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Shear-surface improvement of the austenitic stainless steel AISI 304 using high-speed punching

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The effect of high-speed punching on the quality and corrosion resistance of the shear surface of the austenitic stainless steel, American Iron and Steel Institute (AISI) type-304 (AISI-304 SS), has been investigated. The work presented in this article aims at evaluating the improvement in the shear-surface quality of the AISI-304 SS resulting from the use of high-energy-rate forming (HERF) machine. The appraisal is based on criteria related to the characterization of surface accuracy and corrosion resistance. For this purpose, AISI-304 stainless steels were cut with three different types of cutting machines, namely, laser cutting machine, conventional press at low punch velocity (0.5 m/s), and HERF at high punch velocity (12 m/s). By using the HERF machine, a reduction of more than 50% in the surface roughness average was achieved, and better resistance to both stress-corrosion cracking and pitting corrosion was noticed. Before and after the accelerated corrosion tests, samples were subjected to scanning electron microscopy to study the changes during the cutting process of the samples at room temperature. HERF-cutting was observed to improve the corrosion resistance of AISI-304 SS. Moreover, specimens cut using the HERF machine showed excellent corrosion resistance compared with those cut in a conventional manner with laser.

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1. Introduction

American Iron and Steel Institute (AISI) type-304 stainless steel (SS) possesses the unique combination of superior mechanical properties and resistance to aqueous corrosion. Therefore, it is extensively used as a structural material in the nuclear industry [1]. However, this steel suffers from poor wear resistance in comparison to other SSs, leading to the premature failure of the engineering parts. Many of these failures in the marine, food, chemical, and energy industries are related to erosion wear due to the impact of high-velocity particles entrained in fluid streams [2].

Corrosion of SSs and other iron-based alloys have been extensively studied and well understood in the past few years; their electrochemistry is known in general. The most important interfacial and solid-state processes that lead to corrosion have already been described [3–7].

The key issue related to corrosion resistance is the stability and electrical behavior of the protective oxide layer on the steel surface. This may be investigated using a number of electrochemical methods, such as open circuit potential (OCP) measurements and the polarization method. Several experiments have been carried out to improve the corrosion resistance of AISI-304 SS. For example, in the study of Recco et al. [2], different surface treatments have been combined to improve the corrosion resistance of AISI-304 SS. In addition, the influence of addition of various materials to AISI-304 SSto enhance corrosion resistance has been studied. Cano et al. [8] have carried out an investigation using the X-ray photoelectron spectroscopy technique to define the influence of the implantation of nitrogen, silicon, and argon ions on the chemical composition and structure of the surface of AISI-304 SS, which affects their corrosion properties. Alternatively, Pardo et al [9,10] have attempted to evaluate the effect of (Mo, Mn) and (Cu, Sn) on the corrosion resistance of AISI-304 SS. In a third alternative, the corrosion resistance of AISI-304 SS has been improved using film coatings [11–16]. However, little research has been carried out on the quality of shear-fractured surface and the corrosion-resistance enhancement of AISI-304 SS by high punch speeds. Yaldiz [17] and Davies and Dhavan [18] have shown that the quality of shear-fractured surface improves and the amount of distortion is reduced by the use of high punch speeds. Therefore, further research needs to be focused on the corrosion behavior of the shear surface of AISI-304 SS at high punching speeds.

The objective of the present study is to investigate the impact of high punching speeds on the shear surface—corrosion behavior of AISI-304 SS. For this purpose, AISI-304 SS has been cut with three different types of cutting machines, namely, laser cutting machine (LCM), conventional press (CP) at low punch velocity (0.5 ms^{-1}), and high-energy-rate forming (HERF) machine at high punch velocity (12 ms^{-1}). By using HERF machine, a reduction of more than 50% in the surface roughness average (R_a) has been achieved, and better resistance to stress-corrosion cracking and pitting corrosion are observed. Before and after the accelerated corrosion tests, individual metal specimens were subjected to scanning electron microscopy (SEM) to study the cutting process of the workpiece at room temperature.

