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ABSTRACT

Belleville washer steel springs are characterized by a long fatigue life, better space utilization, low creep tendency, and high force bearing capacity with a small spring deflection. In the case of thicker springs, a greater force bearing and greater stiffness are obtained, but the deflection of the spring is reduced. In such a case, the fatigue life is reduced and there is a very high probability that a Belleville washer spring may fail in a brittle manner, causing additional damage to machinery. In order to prevent such a fracture of a Belleville washer, an elastomeric filling was used on both free surfaces of the spring. Experimental testing and numerical analyses show that enhanced loading characteristics were obtained when the elastomer filling was increasingly involved in the force bearing process. When the elastomer filling is compressed, the stresses in the Belleville washer steel are reduced, because the majority of the deflection stress is shared by the elastomer instead of the steel.

Keywords

Belleville washer spring, elastomer, damping, stress concentration, finite element method

Introduction

Belleville washer steel springs are characterized by long fatigue lives, better space utilization, low creep tendency, and a high force bearing capacity with small spring deflections. The deflection and spring constant can be regulated easily by stacking several springs together along their axial direction either in parallel or in series [1]. These springs are generally used as dampers in situations when small deflections are required. Although their hysteresis losses are small, because there are large stresses on their outer edge they are susceptible to plastic deformation and crack initiation.

Stiffness increases often result in a danger of brittle failure when the ratio between the outer diameter and the thickness is less than 30 and the ratio between the outer and inner diameters is large.

Usually, the maximum washer spring stress is limited by the material properties, and the applied tensile stresses should be less than the yield strength of the material. A problem appears when the washer spring is overloaded with a force that causes greater stresses than allowable. This can lead to a loss of integrity in a stack of washer springs and, subsequently, brittle fracture.

Unlike steel, elastomers have a notably low Young's modulus, large deflections, and large hysteresis losses that make them perfect dampers [2–4]. Elastomers are also known to have a large yield strain relative to other materials.

The integration of both materials has already been explored in situations where the integrity of the component and the dissipation of energy due to vibrations are both essential [5,6]. In this article we propose a composite spring with enhanced spring and damping characteristics. In order to prevent the loss of integrity or cracking of the washer spring, and to improve the characteristic curve as well as to increase the hysteresis loss, we introduced an elastomer filling in the outer and inner space between two washers.

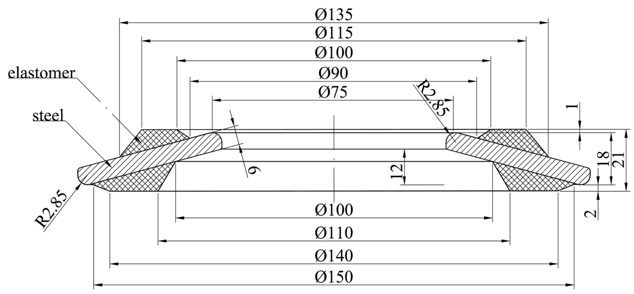
Materials

The Belleville washer springs were made of DIN 38Si6 (AISI 1035) spring steel. The washer dimensions were not standard according to DIN 2093 [7]: the outer diameter $D_e = 160$ mm, the inner diameter $D_i = 70$ mm, the thickness $t = 6$ mm, the cone height $h_0 = 12$ mm, and the total height $l_0 = 18$ mm. The material's Young's modulus is 210 GPa, its Poisson's ratio is 0.3, the yield strength is 1050 MPa, and the tensile strength is 1200 MPa. The material was quenched and tempered.

Samples of the elastomer were obtained from Sava d.d. Kranj, Slovenia, an industrial rubber company (R & D Institute). The material is a mixture of natural and synthetic elastomers with the addition of graphite and proprietary substances. The hardness of the vulcanized elastomer was 68°Sh. The tensile-compression rheological cyclic characteristics of this elastomer provided by the producer were used for the finite element modeling and analyses discussed in the fourth section of this paper. Permission to publish the rheological data was not granted.

The elastomer was bonded to the steel with Chemostil polymer adhesive and then via mold vulcanization of the elastomer on both the inside and outside surfaces of the Belleville washer spring, as shown in **Fig. 1**. Internal and external elastomers are designed in such a way that when a deflection of 9 mm is reached, they fill all the space between two washers in the stack. Because the elastomer characteristic curve is much flatter than the characteristic curve of the steel, pre-compression of the elastomer has to be achieved before the steel components come into contact. To achieve this, the elastomer layer is elevated by 1 mm on the outer side and by 2 mm on the inner side as shown in **Fig. 1**.

