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FAILURE CHARACTERIZATION OF AUTOMOTIVE STRUCTURAL STEELS AT SUB-ZERO TEMPERATURES UNDER SERVICE LOADING

The suspension system of an automobile contributes to its performance and comfort, and its malfunction could lead to an accident. Researchers have extensively studied the durability criteria of these components at room temperature, and a wealth of data is available. The vehicle may be subjected to temperature extremes ranging from 45°C or higher in the desert to –40°C or lower in the Arctic. Subzero temperatures have a significant impact on automobile components and are a serious concern for the automotive industry. The steel alloys used in the manufacturing of automobile components experience ductile to brittle transition (DBT) under such temperature conditions during service loading. The quasi-static and cyclic testing was carried out on stabilizer bars and leaf spring specimens at subzero temperatures to understand the behaviour of automotive materials. The quasi-static strength of the stabilizer bars and leaf springs has been augmented by 21.62% and 55.18%, respectively, at a subzero temperature of –40°C in comparison to room temperature. The fatigue life of leaf springs was improved by 29, 27, and 30% in the number of cycles at higher, medium, and low fatigue loading, respectively. Stabilizer bars were regarded as infinite at all fatigue loadings in subzero temperatures of –40°C. This study investigates the failure characteristics of steels used in automobile stabilizer bars and leaf springs at sub-zero temperatures under quasi-static and cyclic loading conditions. The quasi-static and cyclic fractographic characterizations correlate the mechanical behaviour with the fracture features and mechanisms. This research is critical for the design and development of automotive components under sub-zero temperature conditions in a durable manner.

Keywords: Failure characterization; Stabilizer bars; Leaf Spring; Sub-zero temperature (SZT); Quasi-static and cyclic loading; Steel

1. Introduction

An automobile runs in different climate conditions with varying humidity. The climate conditions range from almost 50-55°C in the desert to –50°C or lower in the Arctic, such as in the western Himalayas. The various components of vehicles are exposed to such conditions under service loadings [1]. These issues are serious for the automotive industry because of their reliability in extreme weather. The energy absorption capacity of carbon steel at subzero temperatures, namely –30, –60, and –90°C, increases, resulting in an improvement in structural crashworthiness. The structural safety level in collision or impact is improved under subzero temperature conditions [2]. High strength low alloy steels (HSLA) are widely used in various structural applications, from marine to agriculture. Bratina et al. [3] observed a considerable amount of quasi-cleavage faceting with river pattens in HSLA steels at –196.15°C. HSLA-100 is observed to be quite ductile at temperatures below –40°C; the ductile-to-brittle transition (DBT) occurs at –80°C with a moderate strain rate, and finally at –196°C, the fracture is completely brittle with high strain rates [4]. The ferritic-pearlitic Martensitic steels were studied at subzero temperatures of –20, –40, –60, and –100,°C for charpy, tensile, and hardness tests. The ultimate tensile strength increased while the impact toughness decreased as temperature reduced. The adiabatic shear bands observed in martensitic steels during impact at –60°C, facilitate the initiation of cracking [5].

Cerik et al. [6] proposed the low temperatures behaviour of high tensile strength steel grades at sub-zero temperatures. As the temperature decreases towards subzero, the deformation resistance and fracture displacement initiation increase. Chandra et al. [7] studied the tensile characteristics of Inconel 718 at sub-zero temperatures. The fracture dimples size is decreased as well there is increasing dimples are observed as temperature decreased towards to –70°C. It showed a decrease in temperature, the material is not completely brittle, and it also has ductile fracture properties. The fracture occurs along the plane of fracture also get reduced. The use of subzero tempera-