2. Experimental procedures

2. 1. Surface-roughness test of shear surface

The material used in this investigation was AISI-304 SS. This SS was cut with three different types of cutting machines, namely, LCM, CP at low punch velocity (0.5 m/s), and HERF machine at high punch velocity (12 m/s). The surface roughness was evaluated using a Talysurf stylus-type profilometer. The surface-roughness values were the central-line averages (R_a) and were used to evaluate the quality of the specimen surface. The surface roughness of each specimen was determined by averaging ten measurements carried out in various portions on the shear surface for each cutting condition.

2. 2 Corrosion-behavior test on the shear surface

The working electrodes (WE) were used for corrosion of the AISI-304 SS samples. The chemical composition of AISI-304 SS is tabulated in Table 1. The WEs were polished with silicon carbide papers from 3 through 1–0.5 µm and with velvet, rinsed twice with distilled water, washed in acetone, rinsed twice with distilled water again, and dried in air. For cyclic voltammetry (CV) measurements**,** deaerated sulphuric acid solution was used as the electrolyte and argon gas was bubbled for at least 45 min before each measurement The counter electrode used for polarization and corrosion measurements was a Pt-gauze electrode. The reference electrode used in all the experiments was a saturated calomel electrode (SCE). All the potentials were referred against the SCE.

The electrochemical behaviors of the specimens were analyzed in 3 wt.% aqueous NaCl solution at room temperature in a Pyrex glass cell. The corrosion behaviors of the samples were investigated using a potentiodynamic polarization technique. Polarization measurements were conducted using an electrochemical analyzer/workstation (Model 1100, CH Instruments, USA) with a three-electrode configuration. The exposed area of the specimens was about 0.5 cm^2. The specimens were covered with a cold-setting resin and immersed into the solution until a steady OCP was reached. After equilibration, polarization started at a rate of 1 mV/sn. Sulphuric acid solution (0.5 M) was used as the electrolyte for OCP measurements. The solution was deaerated by bubbling argon gas for at least 45 min before each measurement. At least four parallel measurements were conducted with freshly polished samples. For CV measurements, the cycle began at a cathodic overpotential of−1200 mV, and the scan was stopped as soon as the specimens reached an anodic overpotential of 1200 mV. After polarization, the specimens were cleaned mechanically and subjected to SEM observations using a Jeol 6390 scanning electron microscope. The results of the corrosion tests were evaluated using E_{corr} and I_{corr} values obtained from the polarization curves.

Table 1. Chemical composition of AISI-304 low-alloy steel.

Designation	Chemical Composition						
	C	Si	Mn	P	S	Cr	Ni
AISI-304 SS	0.070	0.750	1.980	0.042	0.020	18.45	9.88

3. Results and discussion

3.1 Effects of high-speed punching on the AISI-304 SS shear-surface integrity

The microgeometrical quality of the shear surface has been characterized by the parameter of Ra. Fig. 1 presents the relationship between the three different types of cutting machines that cut the AISI-304 SS specimens and the shear-surface roughnesses of the respective specimens. The measured surface Ra values of the specimens are ~0.32, 0.7, and 0.72 µm for the HERF machine, CP, and LCM, respectively. Increase in cutting speed has a tendency of improving the surface finish, thus reducing the Ra parameter, as previously indicated in the reports by Gurnel and Boothroyd [19, 20].

The surface roughness obtained using the HERF machine shows a reduction of more than 50% in the R_a value compared to that obtained using CP. Fig. 2 shows the AISI-304 SSs cut using three different types of cutting machines, namely, LCM, CP, and HERF machineThe surface roughness of the sample obtained with the HERF machine is much less than that of the samples cut using CP and LCM.