FIG. 1 Drawing (units in millimeters) of a composite spring.

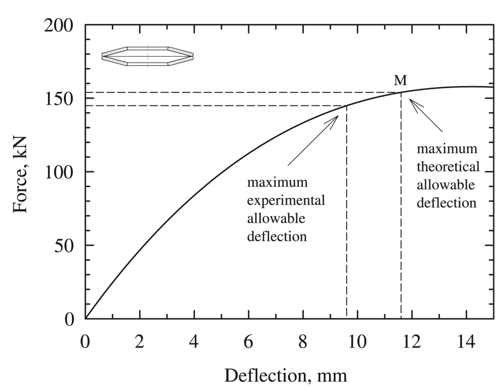


The internal elastomer is shifted outward and the external elastomer inward in order to successfully redistribute strains at the inner and outer edges of the washer along the whole area of the Belleville washer, thereby reducing the strains at the inner and outer edges of the washer.

In order to reduce friction between the Belleville washer and the piston or the base plate, two washers were used in series. The theoretical characteristic spring rate curve for a washer stack of two simple Belleville washers in series is shown in **Fig. 2**. Note that only negligible hysteresis behavior is expected, as hysteresis loss might be due to small friction only between the washer and the piston.

Unfortunately, the spring's rate curve is limited by the maximum strength capacity of the material. In the event of static or quasi-static forces, plastic deformation occurs, when the stresses in certain areas exceed the yield strength. Theoretically, the reference stress is the stress at the point OM, σ_{OM}; this value should not exceed the tensile strength R_m of the material. For spring steel, as per DIN EN 10132-4 [8] and DIN 17221 [9], the tensile yield strength is $R_m \approx 1600\ \mathrm{N/mm^2}$ [10]. Using

FIG. 2 Theoretical characteristic curve of two simple Belleville washers in series [1].



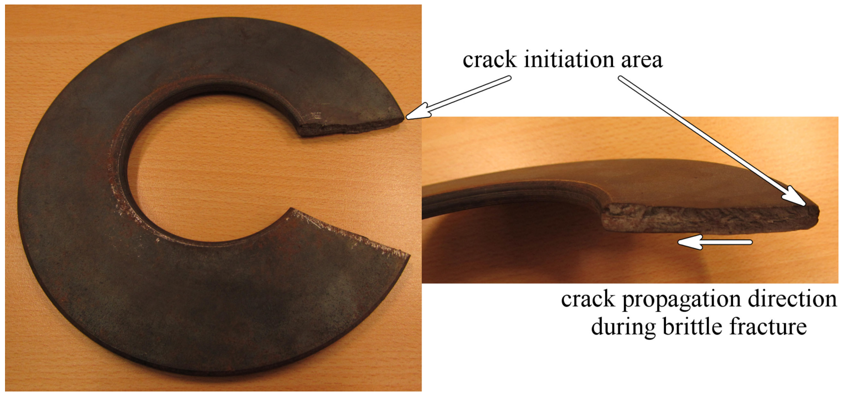


FIG. 3
Fracture surface of a Belleville washer after a static compression test at a force of 145 kN.

calculations for σ_{OM}, we have concluded that the yield strength is achieved for a deflection of $s \approx 5.8$ mm ($s \approx 11.6$ mm for two washers in series) for a single washer that corresponds to a force of 154 kN.

Both maximum deflection and force are much smaller for standard washer springs. The closest standard washer spring is the DIN 2093-B 160 washer, which has dimensions of $D_e = 160$ mm, $D_i = 82$ mm, $t = 6$ mm, and $h_0 = 4.5$ mm. Its maximum allowed force is 41 kN at a deflection of 3.38 mm [10].

