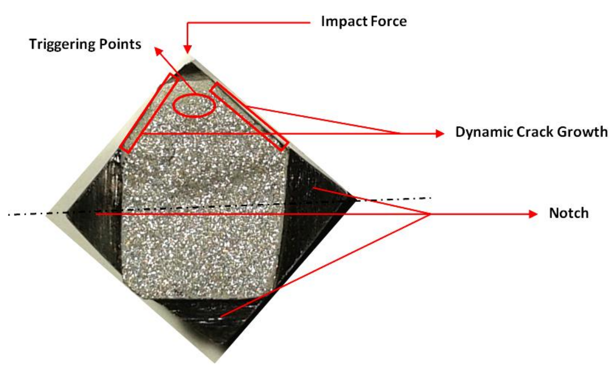


Fig. 25. TSCN specimen with dynamic crack growth.

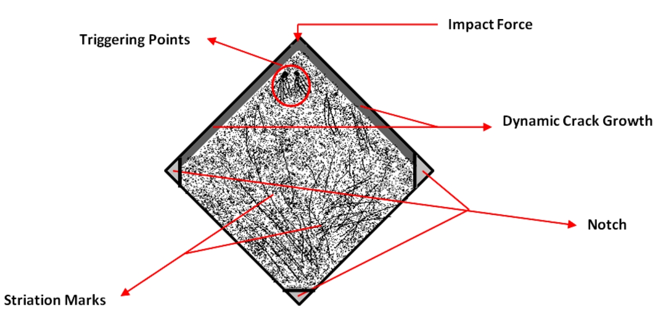


Fig. 26. TSCN specimen with dynamic, static and stable crack growth.

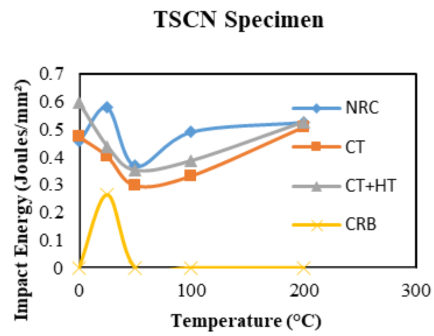


Fig. 27. Impact Energy vs. Temperature of TSCN specimen.

4) Single Side Flat Notch specimen

Failure in Single Side Flat Notch specimen is plane strain fracture. The specimen will fail in Mode-I condition. The fractured surface shows that the crack is initiated by triggering points as shown in Fig. 28, 29, 30.

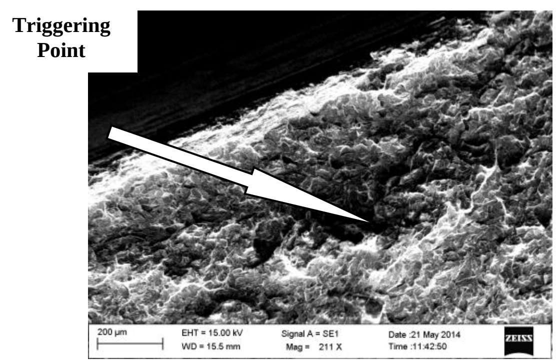


Fig. 28. SEM image of triggering points in SSFN specimen.

Crack will not initiate by only one triggering point, but it is led up by a number of triggering points. Largest triggering points can be identified by the bare eyes. There may be more than one lakh triggering points present on the fractured surface can view by SEM. When the impact force acting on the specimen, initially crack will initiate by the triggering point, and then there will be static crack growth. Later the static crack growth is followed by stable crack growth. Finally, the specimen will get fracture by dynamic or unstable crack growth. The dynamic crack growth is indicated by a grayish line or a band. In this case, specimen absorbs less energy for failure compared to other three types of specimen as shown in Fig. 31.

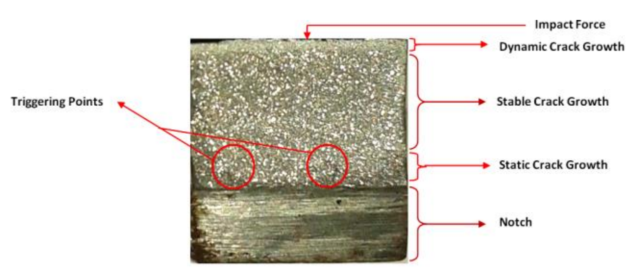


Fig. 29. SSFN specimen with dynamic crack growth.

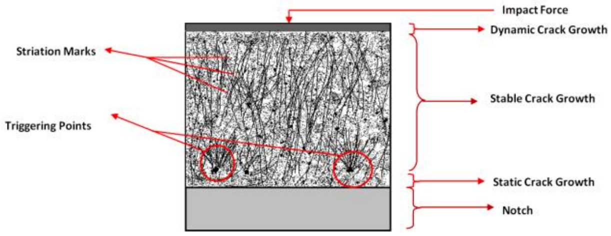


Fig. 30. SSFN specimen with dynamic, static and stable crack growth.

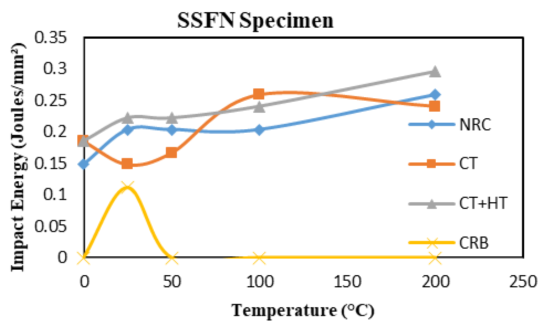


Fig. 31. Impact Energy vs. Temperature of SSFN specimen.

4. Conclusions

Based on experimental analysis carried out on the spring steel material with different condition, the following conclusions have been drawn.

- Double Side Corner V-Notch specimen in normal condition at room temperature has more impact energy.
- Single Side Flat V-Notch specimen with carburized at room temperature has less impact energy.

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