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ture treatment during the heat treatment process in high carbon steels showed improvements in their fracture toughness. This will be quite useful in automotive structural applications [8]. The effect of subzero temperature reduced the retained austenite contents in carburized steel, results in decreasing endurance limit of automotive carburized components [9]. The mechanical properties and microstructure of alloy steel are also influenced by the cooling rate. The sluggish rate of cooling resulted in a large austenite grain size, which in turn led to low impact toughness. Conversely, a rapid cooling rate decreased the size of the initial grain, resulting in strong tensile and impact strength [10]. Kim et al. [11] focused on the development of next generation high strength lightweight steels, such as medium Mn lightweight steel, which possesses a composite microstructure consisting of ferrite, retained austenite, and martensite. The subzero temperature treatment converts the retained austenite into athermal martensite. Karthikeyan et al. [12] observed the EN 24 steel samples kept at –78°C for 24 h, followed by tensile and hardness tests. The sample exhibited mixed modes of ductile and brittle fractures. This leads to elastoplastic grain boundary dislocations due to cleavage facet and micro void coalescence onset. Sallaba et al. [13] correlate the relation between fatigue transition temperature (FTT) and Ductile to Brittle Transition Temperature (DBTT) in high strength S500 steel. The rate of fatigue crack growth diminishes as temperatures fall. The fracture surface shows ductile fracture with dimples at –40°C, while transgranular cleavage planes at –85°C. Rokilan et al. [14] performed a quasi-static tensile test on low (G300) and high (G500) strength cold formed steel sheets at temperatures as low as –70°C. The yield strength and ultimate strength exhibited an increase when subjected to subzero temperatures. Athmarajah et al. [15] investigated the pull-out failure of cold formed high strength G550 and low strength G300 steels used in building construction at subzero temperatures of –10, –30, and –70°C, etc. This will aid in the development of suitable screw designs for cladding systems in combined wind and subzero temperature conditions.

There is numerous steel alloys used in the manufacturing of automobile suspension components that endure static and fatigue loads. The stabilizer and leaf springs play a crucial part in the suspension systems of an automobile. Both these components are essential to the comfort and performance of the vehicle. The leaf springs and stabilizer bars used in light and heavy commercial vehicles. The leaf spring absorbs stresses from the ground to the hub axle and preventing them from being transmitted to the chassis [16-18]. The stabilizer bars prevent vehicles from rolling. It is primarily responsible for reducing body roll when the vehicle departs from the linear path [19-21]. The cold weather has a significant impact on their strength and durability. This is a shadow area in which the fracture mechanism of automobile structures needs to be understood under quasi-static and cyclic loadings at transition temperatures. From the literature survey, the research gaps are identified as:

- Little attention has been having been paid to significant issues such as extreme temperatures, ductile-to-brittle transition temperature (DBTT), sub-zero temperature (SZT) condition etc. in automotive products.
- The correlation between the DBT and fatigue is a subject area that is less understood.
- The Scopus database shows that researchers have published only 50+ research papers on the topic of fatigue at sub-zero temperatures. This highlights the significance of investigating fatigue from the perspective of the DBT, or mechanical property transition, in contrast to the properties observed at room temperature. The conduct of research at –40 or –50°C is crucial in the aerospace and automotive industries, where such weather or climate conditions are endured.

This research is an important step toward developing an evaluation of automotive materials in a realistic environment. This research investigates the fracture mechanism of automotive alloys at subzero temperature climate conditions. This will lead to the development of automotive components that encountered static and fatigue behaviour, as well as the quantification of the safe use of materials.

2. Materials and Testing Methodology

SAE 1040 and C45 steels were chosen for the investigation. SAE 1040 and C45 are ferritic steels having body-cubic-centered (BCC) crystal structures were used in automotive anti-roll bars and leaf springs respectively. The SAE 1040 steel specimen is cylindrical, resembling a tube, while the C45 steel is flat and shaped like a plate. The C45 specimen is subjected to hardening and tempering in order to achieve a surface hardness in between 40-45 HRC. The chemical composition of selected materials was conducted at the Metal Test Lab, Mumbai, as summarized in TABLE 1. SAE 1040 and C45 specimens were subjected to three-point flexural tests, both under quasi-static and fatigue conditions. The span length for the SAE 1040 specimens was 250 mm, whereas for the C45 specimens it was 100 mm. Quasi-static tests were conducted on SAE 1040 and C45 specimens at loading rates of 1 mm/min and 5 mm/min. The fatigue tests were examined at a frequency of 3 Hz.