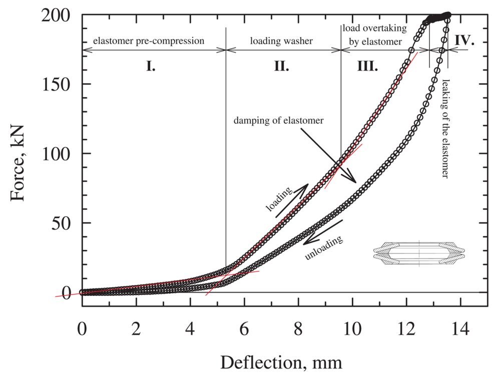
To obtain an experimental force limit, we performed a static compression test on a single Belleville washer with a lower cone height ($h_0 = 3.75$ mm) and a slightly larger outer diameter ($D_e = 164$ mm) and inside diameter ($D_i = 70$ mm). Brittle failure occurred at a compression force of 145 kN and a deflection of 4.75 mm. Fractographic investigation showed that the crack initiated under the surface of the outer radius of the Belleville washer as shown in **Fig. 3**. Therefore, two Belleville washers can provide a maximum deflection of 9.5 mm at 145 kN of compression force. The theoretically obtained maximum force of 154 kN is therefore greater than the experimental force, as we expected.

With the introduction of an elastomer filling on both sides of the Belleville spring as shown in **Fig. 1**, we expect changes in the loading characteristic, but the spring should be applicable as an engineering machine element just like the original Belleville washer spring. We have studied the characteristics of a spring stack composed of the two composite springs in series (**Fig. 4**). To obtain the characteristic curve of the washer stack, deflection was measured as a function of force. The static compression tests were carried out on an INSTRON 1255 universal static-dynamic testing machine at ambient temperature with a constant deflection speed of 5 mm/s. In general, five cycles of loading were required in order to untangle the network of the polymer chains and obtain steady-state hysteresis characteristics [11]. The repeatable loading characteristic is shown in **Fig. 5**.

Figure 5 shows clearly the hysteresis due to the difference in loading and unloading paths. It is an additional benefit of the new modified design, because it is obviously a significant contribution to the damping potential of the spring system. The larger contribution of the hysteresis behavior comes from internal and external friction of the elastomer, while the smaller contribution

FIG. 4
Composite spring.

FIG. 5 Experimental characteristic curve of two composite springs in series.



corresponds to the sliding of the elastomer along the steel plates at internal and external parts of the spring system.

Along the loading path, four different behavior regions can be identified. In region I, the steel part of the spring is not yet in contact with the metal surface, and the elastomer is being pre-compressed. This can be recognized as a shallow slope of the loading curve at the beginning. In region II, the metal and steel parts are in contact and most of the force is taken by the washer. This part of the loading characteristic slope is similar to the Belleville washer characteristic slope illustrated in **Fig. 2**.

However, with further increases in the deflection, the elastomer–metal contact surface increases exponentially, leading to an exponential increase of the loading characteristic slope as well, shown in region III. Consequently, the contact stress between metal and the steel part of the washer is reduced, preventing crack initiation in the contact zone. This can be considered as an additional benefit of the proposed composite spring.

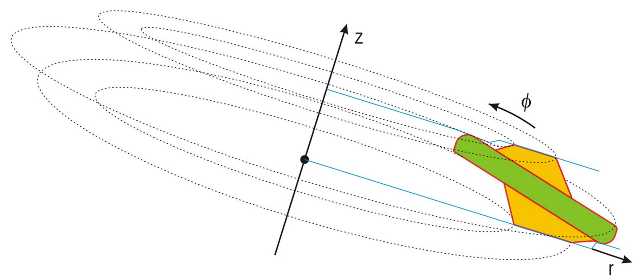
Finally, in region IV, the curve flattens, as the additional deflection forces the elastomer to "leak out" of the space between two washers. The constant loading characteristic of the composite spring can be used as a safety feature that prevents damage of the machine and structure. Because the working domain of many machines is limited by a certain maximum force, it is desirable to have a safety element fail and release deflection without additionally increasing the force when the maximum force is reached. This property is yet another benefit of the proposed composite spring.

Finally, we tried to obtain an experimental force limit of the composite spring. However, even when the spring was subjected to the maximum available compression force provided by the testing machine (i.e., 1000 kN), it did not fail.

