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Influence of Notch Effects Created by Laser Cutting Process on Fatigue Behavior of Metastable Austenitic Stainless Steel

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Abstract

Laser cutting is an attractive and innovative manufacturing process which has many advantages compared to conventional cutting methods. However, with increasing workpiece thickness an increase of the roughness along the kerf surface can be observed, which, in turn, can negatively affect the mechanical properties, in particular the fatigue strength. In this context, the purpose of the present study is to investigate the impact of the geometrical surface characteristics and microstructural changes after laser cutting in order to support the cutting process optimization concerning cyclic durability. Fatigue strength evaluation is performed with specimens cut out by high-power solid-state disk laser from sheets with thickness of 2, 4 and 6 mm made of metastable austenitic stainless steel type 304. Cyclic tests are carried out using a resonant pulsation testing system at test frequencies around 100 Hz at two different load modes, purely reversal load condition ($R = -1$) and tensile-tensile load condition ($R = 0.1$). In order to evaluate separately the effect of surface relief over the cutting kerf and burr in form of re-solidified drops, the fatigue specimens are tested at different surface conditions. The investigation comprises fractographic analyses in order to evaluate the influence of the surface roughness and surface-related macro defects on crack initiation. Additionally, phase analyses are performed to assess the deformation-induced phase transformation during cyclic testing and its influence on fatigue behavior, as well as microstructural investigation to analyze the material microstructural changes during the cutting process and its impact on material mechanical properties. The influence on fatigue strength of parts cut by laser is quantified and the characteristic dominating the fatigue life is identified.

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Keywords: laser cutting; notch effect; fatigue behavior; metastable austenitic stainless steel

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1. Introduction

Laser beam cutting can be classified into the group of thermal cutting methods to manufacture plate-shaped materials. This process is distinguished from conventional cutting methods due to the high material utilization rate, high cutting speed, high flexibility and low material deformation at the cutting kerf region. However, with increasing the material thickness an increasing surface roughness along the cutting surface can be observed, which, in turn, can negatively affect the mechanical properties, in particular the fatigue strength [1, 2]. Based on that and on the lack of reliable fatigue strength data from parts cut by laser, the use of this process to manufacture structural thick parts is restricted, limiting the potential application of this process in such cases. Moreover, in order to optimize the cutting process parameters not only concerning the cutting speed and reliability but also to minimize the influence of laser beam cutting on the cyclic strength, the interaction between the process parameters and geometrical and microstructural changes in the region of the cutting kerf and fatigue crack initiation must be identified. It is known, for instance, that a high cutting speed and a low output power produce less pronounced surface relief. Nonetheless, using this process strategy cutting edges with inhomogeneous characteristics are produced [3]. In the case of metastable austenitic steel AISI 304 the use of fiber laser leads to the creation of a high surface roughness for sheets thicker than 4 mm. On the other hand, using CO_2 laser cutting this behavior is just observed for plates thicker than 8 mm [4]. Furthermore, in addition to the laser cutting process, the material composition and the prior surface quality play an important role on the cutting quality, see i.a. [5, 6]. For example, for steel plates with thickness of 25 mm cut by flame cutting it is shown that Cu and Ni in low content levels have a favorable effect on the cutting quality.

The period of fatigue crack initiation phase on the entire fatigue life of samples and components depends not only on the stress level but also substantially on the initial state of the material (defects-afflicted or quasi defect free), the configuration of the defect (macroscopic notch) and, last not least, the surface quality. The assessment of these influencing factors in high cycle fatigue (HCF) and very high cycle fatigue (VHCF) regime must be separated in order to identify the dominant failure relevant effect and thereby to accomplish the basis for the material or strength-oriented process optimization [7]. Due to its good formability the austenitic stainless steels are among the stainless steels the most common used type of material. Moreover, under certain conditions this material can undergo a deformation-induced transformation from austenite to the harder α′-martensite phase [8], which has a beneficial effect on the fatigue resistance [9] and can be used to locally optimize the static and cyclic strength properties of sheet metals by means of the production process [10]. Additionally, to promote the deformation-induced martensite formation, a critical threshold value of plastic-strain amplitude and a certain amount of accumulated plastic strain needs to be exceeded [11].

2. Laser Cutting Process and Experiments

The geometrical surface characteristics of parts cut by laser, to a large extent, depend on the sheet thickness. For this reason, to investigate the influence of laser cutting process on fatigue behavior, specimens of metastable austenitic stainless steel type AISI 304 were cut out by high-power solid-state disk laser from sheets with 2, 4, 6 mm thickness according to the geometries showed in Fig. 1. The cutting machine used is a Trumpf TruDisk 5001 laser source; the most relevant process parameters are listed in Table 1. The parameters from the “laser beam” group normally are related to the cutting machine and cannot be modified. The beam quality M^2 is a parameter which characterizes the deviation of the real beam dispersion from an ideal laser beam with a Gaussian distribution of energy intensity and $M^2 = 1$. To the category “cutting process” belong the parameters focal position and cutting speed which have a strong influence on cutting quality. For this study, it was determined that for the focal position 0 the laser beam is focused on the workpiece top surface.

During the cutting process not only a surface relief is created over the cutting kerf but also burr in form of re-solidified drops are deposited at the cutting edge. In order to separately evaluate these effects the fatigue specimens were tested at three different conditions – laser cutting without post-processing (as-cut condition), trimmed cutting edges (without burr) and electrochemically polished surfaces. The last condition represents the fatigue behavior of