TABLE 1

Chemical composition of SAE 1040 and C45 steels

Content (%)	C	Mn	P	S	Si	Cr	Mo
SAE 1040	0.41	0.894	0.037	0.0050	0.32	0.167	0.018
C45	0.47	0.7	0.042	0.03	0.30	0.2	0.020

The test specimens are preconditioned in deep freezer at subzero temperatures before the mechanical quasi-static and cyclic testing. SAE 1040 tube specimens are preconditioned at subzero temperatures of 0, –10, –20, –30, and –40°C, respectively. The quasi-static flexural tests were conducted after the preconditioning at the same consecutive sub-zero temperatures. Similarly, the C45 specimens are preconditioned at room and –40°C. After conditioning, the specimens underwent quasi-static flexural tests. The cyclic tests were conducted on both C45 and SAE 1040 only at subzero temperature of –40°C temperatures, after the preconditioning at the same temperatures.

3. Quasi-static and Cyclic Testing Results

The three-point flexural tests were conducted on SAE 1040 tubes and C45 plate specimens at subzero temperatures. The quasi-static flexural strength of SAE 1040 stabilizer bars and C45 leaf springs at –40°C was observed to be increased by 21.62 and 55.18%., respectively. The fatigue tests were conducted under displacement control and the results were configured with stress versus number of cycles.

The lowered temperatures and service loading significantly affect the fatigue life of leaf spring and stabilizer bars. The mechanical properties and fatigue life post DBTT was found to be improved for both leaf spring and stabilizer bars. The quasi-static and fatigue flexural tests results were depicted in TABLES 2 and 3.

4. Fractographic Characterization

Scanning electron microscope (SEM) study was conducted on SAE 1040 and C45 failed tested specimens at BTRA (Bombay Textile Research Association), Mumbai using JEOL JSM IT-200 SEM. The Electron Discharge Machine (EDM) as shown in Fig. 1 was used to cut the specimens through the failed region.

The quasi-static and cyclic damage mechanisms in SAE 1040 and C45 specimens in the present investigation follow the

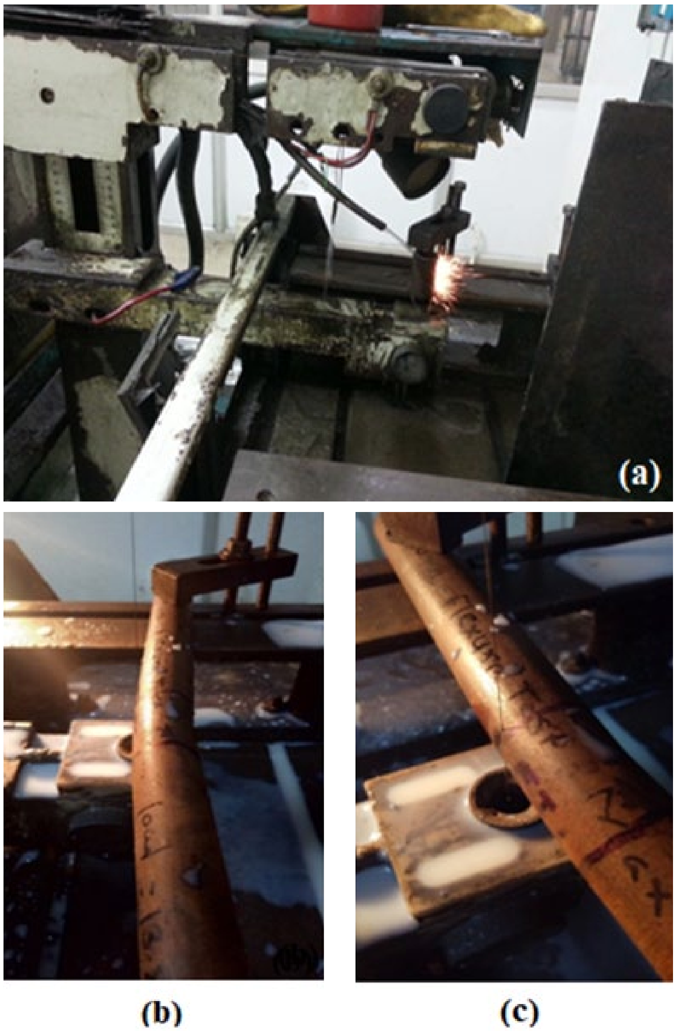

Fig. 1. (a) Electron discharge machine (EDM), (b) flexural fatigue SAE 1040 tube specimen, (c) actual specimen cutting

