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Surface residual stresses induced by torsional plastic pre-setting of solid spring bar

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ABSTRACT

Residual stresses could be induced by the plastic torsion loading of a solid round bar. This article deals with the residual stresses generated at the surface during the process of plastic pre-setting. Residual stresses were measured on the surface of a specimen by x-ray diffraction for different angles of subsequent plastic pre-setting. In addition, the residual stresses were calculated using analytical and numerical modelling by finite element methods. The analytical approach was based on the torsional characteristic, τ–γ, of the material and tension test results. It has been found that the direction of cold rolling on the surface has a significant influence on residual stresses, as it is reflected in the initial stress state. A good agreement between analytical modelling, finite element analysis, and experimental residual stress measurement was obtained.

1. Introduction

Residual stresses in mechanical components are a result of technological processes. Residual stresses usually arise due to additional deformation during cold surface deformation such as cold drawing, stamping, shoot peening, cold rolling, and/or pre-setting. Residual stresses play a significant role in stress magnitude and the failure of a component. One example of residual stresses preventing failure is the cold rolling of the surface of mechanical component in order to induce surface compressive stresses that improve the fatigue life of the component. Torsion specimens were surface cold-rolled and plastic pre-strained in the torsion direction. Surface rolling increases the compressive stress in the surface layers of the specimen, whilst the pre-setting acts in-depth. Both tensile and compressive stresses are in equilibrium within the material. During the usage of the mechanical part residual stresses are cumulative with applied ones. If the latter are time changing, and if the mechanical component is loaded with fatigue, then residual stresses can significantly affect crack initiation. Maximum applied stresses are mostly on the surface of mechanical parts (bending, torsion, or a combination), and the geometric changes and rough surface contribute an additional stress concentration. When the tensile residual stresses cumulate with the tensile applied stress on the surface of the mechanical component, it leads to a very unfavourable situation. Compressive residual stress on the surface is much more desirable and is subtracted from the applied tensile stress during use of the mechanical part. With the use of appropriate manufacturing processes (for example cold surface rolling, or pre-setting into the plastic range) it is possible to add compressive residual stress on the surface of the mechanical component.

The authors in [1] have investigated the influence of residual stresses due to pre-setting on the lifetime of the torsion specimens from spring steel. It was proposed that with an increased pre-setting angle, the lifetime falls at the same amplitude of the applied stress ratio (minimum stress/maximum stress) $R=0$ torsional fatigue. The analytical procedure for determining residual stresses based on the experimentally determined τ–γ characteristics was discussed.

In Ref. [2] authors investigated the influence of residual compressive stress on the lifetime of a torsion alternately-loaded hollow specimen made of spring steel. Residual compressive stress was simulated by a constant axial compressive force, and the specimen was loaded by alternating torsional fatigue at the same time. It has been established that the lifetime of the specimen with the increasing of the compressed axial pre-loading at alternating torsional fatigue, increases as well up to a certain point.

The authors in [3] studied crack shapes and their growth rate for S45 steel specimens under various combinations of torsion and constant axial force loads. They state that the crack propagation angle is about 45° for various loading amplitudes, that the static tension axial force together with cyclic torsion causes the accelerated growth of a crack and lowers the service life, and that the compression axial force, together with torsion, considerably increases the service life

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Nomenclature

C_0-C_5	Constants [dimensionless]
d	Diameter of the specimen [mm], distance between lattice [nm]
dr	Differential of radius [mm]
E	Modulus of elasticity [MPa]
G	Shear modulus [MPa]
l	Actual length of specimen [mm]
n	Order of diffraction [dimensionless]
R	Radius of specimens [mm]
r	Radius – variable [mm]
R_a	Roughness [μm]
R_m	Tensile strength [MPa]
r_p	Radius of proportionality [mm]
$R_{p0,2}$	Yield limit [MPa]
T	Torque [Nm]
T_{cal}	Calculating torque [Nm]
γ	Shear strain [rad]
γ_e	Elastic shear strain [rad]
γ_p	Proportional shear strain [rad]
γ_{pl}	Plastic shear strain [rad]
γ_{ps}	Presetting shear strain [rad]
γ_{res}	Residual shear strain [rad]
Δd	Change the distance between lattice [nm]
ε	Normal strain [dimensionless]
ε_e	Elastic normal strain [dimensionless]
ε_{pl}	Plastic normal strain [dimensionless]
θ	Angle of the diffraction beam [rad]
Θ_e	Elastic twist angle [rad]
Θ_{ps}	Pre-setting twist angle [rad]
Θ_{res}	Residual twist angle [rad]
λ	Wavelength of the x-ray beam
ν	Poisson's ratio [dimensionless]
τ	Shear stress [MPa]
τ_{cal}	Calculating shear stress [MPa]
τ_e	Elastic shear stress [MPa]
τ_p	Proportional shear limit [MPa]
τ_{ps}	Pre-setting shear stress [MPa]
τ_{res}	Residual shear stress [MPa]
б	Normal stress [MPa]
б$_1$, б$_2$	Principal stress components [MPa]
б$_{res}$	Residual stress [Mpa]