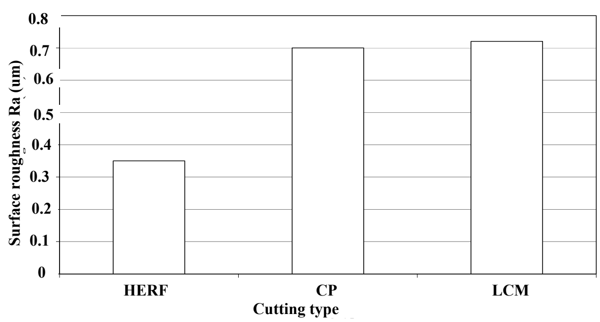
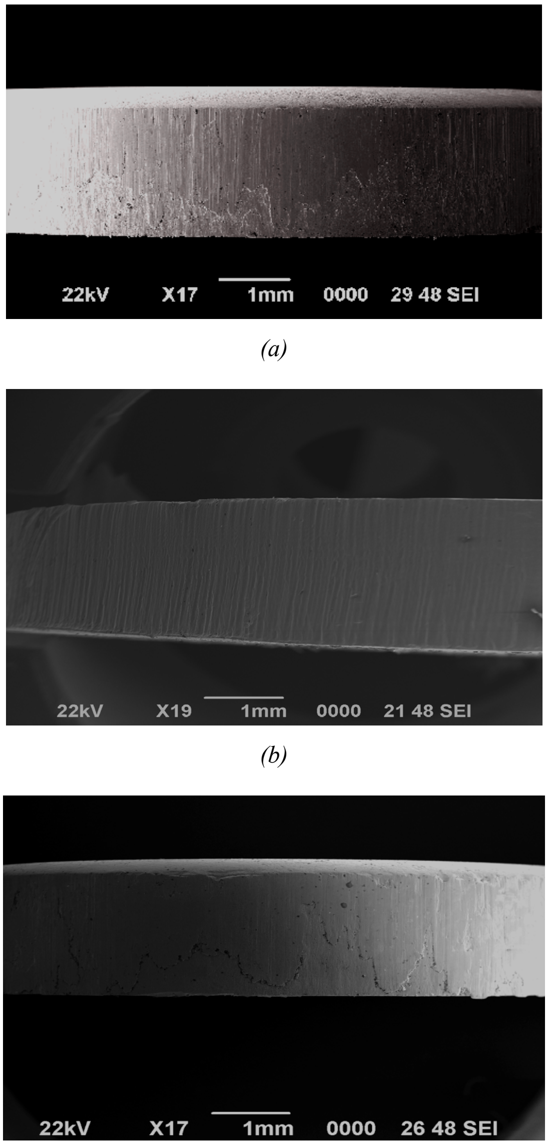


Fig. 1. Surface roughness average (Ra) for different cutting conditions.



(a)

(b)

(c)

Fig. 2. SEM images of the samples characterized by the parameter of roughness average (Ra) (a) CP (b) LCM (c) HERF machine.

3.2 Effects of high-speed punching on the corrosion behavior of AISI-304 SS shear surface

In Table 2, the average values of the OCPs and their standard deviations are listed. The OCP is the most negative for the CP-punched AISI-304 SS, followed by the SS cut with LCM, whereas it is the least negative for the HERF-punched steel. The order of the series can be represented as CP < LCM < HERF machine, as per the OCP values. The OCP has been determined by the equilibrium between the two electrode reactions: hydrogen evolution and iron dissolution. By assuming that the rate of hydrogen evolution reaction is independent of the electrode material, the more negative OCP implies a larger corrosion current and, thus, a greater vulnerability to corrosion.

Table 2. Open circuit potentials (OCPs) in 0.5 mol/dm^3 deaerated sulphuric acid solution (versus SCE).

Cutting Type	Number of experiments	OCP (mV)
Conventional Press	10	-482 ± 8
Lase Cutting Machine	10	-467± 6
HERF Machine	10	-440 ± 5

The potentiodynamic polarization curves of the samples cut using CP, LCM, and HERF machine are shown in Fig. 3. The highest corrosion resistance is shown by the HERF-punched specimen. It is evident that fast cutting can significantly improve the corrosion characteristics of AISI-304 SS. When compared with other cutting speeds, the corrosion resistance is generally worse because of the increasing surface energy after low punching speed.

Compared to the E_{corr} values obtained in this figure, the E_{corr} value of the HERF-punched specimen is ≈ ~925 mV higher than that of the CP-punched specimen and 788 mV higher than the LCM-punched sample (−587 mV, −450 mV, and 338 mV for CP-cut, laser-cut, and HERF-cut specimens, respectively). Moreover, the anodic current values (I_{corr}) of the samples after both conventional and laser cutting are in close proximity to each other and lower than the value for the sample cut with the HERF machine. The improved corrosion behavior of the HERF-cut sample is thus related to the fast cutting of the surface.