TABLE 2

Quasi-static flexural strengths of SAE 1040 and C45 steels

Test Temperatures	Specimen	Loading Rate (mm/min)	Flexural Strength (MPa)	Percentage Improvement (%)
–40°C (SZT)	SAE 1040 stabilizer bars	1	1675.90	21.62
25°C (RT)	SAE 1040 stabilizer bars	1	1377.98	
–40°C (SZT)	C45 leaf springs	5	2834.33	55.18
25°C (RT)	C45 leaf springs	5	1826.42	

TABLE 3

Fatigue life of SAE 1040 and C45 steels

Test Temperatures	Specimen	Fatigue loading	Cycles	Remark
–40°C (SZT)	SAE 1040 stabilizer bars	Low Medium High	1,00,000 1,00,000 1,00,000	SAE1040 steel has an infinite lifespan under all fatigue loads in SZTs, which is an improvement compared to room temperature.
25°C (RT)	SAE 1040 stabilizer bars	Low Medium High	1,00,000 1,00,000 4350	
–40°C (SZT)	C45 leaf springs	Low Medium High	1,00,000 18,850 5,700	The fatigue life at SZT of –40°C has been improved. The infinite life is observed at low fatigue cyclic loading.
25°C (RT)	C45 leaf springs	Low Medium High	76,600 14,800 4,400	

respective nature of the load and subzero temperature environment. At room temperature fractures, the grain boundaries are weaker, whereas at sub-zero temperatures, the grain boundaries shrink due to compressive residual stresses, which makes the grain boundaries stronger. At room temperature, the crack mechanism follows the low energy intergranular fractures, and at subzero temperatures, the mechanism is changed to transgranular mode, which is cleavage or quasi-cleavage. The medium carbon steels, which have BCC crystal structures, experienced failure at subzero temperatures due to the separation of transcrystalline crystallites along specific crystallographic planes called cleavage [22]. The cleavage fractures resemble facet fractures [23]. This fracture passes through the grain, creating 'river patterns' on the facet. River patterns are formed by the connection of cleavage planes to different planes [24,25]. SAE 1040 and C45 metals exhibit BCC structures, which makes them susceptible to the DBTT phenomenon when exposed to changes in temperature.

SAE 1040 demonstrated quasi-cleavage fractography representation at –40°C. These quasi-cleavage fractures show ductile tearing with coarse river marks, and are observed closed to and within range of DBT. The fine steps feather like marks were noticed at temperatures of –30°C and –20°C. This range of subzero temperatures shows a decrease in the absorbed impact energy. The presence of flat facets, plastic ruptures, and tear edges are a few fracture observations that provide clear evidence of quasi-cleavage fractures. At –10°C, the decohesion, cleavage steps, and twin are observed, while at 0°C, the fracture modes are intergranular with deformation traces. Fig. 2 depicts the fracture mechanism of SAE 1040 at subzero temperatures ranging from –40°C to +0°C. Mechanisms such as dislocation pile-up strengthening due to a lack of plasticity, Hall-Petch strengthening, quasi-cleavage, and transgranular fracture were observed under quasi-static loading.