and does not affect the crack propagation angle. It was also stated that the direction of crack propagation depends on alternating stress and does not depend on median stress; however, the service life does depend on the latter.

The authors in [4] developed a method for investigating the growth of micro-structural short cracks in a ductile crystalline material. The crack itself was modelled by a distribution of dislocation dipoles of finite length, whilst the local plasticity was developed by the emission and annihilation of discrete dislocations. Investigations of a short-edged crack showed that the competition between increasing global stress due to crack advance and the increasing shielding effect on the crack's tip from dislocations within the plastic zone influences the crack growth. The distance between the crack tip and the grain boundary is shown to influence the crack growth characteristics, whilst the spreading of plasticity through a grain boundary was found to somewhat retard the crack growth. The theoretical consideration of the fatigue process explained how it is possible to extend the lifetimes of mechanical parts loaded with cyclical torsion fatigue, by using compressed pre-stress in the axial direction [5]. A method of discrete dislocations was introduced in order to explain the process within the crystalline material lattice. This process can lead to increase in the lifetimes of compressed pre-stressed mechanical parts subjected to alternate torsion fatigue-loading.

Other investigations have been performed in the past for smooth and pre-cracked specimens subjected to combined torsion and axial loadings [7,8]. These results confirm that high-cycle fatigue is a stress controlled process. Unfortunately, not many investigations have been concerned with low-cycle multi-axial fatigue. Investigations of the multi-axial fatigue of a specimen with a surface defect show that their results agree with the most popular multi-axial fatigue criteria that of a critical plane criterion [6,7,9]. The problem of residual stresses was extensively studied in several articles [10–14]. Especially, the combined loads are relevant for the problem under investigation. This problem was studied by Zyczkowski [15] and Kobelev [16,17]. Kobelev study an elastic-plastic work-hardening deformation under combined bending and torsion and residual stresses in helical springs. He fund that theory of residual stresses in helical springs allows calculating the stresses during the coiling and presetting.

Residual stresses were introduced into the surface of the torsion test specimen by means of surface cold rolling and using a torsional pre-setting.

The article discusses residual stress distribution on the surface of the torsion loaded specimen during the process of pre-setting and a comparison with analytical and numerical calculation as well.

2. Material characteristics and specimens

Torsion and tensile specimens were made from high-strength spring fine-grain steel grade VCN. The chemical composition is listed in Table 1 as weight%. The used material was hot rolled, forged, and soft annealed during the manufacturing process. The final shape and specimen properties were achieved by the following mechanical processes: programmed turning, milling, polishing and at torsion specimens cold rolling of their surface to a roughness of Ra ≤ 0.1 μm.

Table 1
Mechanical properties of the used spring material (grade VCN).

%	C	Si	Mn	Cr	Ni	Mo	V	Cu	P	S
	0.44	0.28	0.56	0.87	1.41	0.26	0.11	0.12	0.009	0.002
UTS, R_m [MPa]	Yield strength, $R_{p0,2}$ [MPa]		Torsion elastic limit, τ_e [MPa]		Shear modulus, G [GPa]		Modulus, E [GPa]		Hardness, HRc	
2010	1570		800		75		193		52–55	
Tensile fatigue limit $R=0$ [MPa]	Tensile fatigue limit $R=-1$ [MPa]	Torsion fatigue limit $R=-1$ [MPa]	σ_0 [MPa]	ε_0 [−]	Constantα [−]	Hardening exponent [−]				
1200	800	520	1287.5	0.0068	0.01204	0.08269				