The specimen cut in a conventional manner shows active behavior, confirming a low corrosion potential (−587 mV) and very high anodic currents. The HERF-cut specimen is more resistant to general corrosion in comparison with the CP-cut and laser-cut specimens, but it is more susceptible to pitting corrosion. After the potentiodynamic polarization tests, the corroded specimens show the presence of many pits distributed on the surface, which is the typical outcome of chloride attack.

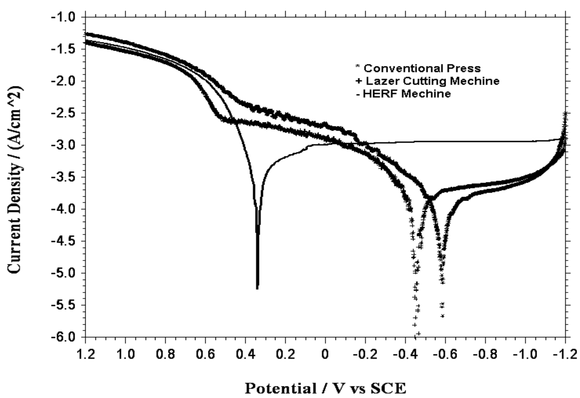


Fig. 3. Potentiodynamic polarization curves of the specimens cut at different punching speeds.

To provide an overall view of the electrochemical processes involved, CV has been used. Figure 4 shows the cyclic voltammograms of AISI-304 SS. The initial potential was set to −0.5 V versus the SCE, and the scans at 0.1 V/s started from the negative direction. For each specimen of cut AISI-304 SS, three potential regions may be defined. In region I, negative with respect to the OCP, the current is negative due to hydrogen evolution (−0.5 to −0.4V versus SCE). In region II, between the OCP and the potential of the passivation peak, the steel is known to dissolve (−0.4 to 0.2V versus SCE). Region III is the passive region (0.2 to 0.5). The passivation peak for the CP-cut and laser-cut samples are very clear, whereas it is very small for the HERF-cutsteel.

A smaller passivation peak implies the presence of a previously existing protective surface oxide layer. This argument leads to the conclusion that the protective oxide layer on the HERF-cut steel is so stable that it is only slightly reduced during the negative scan. In the case of the AISI-304 SS, however, the oxide layer is considerably reduced during the negative scan because the passivation peak exists in the scan. [3]

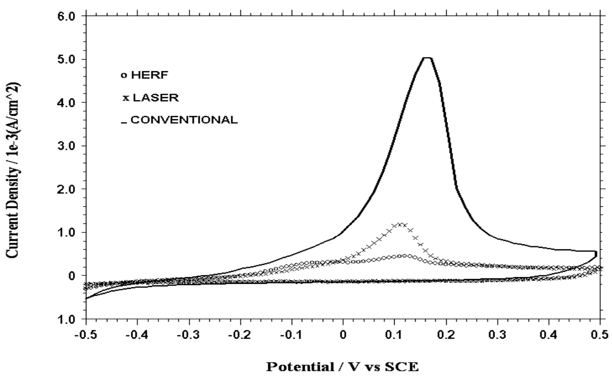
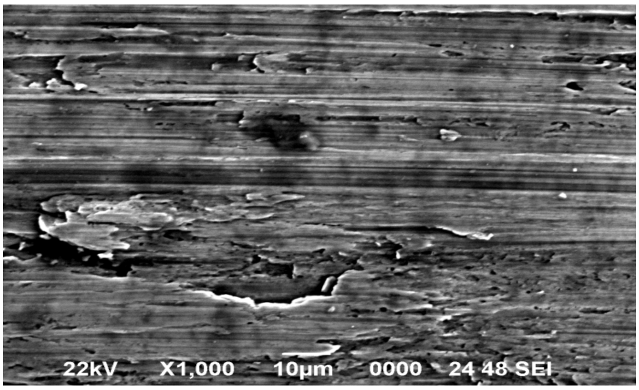
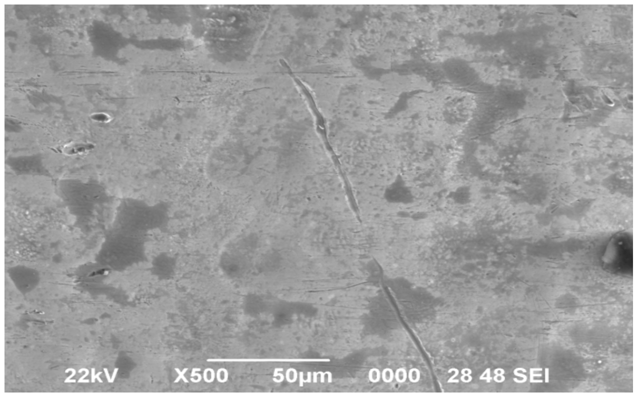