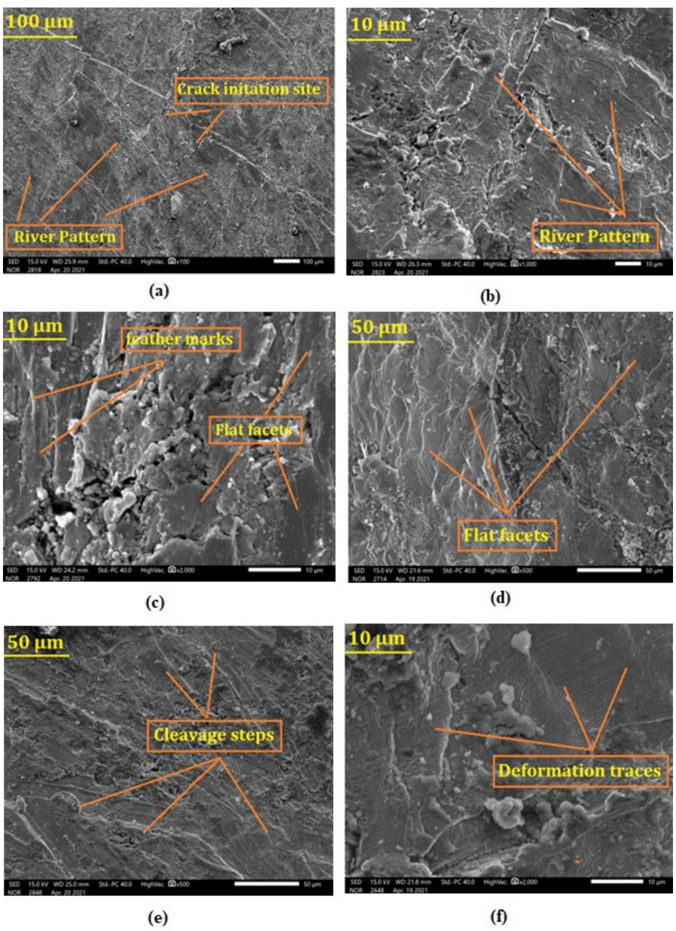

Fig. 2. Scanning electron microscopy of SAE 1040 at subzero temperatures of (a & b) –40 (c) –30 (d) –20 (e) –10 (f) + 0°C in quasi-static loadings

As shown in Fig. 3, distinct transgranular crystallographic faceting and cleavage fractures are detected in fatigue failure mechanisms at a subzero temperature of –40°C. This transgranular faceting mechanism involves very fine and non-distinct features, resulting in a highly smooth failure surface. Most of these cracks are involved in the higher fatigue loading fractures, in contrast to the lower fatigue loading. These specimens also demonstrated a significant increase in fatigue life at subzero temperatures.

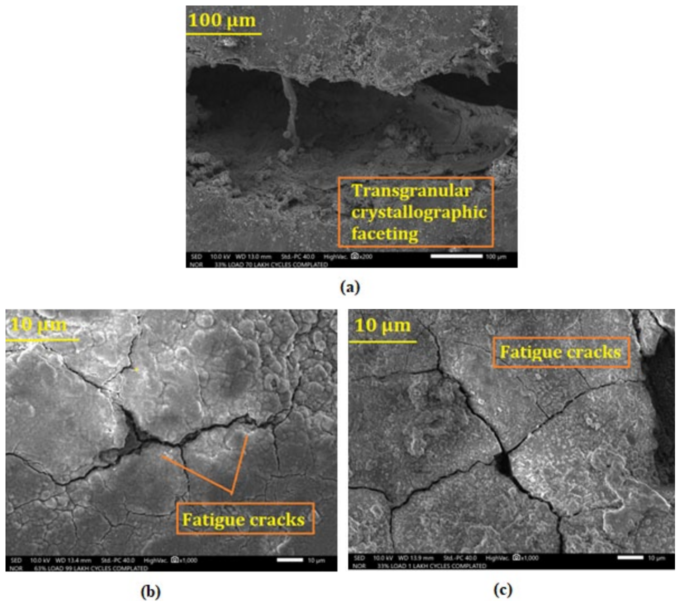

Fig. 3. Scanning electron microscopy of SAE 1040 at subzero temperatures of –40°C (a) higher (b) medium (c) lower cyclic loadings

The fractography investigation of the C45 material was conducted under quasi-static conditions at a temperature of –40°C, as depicted in Fig. 4. The brittleness of C45 steel becomes more evident when it is subjected to cold temperature conditioning. The shift from a ductile to a brittle condition transpires as the temperature of the steel decreases. There is significant evidence indicating that the fatigue strength and durability are superior after DBTT at temperatures below freezing. As temperatures decreased to sub-zero temperatures, the fracture surface of C45 steel exhibited a transition from ductile dimples at room temperature to cleavage at –40°C. The transcrystalline cleavage fracture surfaces were observed under quasi-static flexural stresses. The occurrence of this cleavage results in the creation of brittle cracks following the deformation of the material and the emergence of ductile cracks. The subzero conditioned quasi-cleavage fracture specimen has superior flexural strength properties. This is attributed to its reduced grain size.