NUMERICAL MODELING

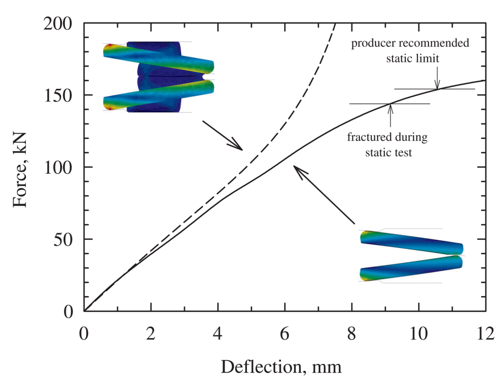
In order to estimate the effect of the elastomer filling on the stress reduction in the steel Belleville washer, numerical modeling of the simple Belleville washer and the composite spring was conducted. The springs are rotationally symmetric, and only the cross-section of the spring was selected for modeling with finite element analysis, as shown schematically in **Fig. 6**. A stress-strain deformation analysis was made using the numerical solver ABAQUS/Standard 6.7-1. Because of the complexity of the physical model, modeling of the washer was done by the pre-preparation model program ABAQUS/CAE and later by modifying the original code of ABAQUS program. Faster computation was ensured by an axial symmetrical plane model that is supported by the numerical packet ABAQUS with a pre-processor and post-processor CAE. To obtain greater precision in the results while keeping the calculation time reasonably small, 2505 square elements of second-order CAX8 were used for the discretization. Meshing was done by part modeling with a high density of elements in the contact area of the three-dimensional model.

FIG. 6 Geometric model of the mechanical spring system used in the numerical simulation.



The mechanical characteristics of the elastomer and the steel were used in the model, as mentioned in the second section of the paper. Contiguous elements from both sides were defined as perfectly stiff objects, and all degrees of freedom were blocked except for the axial vertical movement of the upper element. Normal deformation in the vertical direction was defined with stiff contact, and tangential deformation in the radial direction was determined by a coefficient of static friction of 0.12 between two steel surfaces and 0.8 between steel and the

FIG. 7 Numerically modeled loading characteristics of both the composite spring and a simple Belleville washer with controlled deflection of two springs in series.



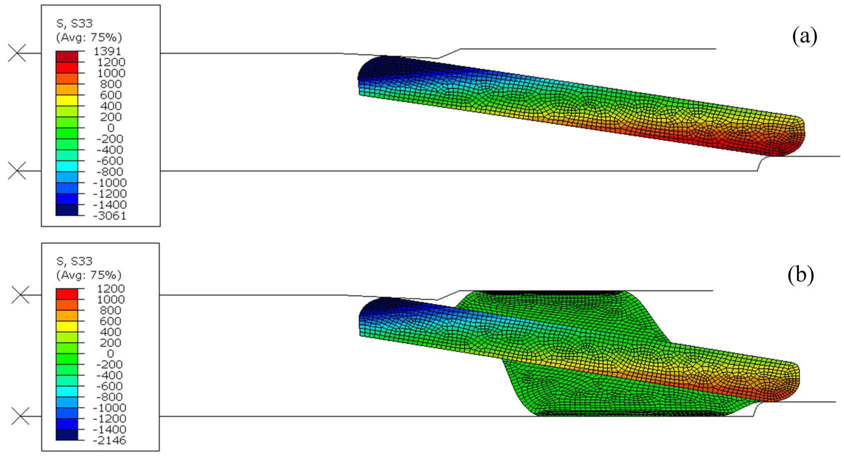


FIG. 8 Numerically modeled distribution of coordinate σ_{33} stress field at a deflection of 2.5 mm for (a) a simple Belleville washer and (b) a composite spring consisting of a washer and elastomer.

elastomer surface (these values were obtained from the literature [1]).

Numerical simulation of the loading assumed deflection control as was used in the experiment. The total force was calculated as a resistance response of the spring system versus deflection. **Figure 7** shows the loading characteristics of two simple washer springs and two composite springs in series. At the beginning, both spring systems have similar characteristics, but after a deflection of 2 mm, the simple washer spring shows regressive characteristics, whereas the composite spring shows progressive characteristics. One can note that the deflection of the composite spring is much less at the same force, so the steel deflection is smaller as well. This leads to lower stresses in the Belleville washer steel.

Figure 8(*a*) shows the radial stresses σ_{33} obtained in the finite element analysis of a single simple Belleville washer compressed to a deflection of 2.5 mm. Note that the values correspond to a deflection of 5 mm for two springs in series and a force of 91 kN. The maximum radial stress σ_{33} at the outer diameter is greater than 1200 MPa. In the case of the single composite spring and the same deflection of 2.5 mm, a force of 104 kN was obtained, as shown in **Fig. 8(*b*)**. The maximum radial stress σ_{33} at the outer diameter is now less than 1200 MPa, in spite of fact that the force is more than 10% greater (e.g., 13 kN greater).