Fig. 4. Cyclic voltammograms for HERF cutting (frame cycle line), laser cutting (diagonal cross line), and conventional cutting (solid black line) of AISI-304 SS specimens in 0.5 mol/dm^3 sulphuric acid solution with a scan rate of 0.1 V/s, start potential of −0.5 V, and a negative first-scan direction.

Thus, CV indicates the the same conclusion as that obtained from the OCP measurements; in other words, it supports the observation that the HERF-cut sample is the most corrosion resistant of the steels. The results obtained from the CV study and OCPs are consistent with the results of the work described by Kerner et al. [3]. Figures 5 and 6 show the SEM micrographs of samples before and after the corrosion test. The reason for the occurrence of the pits is the local breakdown of the passivity occurring during the corrosion tests.



(a)



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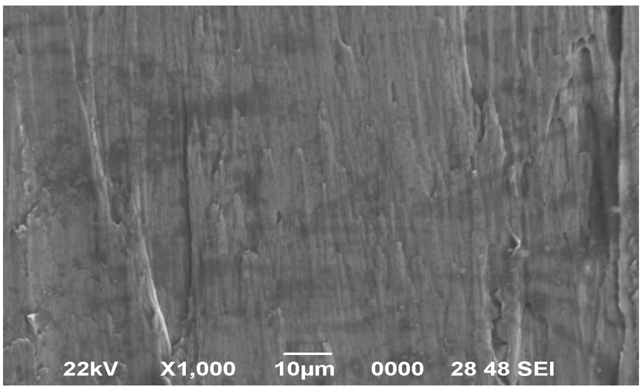

(c)

Fig. 5. SEM micrographs of the samples before corrosion test (a) CP (b) LCM (c) HERF machine.