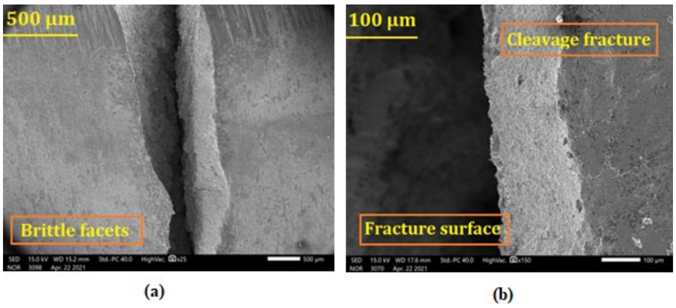

Fig. 4. Scanning electron microscopy of C45 at subzero temperatures of –40°C in quasi-static loadings

Under flexural fatigue testing, the C45 plate specimens showed fatigue striations with crack initiation sites. The intergranular fracture zone occurs during the initiation of the fatigue crack. At -40°C during fatigue loading, interior facets become more brittle, and crack nucleations are transgranular in nature. The lower fatigue loads showed crack initiation and minimal fatigue striations on surfaces with infinite durability, while in medium and high loadings, the fatigue cracks nucleate in transgranular fracture modes, demonstrate delamination, and specimen broken.

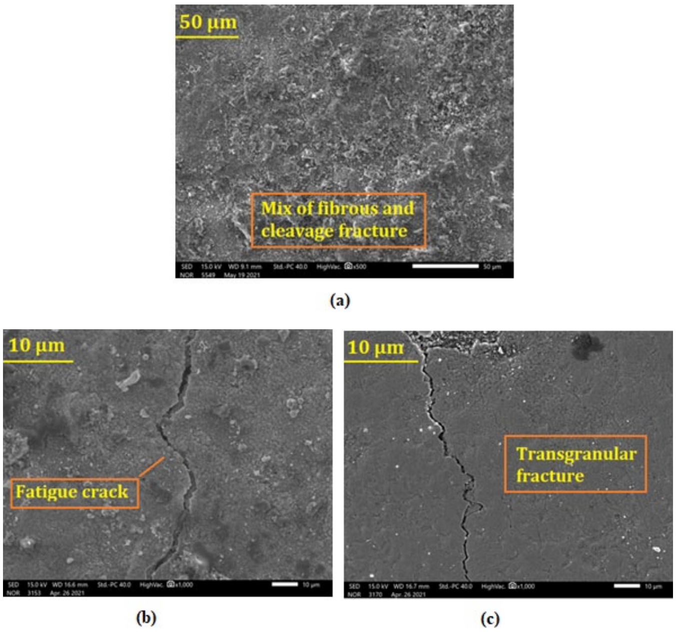

Fig. 5. Scanning electron microscopy of C45 at subzero temperatures of –40°C (a) higher (b) medium (c) lower cyclic loadings

5. Conclusions and Future Scope

The flexural quasi-static and fatigue investigations were carried out on SAE 1040 and C45 automotive steels at subzero temperatures for failure characterization. The steel specimens were preconditioned at subzero temperatures before the mechanical testing. The failure characteristics of automotive steel used in stabilizer bars and leaf springs were analyzed under service loading and summarized as below:

- The flexural strength of the SAE 1040 stabilizer bar increased and showed better mechanical properties at subzero temperatures. The fractographic observations revealed that BCC ferritic SAE 1040 had cleavage, quasi-cleavage, and fine step-like feather marks in the DBT range of –20°C to –40°C. The fatigue specimens at a low temperature of –40°C underwent 100,000 cycles, demonstrating that DBT and sub-zero temperature equilibration treatment enhanced resistance to crack initiation and propagation under cyclic loads. The subzero temperatures fatigue specimen experienced superior quasi-static and durability as compared to room temperature conditioning.
- Subzero temperatures boosted the static flexural strength of the C45 leaf spring. Their fatigue life has been nobly reformed at a temperature of –40°C. The C45 steel leaf spring exhibits transcrystalline cleavage fracture under quasi-static stresses, as demonstrated by a fractographic study. Fatigue striations with intergranular facets were observed in the fracture specimens of C45 steel at increased fatigue loadings. Under the conditions of subzero temperature conditioning, the damaged samples exhibit the formation of cracks on the surface by the process of transgranular nucleation. Therefore, the C45 demonstrates enhanced resistance to fatigue at sub-zero temperatures, although its hardness remains a potential issue.
- The scope of this study has grown to include studies of fracture mechanics at subzero temperatures, the reliability studies of acoustic mechanical and vibrational dynamics components, and unnotched and notched mechanical performance in quasi-static fatigue and dynamic loading could prove opposing outcomes.

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