In order to determine the plasticity of the steel, the von Mises stresses were calculated numerically for the same deflections and forces as used above. **Figure 9** shows the equivalent von Mises stresses σ_{eq} obtained for both the composite spring and the simple washer. The maximum equivalent von Mises stresses σ_{eq} at the outer diameter were larger than 1426 MPa for the single Belleville washer [**Fig. 9(*a*)**], whereas the von Mises stresses σ_{eq} were less than 1200 MPa for the composite spring [**Fig. 9(*b*)**], lower than the ultimate tensile strength of steel.

Numerical finite element analyses showed that the von Mises stresses reach the steel tensile strength at a deflection of about 5 mm for the two springs in series. However, it was experimentally shown that both the simple Belleville washer and the composite spring could reach even greater deflections. This can be attributed to the fact that a better spring steel material has

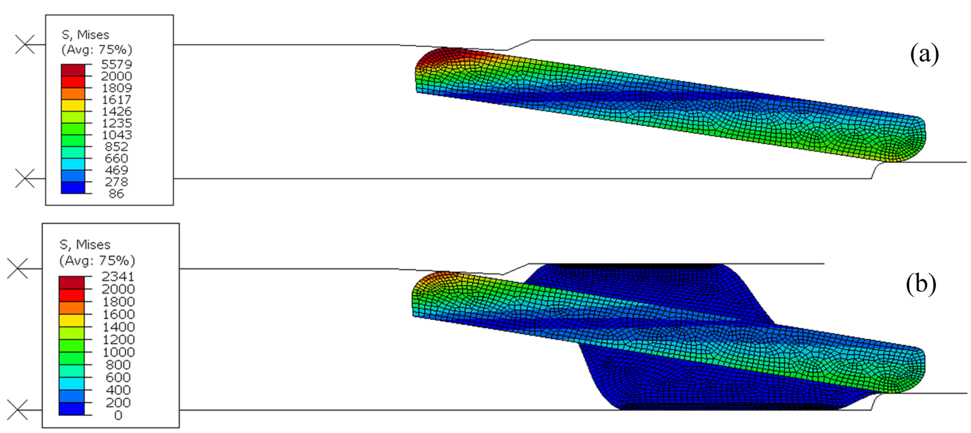


FIG. 9 Numerically modeled distribution of equivalent von Mises stress field at a deflection of 2.5 mm for (a) a simple Belleville washer and (b) a composite spring consisting of a washer and elastomer.

been used than assumed in numerical analysis. However, we can undoubtedly conclude from the finite element analysis that in spite of the fact that the loading characteristic slope of the composite spring increases, the intrinsic stresses of the steel are lower than in the case of the simple Belleville washer.

Conclusion

In this article we present a practical application of a method using an elastomer filling on both free surfaces of a Belleville washer in order to prevent simple washer fracture. Because the elastomer metal contact surface increases exponentially, the loading characteristic slope increases exponentially as well. Consequently, the contact stress between the piston and the steel part of the spring is reduced and the force limit exceeds 1000 kN, which corresponds to the maximum capacity of the testing machine; this can be considered as an additional benefit of the proposed composite spring. It has thus been shown that by combining properties of an elastomer and a Belleville washer spring, it is possible to create a reliable mechanical spring system.

Experimental testing shows the following benefits of the new composite spring design:

- Loading and unloading curves point to a significant hysteresis effect and a damping of the energy, so that the composite spring damps vibration better than the simple Belleville washer.
- Greater forces can be achieved at the same deflection without mechanical failure.
- With elastomer leaking out of the space between the two washers at high forces, an almost constant loading characteristic slope is achieved, which can be used as a safety feature. This is not possible with a simple Belleville washer.

Numerical analyses revealed the reduction of both stresses (radial and von Mises) in the most critical part of the simple Belleville washer within the composite spring. These results point to important benefits of the composite spring and usefulness of its application in the broader area of machine design. The developed composite spring proved to be appropriate for a wider range of uses than conventional springs. In particular, as many machines' working domains are limited by a certain maximum force, it is desirable that a safety element fail and release deflection without additional increasing force when the maximum force is exceeded, which is achieved with composite spring.

A possible drawback of the composite spring is the fact that it can no longer be stacked in parallel.

Only a general idea of the possibilities of developing composite spring systems, based on experimental and numerical evidence, is presented in this article. The capability for greater forces and better protection against fracture than possible with conventional springs justify further investigation. Further investigation of the design and the loading characteristics, including the fatigue, lifetime, and behavior of both materials, is already underway.

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