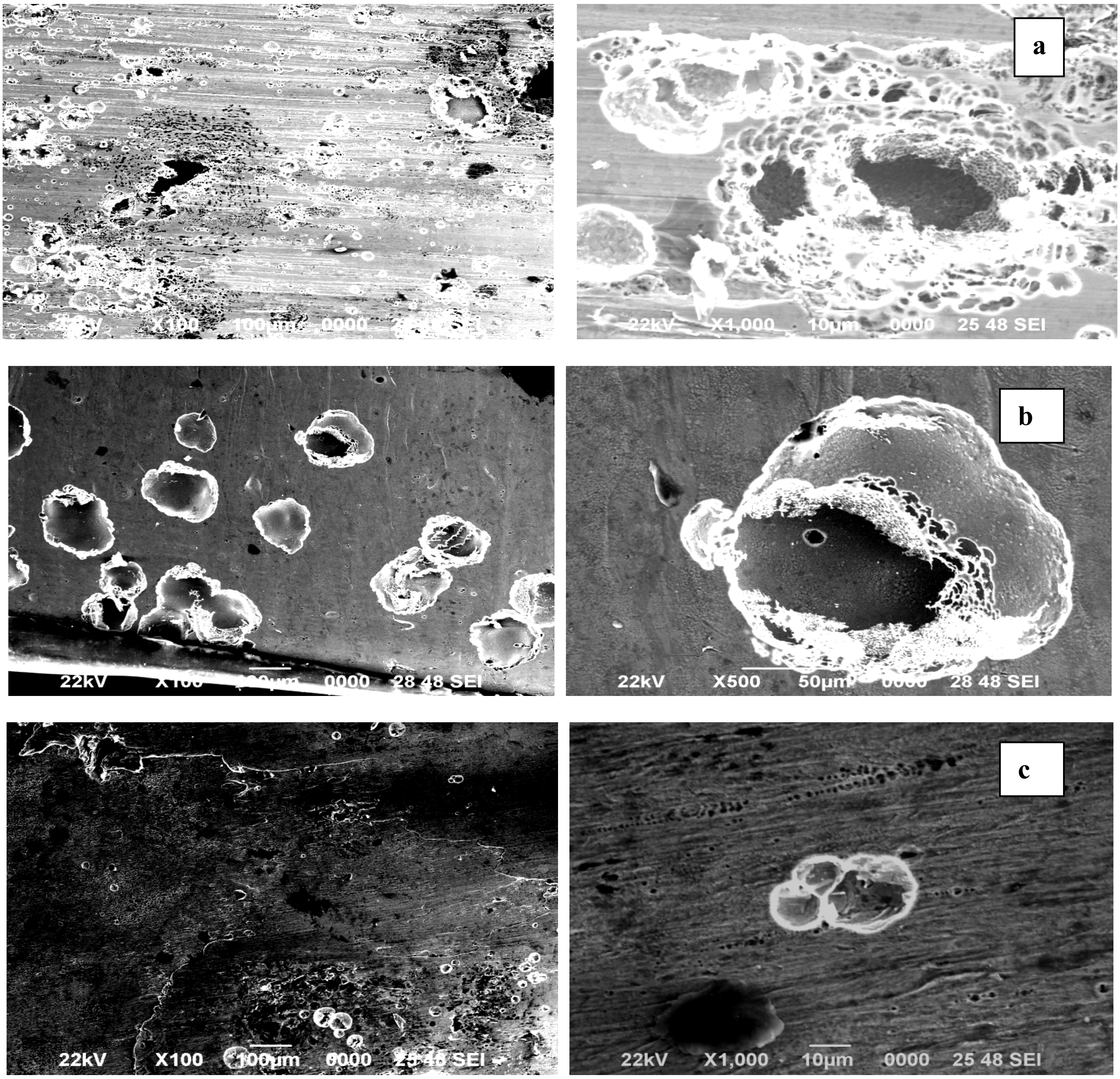

Fig. 6. Corrosion micrographs of specimens after corrosion test (a) CP (b) LCM (c)HERF machine.

Fig. 6 shows the SEM micrographs of the specimens cut using three different types of cutting machines. The metallographic investigations have shown that the effective corrosion generated on all specimens is pitting. The surface of the corroded sample of HERF-cut sample appears almost untouched, and no severe corrosion damage is observed at the end of the corrosion tests. Pitting corrosion produces holes and pits on the surfaces of metals, and these pits may be of different shapes and dimensions. The pits observed in this study are oval in shape, and their average dimensions are 40 to 90 µm. The sizes of the pit cells have been found to be in the range of ~20–35 µm,~170–195 µm, and~120–180 µm for HERF-cut, conventional-cut, and laser-cut specimens, respectively. From the corrosion tests, the HERF-cut specimens have been foumd to have smaller pit dimensions, and they show better corrosion resistance compared with the laser-cut and conventional-cut specimens because a smoother surface is formed on the surface after HERF cutting. However, corrosion resistance is inferior in the laser and conventional cuttings because of the slow speed of cutting of the surfaces.

4. Conclusions

In this study, the effects of high-speed punching on the quality and corrosion-resistance of the shear surface of the austenitic steel AISI-304 SS have been investigated. The following conclusions are obtained:

- Punching speed is very effective on the shear-surface roughness of the samples. When the punching speed is increased, shear-surface roughness of the samples decreases drastically.

- The corrosion resistance of HERF-cut specimen is better than that of the laser-cut and conventional-cut specimens.
- The best corrosion properties are obtained by HERF cutting because the high cutting speed yields the least roughness of the surface.

Acknowledgments

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